*Onderzoeksopdracht*

# Beste landbouwpraktijken van teelten in combinatie met nateelten/vanggewassen

## Eindrapport

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**Consortium**

Universiteit Gent
ILVO Plant
Inagro
Bodemkundige Dienst van België
Hogeschool Gent

# SHORT ENGLISH SUMMARY

## 1. Introduction

In temperate humid climates, catch crops have proven to be a useful tool in the abatement of soil erosion, nutrient leaching and soil organic carbon losses.

In Flanders (Belgium), the environmental policy allows farmers to apply manure after harvest of winter cereals at a rate of 60 kg N $ha^{-1}$, if they sow a catch crop before the 1st of September (on light textures) or before the 15th of October (on heavy textures). Farmers claim that fertilization stimulates catch crop growth and in that way increases benefits of catch crops. Nevertheless, the question was raised whether fertilizing catch crops would affect N losses during winter.

The main objective of this study is to investigate whether the application of pig slurry to catch crops sown after the harvest of winter cereals does not result in higher N losses from the soil between autumn and early spring compared to non-fertilized catch crops.

This report gives an overview of the results of field trials, incubation experiments and simulations carried out with the EU-rotate_N model and formulates scientifically based conclusions about the possibility of applying animal manure after winter cereals in Flanders.

## 2. Experimental lay-out

The main part of the research project was based on field trials which were installed during two consecutive years (2011-2013), each year on 4 locations with different soil textures. After harvest of the winter cereals, pig slurry was applied at rates of 0, ±60 and ±120 kg total N $ha^{-1}$. On each location 3 to 4 common catch crop species (white mustard, Italian ryegrass, black oat and a mixture of English ryegrass, red clover and white clover) were sown. A bare fallow was included. Catch crops were sown on 2 different dates on each location.

## 3. General conclusions

### *3.1 Representativity of the experimental fields*

- Catch crops were sown after harvest of winter cereals on 8 locations and during 2 experimental years (2011-2013). Together they made up a representative sample for agricultural soils which are used for winter cereal cultivation in Flanders.

### *3.2 Soil mineral nitrogen*

- When sown in good circumstances before the 1st of September, non-fertilized and fertilized catch crops developed well, took up soil mineral nitrogen ($N_{min}$) from the soil in autumn and reduced the risk of N losses during winter.
- For catch crops sown before the 1st of September, no significant mean differences (< 5 kg N $ha^{-1}$) were found in autumn (October-November) between non-fertilized catch crops and catch crops fertilized with a 60 kg N $ha^{-1}$ pig slurry application. However, significant differences were found for the corresponding bare fallows.
- For catch crops sown before the 1st of September, no significant mean differences (≤ 10 kg N $ha^{-1}$) were found in spring (February-April) between non-fertilized catch crops and catch crops fertilized with a 60 kg N $ha^{-1}$ pig slurry application, except for black oat where differences were significant.

- For catch crops sown before the 1st of September, significant mean differences (8-21 kg N $ha^{-1}$) were found in autumn (October-November) between non-fertilized catch crops and catch crops fertilized with a 120 kg N $ha^{-1}$ pig slurry application. For the corresponding bare fallows these differences were bigger and also significant.
- For catch crops sown before the 1st of September, slightly bigger but non-significant mean differences (1-26 kg N $ha^{-1}$) were found in spring (February-April) between non-fertilized catch crops and catch crops fertilized with a 120 kg N $ha^{-1}$ pig slurry application. Exceptions to this case are white mustard and black oat sown at the end of August where these differences were significant.
- If catch crops were sown after the 31st of August, a 60 kg N $ha^{-1}$ pig slurry application led to a significant increase in $N_{min}$ in autumn compared to non-fertilized treatments.
- Non-frost resistant catch crops die during winter and mineralize partly in spring; fertilized and/or late sown catch crops release more $N_{min}$ than non-fertilized and/or early sown catch crops.

### *3.3 Simulated N losses*

- Simulations showed strong reduction of nitrate leaching due to the presence of catch crops on 6 out of 8 field trials and under different weather conditions on loamy sand and silt loam. Under grass-clover nitrate leaching was higher than under the 3 other catch crops. In general the reduction of nitrate leaching by catch crops was stronger on heavier soil textures and with lower initial $N_{min}$ contents.
- Simulated average nitrate concentrations at 90 cm depth showed only small positive or negative differences between early sown catch crops with or without application of manure (60 kg N $ha^{-1}$). When sown late, a relatively high increase of the nitrate concentration was simulated due to the application of manure, but only under black oat and under grass-clover during cold and/or wet weather conditions, for which an overestimation by the model could not be excluded.
- Simulated gaseous N losses were generally small (< 7 kg N $ha^{-1}$) and even negligible on sandy soils. Gaseous losses increased slightly with increasing manure application rate, both under bare fallows and under catch crops. The major part of the gaseous N losses was released shortly after application of the manure. Between corresponding treatments with and without catch crops, gaseous losses were comparable or smaller under catch crops.

### *3.4 N-release from incorporated catch crops*

- The net release of mineral N from incorporated aboveground parts of catch crops in a mineralization experiment was positively correlated to the C:N ratio. Non-frost resistant catch crops had an immobilizing effect and should be incorporated 4 to 6 weeks before the sowing date of the next crop. Frost resistant crops released N faster in the mineralization experiment, implying that they could be incorporated shortly before the sowing date of the next crop.
- The N release from the (fertilized) catch crop should be taken into account to avoid over-fertilization of the next crop. When incorporated in spring, non-frost resistant crops (with or without application of 60 kg N $ha^{-1}$) release about 10 kg N $ha^{-1}$ during the growing season of the next crop. Frost resistant crops release about 20 kg N $ha^{-1}$ (without manure application) to 30 kg N $ha^{-1}$ (with application of 60 kg N $ha^{-1}$). When catch crops are incorporated in autumn it is important to assess the past winter to decide whether the N-delivery has to be taken into account or not: during a warm and wet winter N will be mineralized and leached. Only during a cold and/or dry winter the full N delivery has to be taken into account.
- Flail mowing of catch crops before incorporation in autumn or during winter increased the risk of N losses and should be avoided.

### *3.5 Soil organic matter and biological soil quality*

- Aboveground parts of catch crops contribute to the soil organic matter after incorporation. In an incubation experiment the highest humification coefficient was found for black oat (48-56%) and the lowest for white mustard (26-33%). Humification coefficients were always slightly higher on silt loam than on sandy loam.
- Average aboveground effective organic carbon (EOC) yields for early sown catch crops were between 77 and 512 kg ha$^{-1}$ (non-fertilized) and between 129 and 736 kg ha$^{-1}$ (fertilized with 60 kg N ha$^{-1}$) on heavy textures at the end of November. On light textures in spring, average EOC yields were between 132 and 572 kg ha$^{-1}$ for non-fertilized catch crops and between 210 and 718 kg ha$^{-1}$ for fertilized (60 kg N ha$^{-1}$) catch crops. Average aboveground EOC yields were always highest for black oat and lowest for the grass-clover mixture.
- Fertilization (60 and 120 kg N ha$^{-1}$) of catch crops increased aboveground C and EOC yields significantly for all catch crops in autumn and for frost-resistant crops also in spring. However, the effect of fertilization (60 kg N ha$^{-1}$) on aboveground EOC yield was small (41 to 224 kg EOC ha$^{-1}$) compared to the differences in EOC yields between catch crop species. Black oat showed the highest absolute increase in EOC yield due to fertilization.
- Simulations with a 4-year rotation including 2 years of winter barley followed by catch crops led to an increased OC content of the soil after 30 years compared to simulations without catch crops in the same rotation. The increase was highest for the simulation with early sown black oat. The simulated OC content was higher when catch crops were receiving a manure application as a result of the carbon input from the manure at one side and the higher C yield of the catch crop at the other side.
- Shortly after incorporating catch crops, microbial biomass and enzyme activities increased. The increase was proportionally higher for fungi than for bacteria. Effects were highest and longer lasting (up to 14 weeks) for black oat.

