Decomposition rate of organic fertilizers: effect on yield, nitrogen availability and nitrogen stock in the soil

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Preface

The MAC field trial (Manure As Chance) is a unique long-term field trial, that has been running for 13 years. With 12 different organic fertilizer and one artificial fertilizer strategies, it offers the opportunity to study the long-term effects of different types and quantities of organic fertilizers on yield, product quality and soil properties. We were glad that the project “Bedrijfsinterne Optimalisatie” (Internal Farm Optimization) provided the opportunity to analyse the nitrogen dynamics of for the period 1999-2011 We thank the Ministry of Economics, Agriculture and Innovation (EL&I) for financing this work. We invite other researchers to use these experimental plots for their own research questions. A start has already been made, some of the treatments being used for a soil phosphate study. Feel welcome to contact about research questions which might be answered using this experimental field.

Geert-Jan van der Burgt
Project leader

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Contents

Summary

The nitrogen of organic fertilizers does not fully mineralize within a season, and hence will partly become available in later years. This effect is taken into account for the first year but generally not in later fertilizer applications. If it would be taken into account, fertilizer use could be more efficient.
This study is an analysis of a 13-year field trial where crop yield was measured in 13 fertilizer treatments which differ in total N applied and decomposition rate. This is complemented with a model study in which mineralization and soil nitrogen content were calculated.
We intended to show step by step that the use of fertilizers with a low decomposition rate, relative to fertilizers with a high decomposition rate, lead in the course of years to an increase in soil organic nitrogen, an increased nitrogen mineralization and availability and that this results in increased yields. Some of the results in these four steps in our work give support to this, but there are more factors at play.
We show that when using, for example, deep stable manure, after some years the available nitrogen may for 50% or more be derived from manure applied in former years. This makes clear that, at least in agricultural systems that use a substantial amount of organic fertilizers, it is worthwhile taking this delayed mineralization into account.

Samenvatting

Stikstof uit organische mest komt niet volledig beschikbaar in het jaar van toediening. Een deel komt in de volgende jaren pas beschikbaar. In de bemesting wordt daar bij de toepassing in het eerste jaar rekening mee gehouden (werkingscoëfficiënt van stikstof) maar in de volgende jaren meestal niet. Als dat wel gedaan zou worden zou dat de stikstofefficiëntie kunnen verhogen.
Dit rapport gaat over de analyse van een 13-jarige veldproef waarin de opbrengst is gemeten van verschillende gewassen in 13 bemestingsvarianten. Die verschillen onder andere in totale N-gift en in afbraaksnelheid van de organische stof. Dit is aangevuld met een modelstudie waarin mineralisatie en bodemstikstof worden berekend.
We wilden stap voor stap aantonen dat meststoffen met een lage afbraaksnelheid, vergeleken met die met een hoge afbraaksnelheid, leiden tot een opbouw van bodemstikstofvoorraad, toename van mineralisatie van stikstof, toename van beschikbaarheid van stikstof voor het gewas en uiteindelijk hogere opbrengst. Enkele van deze vier stappen in ons werk leveren een ondersteuning van dit proces op, maar er zijn meerdere factoren die een rol vervullen.
Als bijvoorbeeld rundveepotstalmest gebruikt wordt kan na een aantal jaar meer dan 50% van de beschikbaar komende stikstof afkomstig zijn van bemestingen uit voorgaande jaren. Dat maakt duidelijk dat, in ieder geval in landbouwsystemen met een aanzienlijke input van organische mest, het de moeite waard is om met deze vertraagde mineralisatie rekening te houden.

1 Introduction

In Dutch agriculture the issue of fertilizer application has been receiving a lot of attention for several decades. It has shown to be difficult for Dutch agricultural practice to fulfill the European Nitrate directive and Water directive. Careful management is needed to be able to obtain high yields without burdening the environment. Current Dutch policies are based on maximum amounts of nitrogen application per crop, on a maximum load of nitrogen in applied manure and on a maximum of applied phosphate, dependent on soil phosphate conditions. However, organic fertilizer does not fully decompose in one season, and for this a ‘ decomposition rate’ for each type of organic fertilizer has been introduced. For example, it is estimated that slurry decomposes for 60% in the first year and plant compost decomposes only for 10% in the first year. Therefore, one has to apply more nitrogen in total in order to have a certain amount of *mineral* nitrogen available for the crop. This surplus nitrogen may become available in later years. This fact is usually not taken into account both in fertilizer policy and in agricultural practice. In recent research projects this has been subject of study (Bokhorst and Van der Burgt, 2012). So farmers may enhance their nitrogen efficiency if they *do* take this into account in their choice of fertilizer type and nitrogen input level. Mineralization of nitrogen from former organic fertilizer applications may increase crop yield, but at the same time it may increase leaching and hence reduce efficiency.