### *3.6 Choice of a catch crop*

- Catch crops which are known to show limited growth under cold weather conditions should not receive any manure application when sown after mid-August. Limited growth at lower temperatures was simulated for black oat and for the grass-clover mixture.
- It is advisable to choose non-frost resistant catch crops if these are incorporated in autumn (on heavy soils): they take N up more quickly and release N more slowly after incorporation.
- In case of a late crop (such as maize) following a catch crop incorporated in spring, it is advisable to choose frost resistant catch crops to reduce risks of N losses in spring.
- If the contribution of the catch crop to the soil organic matter pool is considered as important, black oat seems to be the preferred catch crop.
- All catch crops should be sown under favorable conditions. If this cannot be guaranteed by the farmer (through irrigation during drought or resowing catch crops after storm) the catch crop must not be fertilized.
- The choice of a catch crop can also be influenced by different other factors: catch crops can play an important role in the abatement of soil erosion, in the suppression of weeds and in pest control of nematodes. Some catch crops can also serve as animal fodder.

# EXTENSIVE ENGLISH SUMMARY

## 1 INTRODUCTION

In temperate humid climates, catch crops have proven to be a useful tool in the abatement of soil erosion, nutrient leaching and soil organic carbon losses.

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The main objective of this study is to investigate whether the application of pig slurry to catch crops sown after the harvest of winter cereals does not result in higher N losses from the soil between autumn and early spring compared to non-fertilized catch crops.

This report gives an overview of the results of field trials, incubation experiments and simulations carried out with the EU-rotate_N model and formulates scientifically based conclusions about the possibility of applying animal manure after winter cereals in Flanders.

## 2 FIELD EXPERIMENTS

### 2.1 EXPERIMENTAL LAY-OUT

The main part of the research project was based on field experiments which were installed during two consecutive years (2011-2013), on 4 locations with different soil textures (loamy sand, sandy loam, silt loam and clay loam, according to the USDA classification). The winter cereals were triticale on sand and sandy loam, winter barley on sandy loam and loam and winter wheat on silt loam and clay loam. Pig slurry was applied at rates of 0, ±60 and ±120 kg total N $ha^{-1}$. On each location 3 common catch crop species were sown (white mustard, Italian ryegrass and black oat). A grass-clover mixture (English ryegrass, red clover and white clover) was also sown on 3 locations, considering its importance in organic agriculture. A control without catch crops (bare fallow) was included. In order to include the effects of sowing time, catch crops were sown on 2 different dates on each location. In the first year (2011-2012) the 1st and the 2nd sowing date were in the 1st and the 2nd half of August, respectively. In the second year this was similar on 1 location; on the other 3 locations winter cereals were harvested late, resulting in a 1st sowing date in the 2nd half of August. Therefore, the 2nd sowing date was moved to the 1st half of September. The field experiments were carried out in 4 replications (blocks) on each location.

### 2.2 REPRESENTATIVITY OF THE FIELD EXPERIMENTS

The distribution of the soil textural classes at the different locations proved to be representative for the soil types used in Flanders for cultivating winter cereals. Other important physical and chemical soil characteristics (pH, $CaCO_3$, OC, K and P) did not show extreme values for any of the locations, indicating that the results of this study can be considered as representative for the agricultural soils of concern.

Weather circumstances for both experimental years were different during summer and autumn. In the 1st year weather circumstances were ideal for a good development of catch crops. August was humid but from September to November the weather was relatively dry, sunny and warm. Nitrate leaching was not likely to occur before December. In the 2nd year it was very dry from mid-August until mid-September, resulting in late germination on clay loam. Weather circumstances in autumn were quite normal and favorable for catch crop growth. Winter was similar for both experimental years. December was very wet so nitrate leaching was likely to occur; mineralization was likely to continue due to relatively high temperatures in the 1st year. In both years, a longer frost period appeared in January and February. In March, temperatures remained cold in the 2nd year, inhibiting mineralization. In the 1st year March was relatively dry, reducing the risks of nitrate leaching.

Summarized over both experimental years, precipitation was normal to low in autumn, high to very high in December-January and normal to low in February-March. Temperatures were normal to high in autumn and in December-January and normal to low in February-March.

## 2.3 RESULTS FIELD EXPERIMENTS

### 2.3.1 CATCH CROP YIELDS

#### 2.3.1.1 HARVEST AND ANALYSIS

Catch crops were harvested on all locations at the end of October and at the end of November. On locations where they were not incorporated before winter, catch crops were also harvested in early spring (February-April). Fresh yields were weighed and dry matter, N and C content were determined.

#### 2.3.1.2 ABOVEGROUND NITROGEN YIELD

Aboveground N yield was an important parameter in this research project: N uptake by the catch crop depletes the soil mineral N and prevents nitrate leaching during wet and cold winter months. After manure application to the catch crop, N uptake should increase to take up the N released from the manure. It was not possible to draw clear-cut conclusions for the effect of all factors on N yield: analysis of variance (ANOVA) showed significant interaction of effects of sowing date, manure level, catch crop and location for all harvesting dates.

1. *Effect of location*

Aboveground catch crop N yield was strongly dependent on the location, especially in the 2nd experimental year, when interaction of texture and drought seemed to have been crucial for the development of the catch crops during the first weeks. In Oostende catch crops germinated only at the end of September. In the 1st year stormy weather circumstances shortly after sowing negatively affected the development of the catch crops in Rukkelingen-Loon. In good circumstances N yields in autumn were between 25 and 130 kg $ha^{-1}$ for early sown catch crops. For late sown catch crops N yields were similar or slightly smaller. For locations where catch crops were sown during an extended dry period or after the 1st of September, very low N yields were observed.

2. *Manure effect*

Where catch crops had developed well, aboveground N yields were clearly positively correlated to the manure application level. However, differences were small compared to the manure N dose and in most cases only significant between 0N and 120N treatments. In spring, the manure effect was only clearly visible for frost resistant catch crops (Italian ryegrass and grass-clover mix), which indicates that fertilized non-frost resistant crops (white mustard and black oat) release more N during winter than the non-fertilized ones.

#### 3. *Effect of sowing date*

Aboveground N yields were clearly influenced by sowing date: on some locations significant differences were found between all corresponding treatments of the 1st and the 2nd sowing date. Due to the fast youth growth of non-frost resistant crops, significant differences were limited to frost resistant crops on other locations: especially for grass-clover the N yield was much smaller for the late sown crop, which was a result of the very slow development of English ryegrass and clover. In spring, the effect of sowing date was in general less explicit than in autumn.

#### 4. *Differences amongst catch crops*

Summarized over all locations, sowing dates and manure levels, aboveground catch crop N yield was clearly highest for white mustard, followed by black oat. Italian ryegrass and grass-clover always had the smallest N yields. During winter, a big part of the N yield was lost for white mustard. In spring, N yield was highest for Italian ryegrass and black oat, followed by grass-clover and white mustard.

### 2.3.1.3 ABOVEGROUND CARBON YIELD

Catch crops can also produce large amounts of carbon. After incorporation into soil, the aboveground C yield will contribute to the soil organic matter. The effects of the different experimental factors on C yield were similar to the effects on N yield.

#### 1. *Effect of location*

The differences in aboveground C yields between locations were not very high in cases where catch crops had developed well. In autumn, C yields varied between 1 and 3 ton C $ha^{-1}$ for early sown catch crops and between 0.5 and 1.5 ton C $ha^{-1}$ for late sown catch crops. In Rukkelingen-Loon, where a storm occurred after sowing the early catch crops, and in Oostende, where drought inhibited catch crop germination, catch crop C yields were lower. For locations where catch crops were sown after the 1st of September, catch crop yields were also low.

#### 2. *Effect of sowing date*

Aboveground C yields were generally higher for early sown catch crops than for late sown catch crops. Differences in C yields between sowing dates were more explicit in autumn than in spring. If late catch crops were sown after the 1st of September, differences with the early catch crops were very large. Only in Rukkelingen-Loon, higher C yields were found for late catch crops than for early catch crops, probably due to the effects of the storm shortly after sowing the early catch crops.

#### 3. *Manure effect*

In autumn, aboveground catch crop C yield and the manure level were clearly positively correlated. In spring, differences in C yield between the 3 manure levels were less clear or even absent. Exceptions to this case are grass-clover in Merelbeke and black oat in Bottelare in the 2nd year. For late sown non-frost resistant catch crops the decrease in C yields during winter was higher for fertilized crops than for non-fertilized crops. For late sown frost resistant crops the increase in C yields during winter was lower for fertilized crops than for non-fertilized crops.

4. *Differences amongst catch crops*

Aboveground C yields differed between catch crops depending on the harvest date. In general higher C yields were found under black oat and white mustard, followed by Italian ryegrass and grass-clover. Differences were more explicit in autumn than in spring: for non-frost resistant catch crops (especially white mustard) C yields decreased more during winter.

## 2.3.2 SOIL MINERAL NITROGEN

### 2.3.2.1 SAMPLING AND ANALYSIS

To determine the evolution of soil mineral nitrogen, 3 soil layers (0-30 cm, 30-60 cm and 60-90 cm) were sampled at 7 sampling dates. The first sampling (preceding the manure application) was done per block without considering any factor; before the 2nd sowing date, sampling was done per block considering manure level as the only factor. Afterwards, treatments were sampled per block taking all factors into account. Each sampling consisted of a mixed sample of at least 5 augerings. For each sample, the content of $NO_2^-$ + $NO_3^-$ and $NH_4^+$ was determined with a segmented flow analyzer after extraction with KCl (ISO 14256-2:2005).

### 2.3.2.2 RESULTS SOIL MINERAL NITROGEN

The soil mineral nitrogen content ($N_{min}$) was the most crucial variable in this research project as $N_{min}$ is a measure for potential nitrate leaching in the period following the soil sampling. It is assumed that $N_{min}$ can migrate to a depth of 90 cm without being lost, as plant roots can take up $N_{min}$ to that depth. Therefore $N_{min}$ was measured to a depth of 90 cm.

Based on the results of $N_{min}$ it was not possible to draw clear-cut conclusions for all factors: analysis of variance (ANOVA) showed significant interaction of effects of sowing date, manure level, catch crop and location for nearly all sampling dates.

1. *Effect of location*

The results for $N_{min}$ were very different between the locations and were mainly explained by the success of the catch crops development, as mentioned in part 2.3.1. Initial $N_{min}$ contents were quite similar for all locations shortly after harvest of the winter cereals, varying between 30 and 80 kg N $ha^{-1}$. N immobilization by the residues of the winter cereals differed between locations, probably due to differences in the quantity and the composition of the residues; differences in texture and moisture content of the soil may have influenced immobilization too. During winter months it was observed that nitrate leaching was faster on sandy soils than on non-sandy soils (see also point 4).

2. *Effect of sowing date*

For catch crops that were sown before the 1st of September, significant effects of sowing date in autumn were mainly observed for frost resistant catch crops (Italian ryegrass and grass-clover): $N_{min}$ was higher under late sown catch crops. In spring, the effect of sowing date was significant only for non-frost resistant catch crops (white mustard and black oat), especially for those that received a manure application, and also if they were incorporated (but not flail mown). Differences in $N_{min}$ were significant in autumn between late catch crops sown after the 31st of August and well developed early catch crops.

#### *3. Manure effect*

The manure effect depended mainly on the sowing date. For early sown catch crops, only small differences in $N_{min}$ were observed for all manure levels and sampling dates between October and January. Only in Oostende, where catch crops did not develop well, the manure effect was clearly observed. For late sown catch crops (but sown before the 1st of September) differences were only distinguishable between the 0N and 120N manure treatments in autumn. In spring, the manure effect (60N and 120N) could only be observed under non-frost resistant catch crops for both sowing dates. In Rukkelingen-Loon, where catch crops were flail mown in December and incorporated in January in the 2nd year, the manure effect was clear in January and slightly visible in spring; in the 1st year -  when catch corps were also incorporated but not flail mown - this was less explicit. For very late sown catch crops (after the 31st of August), $N_{min}$ was always clearly positively correlated with the manure dose. In spring, no clear-cut effect could be observed.

#### *4. Effect of catch crop type*

In autumn, $N_{min}$ was significantly smaller under all early sown catch crops than under bare fallow on nearly all locations. Differences in $N_{min}$ under different catch crops species were not significant. For late sown catch crops significant differences were observed: $N_{min}$ was often higher under Italian ryegrass and grass-clover than under white mustard and black oat. Under late sown Italian ryegrass and grass-clover $N_{min}$ was not always significantly different from $N_{min}$ under the bare fallow.

In spring, $N_{min}$ was in most cases significantly higher under bare fallow than under frost resistant crops (also after incorporation without being flail mown). Under non-frost resistant crops, $N_{min}$ was not significantly different from $N_{min}$ under the bare fallow (no N uptake after winter). Additionally, a part of the N taken up earlier was released from the dead biomass. Furthermore, more N was released from non-frost resistant crops (with higher N yields) than from frost resistant crops (with lower N yields). This is particularly important for the catch crops which were flail mown.

In January, no significant differences could be observed in $N_{min}$ between catch crop treatments (excluding flail mown treatments). $N_{min}$ was significantly higher under the bare fallow than under catch crops on non-sandy soils, indicating that the extra $N_{min}$ under bare fallow had leached out only partly. On sandy soils (Bottelare) the extra $N_{min}$ had leached out completely since no significant differences were observed in $N_{min}$ between the bare fallow and the catch crop treatments.