The Louis Bolk Institute has a long-term field trial in which the performance of 13 fertilizer types and combinations is compared. Except for one (artificial fertilizer) all fertilizers are organic. The trial has been running for 13 years. The results of this trial are interesting since there are only few trials of such length. Zanen et al (2008) gave an overview of results up to 2006; Bokhorst et al (2008) summarized this in a leaflet. We combine the trial results of twelve years on yield with a model study to gain insight in the nitrogen dynamics in the soil. The fertilizer treatments cover a range of nitrogen, phosphorus and organic matter input levels and different decomposition rates of the organic matter applied. Hence, we can study the effect of low decomposition rate for various levels of total nitrogen input. Also, we compare the soil nitrogen dynamics for a high input regime with a low input regime.

Our hypothesis consists of four parts. After a number of years the use of slow decomposing fertilizer, relative to fast decomposing fertilizer, is expected to result in a relative build-up of soil organic matter and soil N content (1). This in turn may enhance mineralization (2) and hence the nitrogen availability (3), which is in the end expected to increase yield (4). So we expect the yield to diverge over the years when in different treatments the same level of first-year available nitrogen is applied, but different levels of total nitrogen because of differences in decomposition rates of the organic matter. Similarly, we expect the yields to converge when the same total nitrogen is added, but with a different decomposition rate.

Studying mineralization and soil nitrogen build-up is relevant for several reasons. As different crops are grown, mineralization is expected to be more consistent over the years than yields and therefore more useful to study trends. Soil nitrogen build-up is investigated by making nitrogen balances. The NDICEA model was used to calculate mineralization and the various in- and outflows. This shows us the nitrogen build-up, and also gives insight in the various nitrogen losses.

Chapter 2 gives a brief description of the experiment and our approach. A more detailed description can be found in Zanen et al (2008). In chapter 3 we present and discuss the results for each part of the hypothesis. We start with the last part of our hypothesis, yield, since the yields are observed values, and work back towards soil N budgets based on model calculations. In chapter 4 we come to overall conclusions which are discussed in chapter 5.

2 Methods

2.1 Experimental setup

The trial field is situated in Lelystad (52.32.30 N; 5.30.17 E), on an organic farm in the reclaimed lands, on a sandy loam soil. The trial started in 1999 and consists of 13 fertilizer treatments laid out in 4 replicates, resulting in 52 plots. The plots within the replicates are randomized and the plot size is 63 m^2 (7m by 9m). The field is an integral part of the farm system, so the crop rotation is set by the farmer.

For some treatments the fertilizer application is aimed at 67 kg ha^{-1} readily available nitrogen per year. This is the amount of nitrogen that is present in mineral form or expected to mineralize within the first season. Additionally, two constraints are taken into account: a maximum phosphorus application of 80 kg ha^{-1} and -for the compost treatments- a maximum organic matter application of 6000 kg ha^{-1} because of risk of heavy metal contamination. These constraints are in line with Dutch legislation in 1999, the year that the trial started.
Decomposition rate is defined as the fraction of fertilizer-N that decomposes in the first year, including the fertilizer N fraction which is already inorganic. For the decomposition rate commonly accepted 'rule-of-thumb-values' are used. Nitrogen application for 67 kg ha^{-1} mineral nitrogen is calculated as follows:

$$nitrogen\ application = \frac{67}{decomposition\ rate}$$

Table 1 shows the fertilizer treatments and their corresponding nitrogen and phosphorus applications and decomposition rates.