### 2.3.3 CONCLUSION

In general, aboveground N yields in autumn were highest for white mustard, followed by black oat. Italian ryegrass and grass-clover showed lower N yields. In spring, aboveground N yields were highest for Italian ryegrass and black oat, followed by grass-clover and white mustard. The share of clover in the dry mass yield of the grass-clover mixture was small.

When catch crops had developed well, differences in N yields between manure levels were clearly visible. Only small differences in $N_{min}$ were observed. Italian ryegrass and especially grass-clover (English ryegrass + clover) developed more slowly and should therefore not be used for late sowing. Their roots were not able to take up $N_{min}$ from deeper soil layers. The difference between Italian ryegrass and the grass-clover mixture was attributed to the slower development of English ryegrass and clover. White mustard and to a lesser extent black oat are not frost resistant, and thus did not continue to take up $N_{min}$ during and after winter, but rather lost a part of the N which was taken up in autumn. This led to increased $N_{min}$-contents in the soil in spring, which can be an advantage if this

N release and the N uptake by the next crop are synchronized. It is important that the additional N released from the catch crop in spring is taken into account in the fertilization rate for the next crop (see also part 4.2).

## 2.4 STATISTICAL EVALUATION OF THE MANURE EFFECT

The effects of different factors were discussed in part 2.3. However, different statistical tests were used for different subsets (= data for 1 location, 1 sowing date and 1 sampling date). It was not possible to draw general statistical conclusions. In this part of the report we focused on the manure effect and used uniform statistical tests in order to answer the main research question.

### 2.4.1 MANURE EFFECT ON SOIL MINERAL N

The risk of N losses becomes relevant only from October onwards and therefore the results for $N_{min}$ for September were omitted from the statistical analysis. The results for January were not analyzed statistically, as they showed only small differences in $N_{min}$ between the 3 manure levels, indicating that nitrate leaching had taken place already (see part 2.3.2.2). Only in spring differences became distinguishable again due to mineralization. As these differences could still induce higher N losses (in absence of a next crop), the manure effect on $N_{min}$ in spring was also statistically analyzed.

The dataset was divided into subsets based on location, catch crop, sowing date and sampling date. $N_{min}$ was statistically analyzed using a paired t-test. For 93% of the subsets a normal distribution of the dataset was proven by a Shapiro-Wilk test. Based on this, normal distributions of the populations were assumed. The p-values of the paired t-tests were based on individual comparisons and were not corrected according to Bonferroni, as many samples were tested, each time on only 4 replications. Correction would have resulted in very weak tests. One-sided p-values were considered significant if $p < 0.05$.

The number of individual p-values was clearly affected by the harvest date, sowing date, manure dose, catch crop species and location/experimental year. Remarkably $N_{min}$ was not always significantly different for the different manure levels of the bare fallow, especially in the 1st experimental year. As nitrate leaching was not likely to occur before winter (definitely in the drier 1st year), this was attributed to N immobilization by the winter cereals residues.

Different locations and experimental years together could be considered as a representative sample for the practical situation in Flanders, even though it is necessary to remind that the late sown catch crops were sown later than usual in the 2nd year on 3 locations. The output of the individual statistical tests were summarized for the 8 locations/2 years, without including those cases were catch crops were sown after the 31st of August. For 88% (early sown catch crops) and 79% (late sown catch crops) of the individual comparisons no significant differences were found between catch crops with and without a manure application of 60 kg N $ha^{-1}$. In case of a manure application of 120 kg N $ha^{-1}$, no significant effect was found for 83% (early sown catch crops) and 58% (late sown catch crops) of the individual comparisons. In spring these values were respectively 90% and 84% for the 60N manure dose and 77% and 58% for the 120N manure dose. Thus, the number of significant differences increased due to late sowing and with increasing manure application rate.

In order to obtain overall statistical conclusions about the manure effect on $N_{min}$ under different catch crops paired t-tests were carried out over the 8 locations/2 experimental years for autumn and for spring. As $n \geq 30$ normality of the data was assumed based on the central limit theorem. In order to maintain a sufficiently severe test, the Bonferroni correction was applied carefully. The bare fallow was not taken into account, the 60N and 120N manure dose were evaluated separately and we did the statistical analysis twice: once for autumn and spring values separately and once for autumn and spring values combined. The Bonferroni correction was applied on the significance limit (0.05). For the overall one-sided test ($p < 0.05$), differences were therefore found significant if non-corrected two-sided p-values were < 0.013 or < 0.007 for respectively the separate and the combined statistical analysis.

The manure effect (60N) on $N_{min}$ was not significant under early sown catch crops. For late sown catch crops, the manure effect was always significant in autumn, but also included those catch crops which were sown after the 31st of August. Excluding situations where catch crops were sown after the 31st of August, no significant effect of the 60N manure dose was found in autumn. The effects of a higher manure dose (120N) were significant but small (8-21 kg N $ha^{-1}$) under all catch crops in autumn. For the bare fallow a significant effect of both manure doses (60N and 120N) was found for all situations in autumn (15-48 kg N $ha^{-1}$). In spring a significant effect on the bare fallow was found only for the 120N manure dose, indicating that additional mineralization of manure N was limited after the winter. Under fertilized and non-fertilized catch crops, significant differences in spring were only found for black oat (for 60N and 120N) and white mustard (for 120N only). These were attributed to differences in N release between the fertilized and non-fertilized dead catch crop.

### 2.4.2 MANURE EFFECT ON CATCH CROP CARBON YIELD

The main objective of this study was to investigate the effect of a manure application to catch crops on soil mineral N. The evaluation in 2.4.1 did not show significant negative effects for a manure application of 60 kg N $ha^{-1}$. However pig slurry application before sowing a catch crop did not result in a decrease in $N_{min}$ compared to a non-fertilized catch crop, i.e. a non-fertilized catch crop developed sufficiently well to deplete soil mineral N after harvest of the winter cereal. Would it then be advisable to allow a farmer to fertilize his catch crop?

To answer this question, other advantages of catch crops were also considered. After incorporation, a catch crop also contributes to the build-up of soil organic carbon. A fertilized catch crop may accumulate more organic C and contribute more to the soil organic carbon pool. The manure application itself also represents an additional C input. Other advantages of a higher catch crop biomass (as a result of a manure application) include a more efficient abatement of soil erosion and weed suppression.

As catch crops are commonly incorporated between November and April, aboveground C yields were statistically compared between fertilized and non-fertilized catch crops in November and in spring only. In order to obtain overall statistical conclusions about the manure effect on C yields for different catch crops, paired t-tests were carried out over the 8 locations/2 experimental years, similarly as for $N_{min}$ (see part 2.4.1). The differences between locations/years could be seen as a representative sample for the practical situation in Flanders. The normality of the data was checked. In the evaluation of the p-values the Bonferroni correction was taken into account.

The overall statistical analysis showed that fertilization of catch crops had a significant positive effect on the aboveground C yield for all catch crops in November. In spring this effect was still significant for most early sown catch crops, but not for the 60N manure dose on white mustard. For late sown non-frost resistant catch crops the positive effect of fertilization on C yields was not significant in spring as a larger share of the extra C yield was lost during winter.

The mean differences in C yield between fertilized and non-fertilized catch crops varied between 26 and 450 kg C $ha^{-1}$ or between 24 and 514 kg C $ha^{-1}$ when badly developed catch crops (Oostende) and catch crops sown after the 31st of August were not taken into account.

### 2.4.3 CONCLUSION

Mean differences in $N_{min}$ between fertilized and non-fertilized bare fallows were small but significant in autumn. Between fertilized and non-fertilized catch crops mean differences in $N_{min}$ were mostly small. A pig slurry application of 60 kg N $ha^{-1}$ did not result in a significant increase of $N_{min}$ under catch crops in autumn, for catch crops sown before the 1st of September. An application of 120 kg N $ha^{-1}$ did result in a significant increase of $N_{min}$ under all catch crops in autumn. In spring, significant differences between manure levels were only observed under bare fallows and under non-frost resistant catch crops (for the 60N manure dose only under black oat).

Based on the statistical analyses we conclude that a pig slurry application of 60 kg N $ha^{-1}$ on the stubble of winter cereals, followed by catch crops sown before the 1st of September, did not result in higher risk of N losses during winter. However pig slurry application before sowing a catch crop did not result in a decrease in $N_{min}$ compared to a non-fertilized catch crop, i.e. a non-fertilized catch crop developed sufficiently well to deplete soil mineral N after harvest of the winter cereal. It was shown that a pig slurry application of 60 kg N $ha^{-1}$ significantly increased aboveground catch crop C yields at the end of November for all catch crops and in spring also for frost resistant catch crops, with expected positive effects on weed suppression, on the control of soil erosion and on soil fertility in general.

# 3 MODEL SIMULATIONS OF N-DYNAMICS

## 3.1 INTRODUCTION

As in situ measurements of N losses by nitrate leaching and denitrification were practically unrealizable, estimations of N losses based on soil mineral N and catch crop N yield were done by simulations with the EU-rotate_N model. At first, a calibration and validation of the model parameters was performed to simulate measured $N_{min}$ and $N_{plant}$ as precisely as possible. This allows us to assume that simulated N losses correspond to N losses that appeared in those specific situations. Following the calibration and validation, project results were extrapolated to conditions (mainly weather conditions) which were not experienced in the field experiments.

## 3.2 CALIBRATION

After profound analysis of the very extensive set of model parameters, it was decided to calibrate the EU-rotate_N model in a stepwise manner. In this procedure only parameters which do not influence the model output in earlier steps can be calibrated. Parameter boundaries were defined for each parameter to prevent that calibration would lead to parameter values that deviate too much from the original model parameters.

The software program PEST was used to calibrate the model parameters. Calibration was carried out on 3 locations with different soil textures.

The different calibration steps were carried out as follows:

1. Calibration of the N mineralization from soil organic matter based on $N_{min}$ measurements on the non-fertilized bare fallow from incubation experiments.
2. Calibration of the mineralization of the winter cereal residues based on $N_{min}$ measurements on the non-fertilized bare fallow.
3. Calibration of the mineralization of the pig slurry based on $N_{min}$ measurements for the fertilized bare fallows.

4. Calibration of the N uptake by catch crops based on $N_{min}$ measurements, aboveground N yields ($N_{plant}$) and dry matter yields for all treatments with catch crops.

Validation of the calibrated model parameters was carried out to investigate whether the model can be used in similar simulations independently of the experimental fields that were used for calibration. Where possible, validation was carried out using results of experimental fields from the complementary experimental year to include the variation of weather circumstances.

The model accuracy was evaluated based on the residuals, which are the values of the deviations between the simulated and the measured $N_{min}$ and $N_{plant}$. These residuals were compared to the corresponding standard deviations on the measurements. The higher the ratio between residual and standard devation, the smaller the probability that the measured value in the field is properly estimated by the simulated value.

The model accuracy for $N_{min}$ (based on the average ratio) was good for the bare fallow treatments and acceptable for white mustard and Italian ryegrass treatments. For black oat treatments the average ratio was higher and it was highest for the grass-clover treatments, especially for the early sown treatments. Higher ratios were general due to an overestimation of the $N_{min}$ measurements and the overestimation was higher with increasing manure application rates.

The model accuracy for $N_{plant}$ was variable. Generally the best results were found for late sown black oat and early sown grass-clover treatments (without simulating N-fixation). For the less accurately simulated treatments, measured $N_{plant}$ was always overestimated and the overestimation was higher with increasing manure application rates. Since inaccurate $N_{plant}$ simulations did not always result in inaccurate $N_{min}$ simulations, the ratio between aboveground and belowground biomass N was assumed to be more variable in reality than simulated, but total N uptake was assumed to be simulated rather well.

## 3.3 MODEL-OUTPUT

The calibrated model allowed to simulate N losses for the different experimental fields and to answer the research question directly.

### 3.3.1 NITRATE LEACHING

In the first experimental year weather circumstances during autumn were rather dry and warm and the main part of nitrate leaching was simulated from mid-December onwards. For the bare fallows simulated leaching was always positively correlated with the manure application rate. Differences in leaching due to the application of 60 kg N $ha^{-1}$ on silt loam and loamy sand (± 20 kg N $ha^{-1}$) were higher than on sandy loam (< 10 kg N $ha^{-1}$), which was explained by immobilization of applied N on sandy loam.

The presence of early sown catch crops resulted everywhere in a high reduction of simulated nitrate leaching and the differences for different manure application rates were small. Under grass-clover nitrate leaching was higher than under other catch crops and only under grass-clover both manure application rates resulted in a small decrease of nitrate leaching.

Late sowing increased simulated nitrate leaching for grass-clover on silt loam and sandy loam and for black oat on loamy sand. Under grass-clover, manure application rates of 60 en 120 kg N $ha^{-1}$ resulted respectively in a decrease and increase of nitrate leaching. Under black oat on loamy sand, both manure application rates resulted in a increase of nitrate leaching. For late sown Italian ryegrass and white mustard only small changes were simulated compared to the early sown treatments.

In autumn of the second year weather circumstances were wetter and colder and simulated nitrate leaching started already mid-October. For the bare fallows, nitrate leaching was again positively correlated with the manure application rate. Differences in nitrate leaching for different manure application rates on loamy sand (35 – 40 kg N $ha^{-1}$) were higher than on silt loam (11 kg N $ha^{-1}$), which was explained by high differences in $N_{min}$ contents on silt loam in spring.

Similar to the findings for the first experimental year, simulated nitrate leaching under early sown catch crops was highest under grass-clover. Manure application at a rate of 60 kg N $ha^{-1}$ did not result in higher nitrate leaching under all early sown catch crops and at a rate of 120 kg N $ha^{-1}$ an increase was only found under grass-clover.

Under catch crops sown in the second half of August an increase in simulated nitrate leaching was observed under black oat and grass-clover. Under these catch crops a clear increase was also observed with increasing manure application rates. Under late sown Italian ryegrass and white mustard differences in nitrate leaching were small compared to early sown treatments. A manure application rate of 60 kg N $ha^{-1}$ resulted in a small increase or decrease in nitrate leaching, while at a rate of 120 kg N $ha^{-1}$, an increase was observed nearly everywhere.

Under catch crops sown in the first half of September, the differences in simulated nitrate leaching with the bare fallow treatments were smaller and in nearly all cases, an increase of nitrate leaching with higher manure application rates was observed. Nitrate leaching was lowest under white mustard, respectively followed by Italian ryegrass, black oat and grass-clover.