Table 1 The fertilizer treatments and their nitrogen and phosphorus applications and decomposition rate

Treatment	Fertilizer	Readily available N application aimed for (kg ha^{-1} $year^{-1}$)	Decomposa-bility (fraction decomposed in first year)	Total N application aimed for (kg $ha^{-1}year^{-1}$) (average)	Total N application realised (kg $ha^{-1}year^{-1}$) (average)	Constraint (N/P/OM)
1	Deep stable manure, fresh	67	0.45	149	174	N
2	Slurry	67	0.60	112	106	N
3	Artificial fertilizer	67	1	67	67	N
4	Household compost with slurry	67	n.a.[1]	n.a.	172	N
5	Poultry manure with slurry	67	n.a.[1]	n.a.	116	N & P
6	Deep stable manure, lightly composted	45	0.35	129	138	P
t7	Deep stable manure, intensively composted[2]	45	0.35	129	89	P
8	Pig manure	41	0.45	91	95	P
9	Poultry manure	47	0.55	85	92	P
10	Nature compost[3]	24	0.15	160	174	P
11	Household compost	9	0.10	90	74	OM
12	Plant compost, lightly composted	8	0.10	80	58	OM
13	Plant compost, intensively composted	8	0.15	53	41	OM

[1]These are treatments with 2 fertilizers.

[2]This treatment was stopped in 2004.

[3]Nature compost is exempted from the constraint of 6000 kg ha^{-1} organic matter, since this compost has a low heavy metal concentration.

To calculate the amount of fertilizer needed the nitrogen content of the fertilizer was estimated each year. For this the average nitrogen content of the former years was used. The fertilizers were weighed at the field and spread out over the plots manually. Samples of the manure were then taken at the day of application and their nitrogen content was analysed. Thereafter, the exact amount of nitrogen application was calculated. As a result of this procedure, the exact amount of nitrogen and phosphorus applied varied slightly over the years.

Fertilizer is applied in 2 out of 3 years, in which 1.5 times the amount as of table 1 is applied[1]. Table 2 shows the fertilizer application schedule and the crop rotation.

Table 2 Crops grown and fertilizer application.

Year	**Crop**	**Fertilizer application**
1999	Red cabbage	X
2000	Potato	X
2001	Beetroot	X
2002	Carrots	
2003	Parsnip	X
2004	Broccoli	
2005	Squash	X
2006	Cauliflower	X
2007	Potato	
2008	Salsify	X
2009	Parsnip	X
2010	Squash	
2011	Parsnip	X

2.2 Model study

To calculate the nitrogen dynamics we made use of the model NDICEA (Van der Burgt et al, 2006). NDICEA simulates the day-to-day nitrogen dynamics of arable systems for a given soil type and farming system (i.e. manure application and crop rotation). It uses crop yield and crop nitrogen content as input values for backward calculation of the nitrogen dynamics throughout the year. Regional data on rainfall, temperature and evapotranspiration are used. For the crop nitrogen content as well as for the decomposition rate of crop residues and soil organic matter the NDICEA default values were used.
The model was validated by comparing soil mineral nitrogen content measurements with model predictions. Soil mineral nitrogen content was measured in 2010 and 2011, for a total of 7 times. There is a quantitative criterion available for the comparison: a root mean square error (RMSE, Wallach and Goffinet, 1989) of maximally 20 kg ha^{-1} is considered to be within range of allowable variability (Van der Burgt et al, 2006). The RMSE of all 13 treatments was smaller than 20 kg ha^{-1} (see Annex 1 for RMSE values) so we supposed that the NDICEA model describes the nitrogen dynamics in an acceptable way. Since the model can handle a maximum of 12 years, the data from

[1]The initial idea was to apply 67 kg ha^{-1} mineral nitrogen each year, but in 2001 - two years after the start of the trial – the maximum allowed phosphorus application was lowered from 120 kg ha^{-1} to 80 kg ha^{-1}. It was then decided to continue adding 67 kg ha^{-1} mineral nitrogen in two out of every three years, such that the experimental design could stay the same. At that time the trial had run for 3 years. Therefore the first year of non-fertilization has been one year later than scheduled.