### 3.3.2 GASEOUS N LOSSES

Simulated gaseous N losses ($NH_3$, $N_2$ en $N_2O$) were generally small (< 7 kg N $ha^{-1}$) and even negligible on sandy soils. Gaseous losses increased slightly with increasing manure application rate, both under bare fallows and under catch crops. The major part of the gaseous N losses was released shortly after application of the manure. Between corresponding treatments with and without catch crops, gaseous losses were comparable or smaller under catch crops.

## 3.4 SCENARIO-ANALYSES

### 3.4.1 INFLUENCE OF WEATHER CONDITIONS

In order to simulate the influence of different weather circumstances, scenario-analyses were carried out with the parameter set of Merelbeke (loamy sand) and Sint-Denijs (silt loam) since these showed good modeling accuracies. For Lemberge (sandy loam) modeling accuracies were excellent, but due to a rather unrealistic output for the mineralization of soil organic matter, this parameter set was not included in the scenario-analyses.

With the exception of the 120 kg N $ha^{-1}$ manure rate, all treatments were included in the scenario-analyses. For grass-clover no N fixation was simulated. Sowing of catch crops was simulated on August 1st and August 31st. The $N_{min}$ content on 31st of July was taken as measured in the field (32,7 en 74,5 kg N $ha^{-1}$ for Sint-Denijs and Merelbeke respectively), but initial moisture contents were set at moisture contents at field capacity. The composition of manure and cereal residues were maintained as determined for the experimental fields, but the quantity of the applied manure was adjusted in order to apply exactly 60 kg N $ha^{-1}$. In contradiction to how it was done for the late sown catch crop treatments in the field experiments, the manure application and incorporation of the stubble was done the day before sowing, as this is more likely to happen in reality.

Daily weather data for 10 different years were obtained from the Royal Meteorological Institute (KMI). These 10 years were selected based on precipitation and the mean temperature during autumn, in order to create a high variability of weather conditions, including extreme situations.

Generally, the 10 year scenario-analyses on loamy sand an on silt loam revealed only small negative or positive differences in the simulated average nitrate concentration between early sown catch crops with and without a manure application of 60 kg N $ha^{-1}$. Under late sown catch crops, a relatively high increase of the nitrate concentration was simulated due to the application of manure, but only under black oat and under grass-clover during cold and/or wet weather conditions.

### 3.4.2 INFLUENCE OF INITIAL $N_{MIN}$ CONTENT

Based on the weather conditions during autumn and the simulated N losses, a worst-case scenario and a normal scenario for sandy loam and silt loam were selected from the 10 years used in 3.4.1. For each scenario, 3 simulations were carried out with low, average and high $N_{min}$ contents at the harvest of the winter cereal. The average $N_{min}$ content was determined based on measurements on all experimental fields and twice the standard deviation was subtracted and added to the average to calculate the low and high $N_{min}$ contents respectively. The distribution of $N_{min}$ over the 3 soil layers was maintained in all scenarios.

Simulated average nitrate concentrations under bare fallows were clearly higher with increasing initial $N_{min}$ content. Under early sown catch crops this effect was only observed under grass-clover and Italian ryegrass in the worst-case scenario. The effect of a manure application (60 kg N $ha^{-1}$) on the nitrate concentration was nearly independent of the initial $N_{min}$ content under early sown catch crops. When sown late, simulated nitrate concentrations under catch crops increased with increasing initial $N_{min}$ contents and the effect of the manure application became more obvious.

### 3.4.3 EVALUATION OF MAXIMUM N APPLICATION RATES FOR WINTER CEREALS FOLLOWED BY CATCH CROPS

The application of manure on catch crops following winter cereals is only allowed when total maximum N application rates are respected. The farmer has to reduce the N application rate to the cereal with the amount of N that he wants to apply on the catch crop. From literature it appeared to be not likely that the reduction of 60 kg N $ha^{-1}$ would lead to a lower initial $N_{min}$ content at the harvest of the winter cereal. This assessment made further simulations irrelevant.

## 3.5 CONCLUSION

Following a calibration and validation procedure, the EU-rotate_N model showed accurate simulations for $N_{min}$ under bare fallows, white mustard and Italian ryegrass. Under black oat and grass-clover, $N_{min}$ contents were generally overestimated and the overestimation was higher with increasing manure application rates. The modeling accuracy for $N_{plant}$ was variable, which was attributed to non-simulated fluctuations in the ratio between aboveground and belowground biomass.

Simulated average nitrate concentrations showed only small positive or negative differences between early sown catch crops with or without application of manure (60 kg N $ha^{-1}$). When sown late, a relatively high increase of the nitrate concentration was simulated due to the application of manure, but only under black oat and under grass-clover during cold and/or wet weather conditions, for which an overestimation by the model could not be excluded. Simulated gaseous N losses were generally small (< 7 kg N $ha^{-1}$) and differences between treatments with and without manure were limited.

# 4 INCUBATION EXPERIMENTS

## 4.1 OBJECTIVES

Catch crops do not only play a crucial role in the reduction of N losses during autumn and winter, but also contribute to an improved soil fertility in the growing season of the next crop. Once the catch crop has been incorporated, mineralization will start as soon as weather circumstances allow it.

The release of mineral N from the catch crop is an advantage if the next crop is able to take it up immediately. This implies that fertilization of the next crop should be reduced. However, if the next crop is sown long after incorporation of the catch crop and the released N cannot be taken up sufficiently, there is a risk of nitrate leaching or denitrification in spring.

Incorporation of a catch crop also contributes to build up soil organic matter. The maintenance of the soil organic matter content is crucial for the future productivity of the Flemish agricultural soils. Therefore, it is important to know the effective organic carbon content of catch crops, e.g. for the implementation in long term simulation models of soil organic matter (such as e.g. in the current Flemish-Dutch Demeter project).

To determine both the N and C mineralization of the incorporated catch crops, incubation experiments were carried out. The results of these experiments were also used to calibrate the EU-rotate_N model (see part 3.2). The incorporation of a catch crop may also influence the quantity and the composition of the soil microbial biomass. To evaluate these effects for different catch crops, biological soil quality parameters were determined during the incubation experiments.

## 4.2 N-MINERALIZATION

### 4.2.1 PROCEDURE

During winter, the upper soil layer (0-30 cm) was sampled for bare fallow (0 – 60 - 120N), white mustard (0 – 60 – 120N), Italian ryegrass (0N), black oat (0N) and grass-clover (0N) in Lemberge (sandy loam) and Rukkelingen-Loon (silt loam). Early sown catch crops were harvested on the 0N treatment and incubated. All soils were maintained at a constant moisture content (50% water filled pore space), a temperature of 15°C and a relative air humidity of 70% during the incubation (3 months). The experiment was carried out in 3 replicates. On 7 sampling dates, soil $N_{min}$ content ($NO_2$-N, $NO_3$-N and $NH_4$-N) was determined with a continuous flow autoanalyzer.

### 4.2.2 RESULTS

#### 4.2.2.1 MANURE EFFECT UNDER BARE FALLOW AND UNDER WHITE MUSTARD

The manure effect was investigated under bare fallow and under white mustard (without incorporation of catch crop). At the start of the incubation only small differences were measured in $N_{min}$ between fertilized and non-fertilized treatments. Incubation induced for each treatment a systematic increase in $N_{min}$. At the end of the incubation a significant effect of the manure dose was observed in the soil from bare fallow, but not in the soil from the white mustard treatment. The manure effect had thus been neutralized by the presence of a catch crop in autumn. At the end of the incubation, a significant effect of the soil texture/location was found for both bare fallow and white mustard: N mineralization was smaller on silt loam than on sandy loam.

#### 4.2.2.2 NET N-MINERALIZATION FROM INCORPORATED CATCH CROPS

On both soil types, a similar significant effect of the catch crop type was found: black oat showed strong immobilization and had released the lowest net amount of N at the end of the incubation experiment. Grass-clover did not show any immobilization and had released the highest net amount of N at the end of the incubation experiment. The N release from Italian ryegrass was quite similar to the N release from grass-clover. White mustard initially immobilized N but released N afterwards. For the different catch crops, net amounts of mineralized N showed a strong negative linear relationship with the C:N ratio of the incorporated material.

The net mineralized N at the end of the incubation was significantly smaller on silt loam than on sandy loam. Furthermore, the immobilizing effect of white mustard and black oat lasted longer on silt loam.

### 4.2.3 INDICATIVE NUMBERS FOR N-DELIVERY FROM INCORPORATED CATCH CROPS

The part of the N yield that is available for uptake by the next crop was determined by combining the average aboveground N yields and the net N mineralization rates. When incorporated in spring, non-frost resistant crops (with or without application of 60 kg N ha$^{-1}$) release about 10 kg N ha$^{-1}$ during the growing season of the next crop. Frost resistant crops release about 20 kg N ha$^{-1}$ (without manure application) to 30 kg N ha$^{-1}$ (with application of 60 kg N ha$^{-1}$). When catch crops are incorporated in autumn it is important to assess the past winter to decide whether the N-delivery has to be taken into account or not: during a warm and wet winter N will be mineralized and leached. Only during a cold and/or dry winter the full N delivery has to be taken into account.

## 4.3 C-MINERALIZATION

### 4.3.1 PROCEDURE

During winter, the upper soil layer (0-30 cm) was sampled on the non-fertilized bare fallow, white mustard, Italian ryegrass, black oat and grass-clover in Lemberge (sandy loam) and Rukkelingen-Loon (silt loam). Early sown catch crops were harvested on the 0N treatment and freshly incorporated in amounts corresponding to the yields recorded in the field. For bare fallow only the soil – without incorporated catch crop – was incubated in the experiment. All soils were maintained at a constant moisture content (50% water filled pore space) and a temperature of 15°C during the 3 months incubation. The experiment was carried out in 3 replicates. For black oat, the incubation was extended to 6 months. Soils were stored in air-tight glass jars with a known quantity of NaOH in a solution; the amount of $CO_2$ produced was determined by back-titration of the NaOH solution. The net C mineralization from the incorporated catch crops was calculated by dividing the amount of released $CO_2$ by the total amount of incorporated C.

### 4.3.2 RESULTS

The net C mineralization from catch crops showed a strong negative linear relationship with the C:N ratio of the incorporated catch crops. Grass-clover C mineralized fastest, followed by Italian ryegrass, white mustard and black oat, respectively. C mineralization of the different catch crops was similar on both soil types and, except for white mustard, always slightly faster on sandy loam than on silt loam. After 3 months of incubation, mineralization of most of the catch crops had stabilized, but for black oat incubation had to be extended with 3 months.

### 4.3.3 EFFECTIVE ORGANIC CARBON

Mineralization of organic matter was simulated using a first + zero order kinetics model (Sleutel et al., 2005). For all catch crops the amount of carbon remaining 1 year after incorporation, which is called the effective organic carbon (EOC), was determined by extrapolating the mineralization data to 1 year. The ratio of EOC and the total amount of incorporated organic carbon is defined as the humification coefficient. The highest humification coefficient was found for black oat and the lowest for white mustard. The humification coefficients for catch crops incorporated in sandy loam were always smaller than for catch crops incorporated in silt loam. Only weak positive linear relationships were found between humification coefficients and the C:N ratios of catch crops.

Humification coefficients and differences in aboveground C yields between fertilized and non-fertilized catch crops in the field (see part 2.4.2) allowed to calculate EOC from the aboveground biomass. From all early sown catch crops, black oat had the highest EOC yield and grass-clover the lowest. Differences in EOC between fertilized (60 kg N $ha^{-1}$) and non-fertilized early sown catch crops were relatively small (41-224 kg EOC $ha^{-1}$). Both in November and in spring, black oat showed the highest increase in EOC due to fertilization.

Finally it should be stressed that the EOC values pertain only to the aboveground biomass, while the contribution of the belowground biomass should not be underestimated. Additional research and the draft literature review have shown that the belowground biomass can vary from 10 to 75% of the total biomass of a catch crop. The high variability in this ratio can mainly be explained by the catch crop species and the sampling date.

## 4.4 BIOLOGICAL SOIL QUALITY

### 4.4.1 INTRODUCTION

The presence and the incorporation of catch crops can have an effect on the biological soil quality. A selection of soil samples of the N mineralization experiment (see part 4.2) were used to quantify this effect. On these soil samples, the microbial biomass, the composition and concentration of microbial phospholipid fatty acids (PLFA) and the enzyme activity of dehydrogenase and β-glucosaminidase were determined. Most of the experiments were carried out on 3 sampling dates: just before incorporation and after 4 weeks and 14 weeks of incubation. The selected soil was from Lemberge (sandy loam) and had been sampled in the field in the beginning of January. Each time, non-fertilized treatments were selected. For white mustard soil samples with and without incorporated material were included. For other catch crops only soil samples with incorporated material were included.

### 4.4.2 RESULTS

For none of the sampling dates biological soil quality parameters showed significant differences between the bare fallow and a soil under white mustard (without incorporated material). However, incorporation of aboveground catch crop material caused significant effects on biological soil quality parameters 4 weeks after incorporation, depending on the catch crop type. Effects of incorporated white mustard were clearly smaller, while those of incorporated black oat were bigger and lasted longer (up to 14 weeks). In general, incorporation of catch crops caused a short lasting increase of microbial biomass and enzyme activity, with a proportionally higher increase for fungi than for bacteria.

# 5 MODEL SIMULATIONS OF C-DYNAMICS

In the long term, the use of catch crops in a rotation can lead to an increased organic carbon (OC) content in the soil. Simulations were carried out over a period of 30 years with a 4-year rotation including 2 years of winter barley followed by catch crops. Average C yields of aboveground and belowground parts of catch crops sampled in the experimental fields were used.

Simulations with catch crops in the rotation led to an increased OC content of the soil after 30 years compared to simulations without catch crops in the rotation. The increase was highest for the simulation with black oat. The simulated OC content was higher when catch crops were receiving a manure application as a result of the carbon input from the manure at one side and the higher C yield of the catch crop at the other side.

# 6 GENERAL CONCLUSIONS

## 6.1 REPRESENTATIVITY OF THE EXPERIMENTAL FIELDS

- Catch crops were sown after harvest of winter cereals on 8 locations and during 2 experimental years (2011-2013). Together they made up a representative sample for agricultural soils which are used for winter cereal cultivation in Flanders.