2000 up to 2011 were used. The experiment started in 1999. This first year was modelled separately and the resulting soil organic matter parameters were used as input for the next 12 years calculations.
The model was used to calculate for each treatment the mineralization during the whole year and the nitrogen availability for the crop. The yearly mineralization was calculated as the summation of the mineralization during all 365 days of the year. The nitrogen availability was calculated as the mineralization during crop growth plus the mineral nitrogen content of the soil at day of sowing. Furthermore, the model calculated the total nitrogen in- and output via the processes deposition, leaching, denitrification and volatilization. These values were used to create nitrogen balances. These give an impression of whether soil nitrogen content of the soil has been increasing or decreasing.
Apart from the yield data, this study is for a major part based on model results. Every simulation approach has the challenge of the 'starting point'. In this case the model outcomes of the first years highly depend on the parameter settings of the soil organic matter. The NDICEA model has three pools of soil organic matter, with different quantity, N-content and speed of decomposition. These are model parameters and cannot be measured in the soil. The starting values will influence the results in the first years. In this study we used the first year, 1999, as starting period, using the NDICEA default values for the three pools. We continued the 2000 – 2011 runs with the obtained soil organic matter pools from the end of 1999. This reduces the possible influence of 'wrong' starting data.

2.3 Data analysis

The complete set of 13 treatments (Table 1) was used to correlate yield to nitrogen availability. For further data analysis a selection of treatments was used.
We selected the treatments with the largest contrast in yield, nitrogen application and decomposition rate of applied organic matter. The treatments selected are:

- Deep stable manure, fresh (treatment 1)
- Slurry (treatment 2)
- Artificial fertilizer (treatment 3)
- Plant compost, lightly composted (treatment 12)
- Nature compost (treatment 10)

From here onwards 'deep stable manure' refers to treatment 1 and 'plant compost' to treatment 12.

To be able to compare yields of different crops over time, the crop yield in ton per hectare is transformed in a relative crop yield, 1.00 being equivalent to the average yield per year.

Table 3 shows an excerpt of Table 1: the mineral nitrogen, decomposition rate and the total nitrogen application of the five selected treatments.

Table 3 nitrogen mineralizing from fertilizer application and the total nitrogen in the application of deep stable manure, artificial fertilizer, slurry, plant compost and nature compost.

	Mineral nitrogen application aimed for (kg ha-1 year-1)	Decomposition rate (fraction decomposed in first year)	Total nitrogen application aimed for (kg ha-1 year-1)	Total nitrogen applied (kg ha-1 year-1) (average)
Deep stable manure	67	0.45	149	174
Slurry	67	0.6	112	106
Artificial fertilizer	67	1	67	67
Nature compost	24	0.15	160	174
Plant compost	8	0.10	80	58

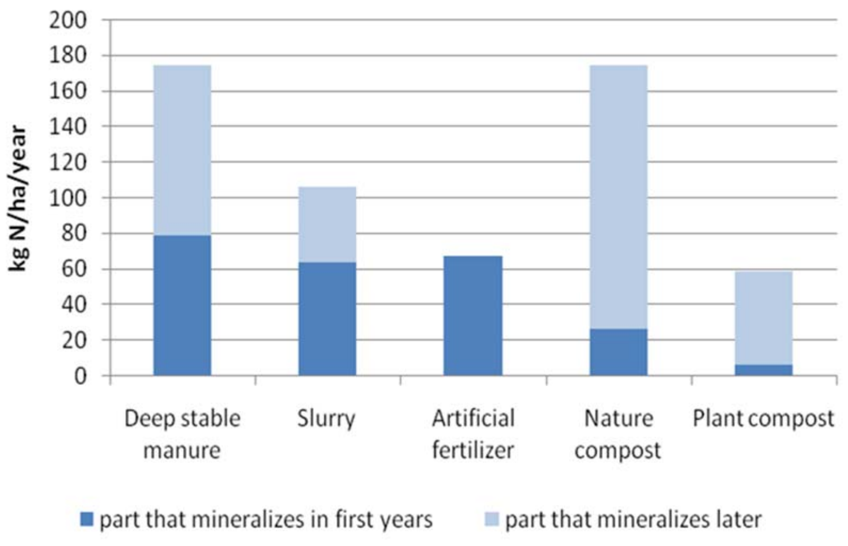

Figure 1: Total nitrogen application in the five treatments selected for analysis and their respective readily available nitrogen applications. Readily available nitrogen application is calculated from total nitrogen application, based on fraction assumed to decompose within a year.