## 6.2 SOIL MINERAL NITROGEN

- When sown in good circumstances before the 1st of September, non-fertilized and fertilized catch crops developed well, took up $N_{min}$ from the soil in autumn and reduced the risk of N losses during winter.

- For catch crops sown before the 1st of September, no significant mean differences (< 5 kg N $ha^{-1}$) were found in autumn (October-November) between non-fertilized catch crops and catch crops fertilized with a 60 kg N $ha^{-1}$ pig slurry application. However, significant differences were found for the corresponding bare fallows.

- For catch crops sown before the 1st of September, no significant mean differences (≤ 10 kg N $ha^{-1}$) were found in spring (February-April) between non-fertilized catch crops and catch crops fertilized with a 60 kg N $ha^{-1}$ pig slurry application, except for black oat where differences were significant.

- For catch crops sown before the 1st of September, significant mean differences (8-21 kg N $ha^{-1}$) were found in autumn (October-November) between non-fertilized catch crops and catch crops fertilized with a 120 kg N $ha^{-1}$ pig slurry application. For the corresponding bare fallow treatments these differences were bigger and also significant.

- For catch crops sown before the 1st of September, slightly bigger but non-significant mean differences (1-26 kg N $ha^{-1}$) were found in spring (February-April) between non-fertilized catch crops and catch crops fertilized with a 120 kg N $ha^{-1}$ pig slurry application. Exceptions to this case are white mustard and black oat sown at the end of August where these differences were significant.

- If catch crops were sown after the 31st of August, a 60 kg N $ha^{-1}$ pig slurry application led to a significant increase in $N_{min}$ in autumn compared to non-fertilized treatments.

- Non-frost resistant catch crops die during winter and mineralize partly in spring; fertilized and/or late sown catch crops release more $N_{min}$ than non-fertilized and/or early sown catch crops.

## 6.3 SIMULATED N LOSSES

- Simulations showed strong reduction of nitrate leaching due to the presence of catch crops on 6 out of 8 field trials and under different weather conditions on loamy sand and silt loam. Under grass-clover nitrate leaching was higher than under the 3 other catch crops. In general the reduction of nitrate leaching by catch crops was stronger on heavier soil textures and with lower initial $N_{min}$ contents.

- Simulated average nitrate concentrations at 90 cm depth showed only small positive or negative differences between early sown catch crops with or without application of manure (60 kg N $ha^{-1}$). When sown late, a relatively high increase of the nitrate concentration was simulated due to the application of manure, but only under black oat and under grass-clover during cold and/or wet weather conditions, for which an overestimation by the model could not be excluded.

- Simulated gaseous N losses were generally small (< 7 kg N ha$^{-1}$) and even negligible on sandy soils. Gaseous losses increased slightly with increasing manure application rate, both under bare fallows and under catch crops. The major part of the gaseous N losses was released shortly after application of the manure. Between corresponding treatments with and without catch crops, gaseous losses were comparable or smaller under catch crops.

## 6.4 N-RELEASE FROM INCORPORATED CATCH CROPS

- The net release of mineral N from incorporated aboveground parts of catch crops in a mineralization experiment was positively correlated to the C:N ratio. Non-frost resistant catch crops had an immobilizing effect and should be incorporated 4 to 6 weeks before the sowing date of the next crop. Frost resistant crops released N faster in the mineralization experiment, implying that they could be incorporated shortly before the sowing date of the next crop.

- The N release from the (fertilized) catch crop should be taken into account to avoid over-fertilization of the next crop. When incorporated in spring, non-frost resistant crops (with or without application of 60 kg N ha$^{-1}$) release about 10 kg N ha$^{-1}$ during the growing season of the next crop. Frost resistant crops release about 20 kg N ha$^{-1}$ (without manure application) to 30 kg N ha$^{-1}$ (with application of 60 kg N ha$^{-1}$). When catch crops are incorporated in autumn it is important to assess the past winter to decide whether the N-delivery has to be taken into account or not: during a warm and wet winter N will be mineralized and leached. Only during a cold and/or dry winter the full N delivery has to be taken into account.

- Flail mowing of catch crops before incorporation in autumn or during winter increased the risk of N losses and should be avoided.

## 6.5 SOIL ORGANIC MATTER AND BIOLOGICAL SOIL QUALITY

- Aboveground parts of catch crops contribute to the soil organic matter after incorporation. In an incubation experiment the highest humification coefficient was found for black oat (48-56%) and the lowest for white mustard (26-33%). Humification coefficients were always slightly higher on silt loam than on sandy loam.

- Average aboveground effective organic carbon (EOC) yields for early sown catch crops were between 77 and 512 kg ha$^{-1}$ (non-fertilized) and between 129 and 736 kg ha$^{-1}$ (fertilized with 60 kg N ha$^{-1}$) on heavy textures at the end of November. On light textures in spring, average EOC yields were between 132 and 572 kg ha$^{-1}$ for non-fertilized catch crops and between 210 and 718 kg ha$^{-1}$ for fertilized (60 kg N ha$^{-1}$) catch crops. Average aboveground EOC yields were always highest for black oat and lowest for the grass-clover mixture.

- Fertilization (60 and 120 kg N ha$^{-1}$) of catch crops increased aboveground C and EOC yields significantly for all catch crops in autumn and for frost-resistant crops also in spring. However, the effect of fertilization (60 kg N ha$^{-1}$) on aboveground EOC yield was small (41 to 224 kg EOC ha$^{-1}$) compared to the differences in EOC yields between catch crop species. Black oat showed the highest absolute increase in EOC yield due to fertilization.

- Simulations with a 4-year rotation including 2 years of winter barley followed by catch crops led to an increased OC content of the soil after 30 years compared to simulations without catch crops in the same rotation. The increase was highest for the simulation with early sown black oat. The simulated OC content was higher when catch crops were receiving a manure application as a result of the carbon input from the manure at one side and the higher C yield of the catch crop at the other side.

- Shortly after incorporating catch crops, microbial biomass and enzyme activities increased. The increase was proportionally higher for fungi than for bacteria. Effects were highest and longer lasting (up to 14 weeks) for black oat.

## 6.6 CHOICE OF A CATCH CROP

- Catch crops which are known to show limited growth under cold weather conditions should not receive any manure application when sown after mid-August. Limited growth at lower temperatures was simulated for black oat and for the grass-clover mixture.

- It is advisable to choose non-frost resistant catch crops if these are incorporated in autumn (on heavy soils): they take N up more quickly and release N more slowly after incorporation.

- In case of a late crop (such as maize) following a catch crop incorporated in spring, it is advisable to choose frost resistant catch crops to reduce risks of N losses in spring.

- If the contribution of the catch crop to the soil organic matter pool is considered as important, black oat seems to be the preferred catch crop.

- All catch crops should be sown under favorable conditions. If this cannot be guaranteed by the farmer (through irrigation during drought or resowing catch crops after storm) the catch crop must not be fertilized.

- The choice of a catch crop can also be influenced by different other factors: catch crops can play an important role in the abatement of soil erosion, in the suppression of weeds and in pest control of nematodes. Some catch crops can also serve as animal fodder.