The treatments selected differ in either application of readily available nitrogen or total nitrogen application (Figure 1). This limited the number of comparisons between treatments that could be made. Two different kinds of comparisons can be made: treatments with the same application of readily available nitrogen, and treatments with the same total nitrogen application. Deep stable manure, slurry and artificial fertilizer have a fairly similar application of readily available nitrogen, but a different total nitrogen application. Deep stable manure and nature compost have a similar total nitrogen application. This holds as well for artificial fertilizer and plant compost. For this part of the study we included the 1999 yield data.

Nitrogen balances were made for the selected treatments for the period 2000 - 2011. Separate balances were made for the first 6 years and the following 6 years of this period, such that time effects can be seen. Both periods contain two years of non-fertilization.

2.4 Statistical analyses

Data were analysed with GenStat 13.0. Repeated measurement analysis of variance was used to test whether any yield differences could be observed between treatments. Least significant difference ($P<.05$) was used to assess differences between treatments.

Regression analysis was done for the yield against the nitrogen availability as calculated by NDICEA.

3 Results and discussion

First, yield differences between treatments are analysed. Then, we correlate yield to nitrogen availability as calculated by NDICEA to test whether nitrogen is indeed the explaining factor for crop yield. Thirdly we study the effect of the different treatments on nitrogen mineralization (which determines availability), and lastly we study the effects on soil nitrogen content. For these last two analyses we use the comparisons as described above in paragraph 2.3. For the study of the soil nitrogen content we have created nitrogen balances that also give insight in nitrogen losses and hence in efficiency.

3.1 Crop yield

Table 4 shows crop yield in tons ha^{-1}, and Table 5 shows relative crop yield. The data from Table 5 are used in the further analysis. In 2002 no yield measurements were done.

Table 4 Crop yield (ton/ha)

Year	Crop	Deep stable manure	Slurry	Artificial fertilizer	Plant compost	Nature compost
1999	Red cabbage	48.0	42.8	41.3	35.7	41.6
2000	Potato	35.4	35.6	35.1	35.7	37.1
2001	Beetroot	26.8	29.2	27.4	17.9	19.0
2002	Carrots					
2003	Parsnip	42.2	35.5	33.7	26.7	34.0
2004	Broccoli	9.0	7.3	6.9	6.1	9.2
2005	Squash	17.8	16.9	14.9	14.6	13.8
2006	Cauliflower	19.5	11.7	9.0	8.9	15.8
2007	Potato	23.5	19.9	18.6	20.9	25.4
2008	Salsify	18.2	20.0	19.2	16.3	19.1
2009	Parsnip	47.9	37.2	29.2	30.0	38.6
2010	Squash	22.3	22.8	18.4	20.1	19.3
2011	Parsnip	34.8	32.0	23.3	25.5	31.3

Table 5 Relative crop yield (relative to the average of all treatments, which is set at 1.00)

Year	Crop	Deep stable manure	Slurry	Artificial fertilizer	Plant compost	Nature compost
1999	Red cabbage	48.0	42.8	41.3	35.7	41.6
2000	Potato	35.4	35.6	35.1	35.7	37.1
2001	Beetroot	26.8	29.2	27.4	17.9	19.0
2002	Carrots					
2003	Parsnip	42.2	35.5	33.7	26.7	34.0
2004	Broccoli	9.0	7.3	6.9	6.1	9.2
2005	Squash	17.8	16.9	14.9	14.6	13.8
2006	Cauliflower	19.5	11.7	9.0	8.9	15.8
2007	Potato	23.5	19.9	18.6	20.9	25.4
2008	Salsify	18.2	20.0	19.2	16.3	19.1
2009	Parsnip	47.9	37.2	29.2	30.0	38.6
2010	Squash	22.3	22.8	18.4	20.1	19.3
2011	Parsnip	34.8	32.0	23.3	25.5	31.3

There are statistically significant differences (repeated measure ANOVA, $p<0.05$, lsd: 0.033).The lsd is depicted in Fig. 2, 3 and 4, such that can be seen which of the results differ significantly. In the following section these results will be elaborated on.

3.1.1 Relative yield of treatments with similar readily available nitrogen

From 1999 until 2001 the differences in relative yield of the treatments deep stable manure, slurry and artificial fertilizer were small (Figure 2). In the first three years differences were negligible. From 2003 onwards crop yield was almost always higher in the treatment with higher total nitrogen application: deep stable manure gave a higher yield than slurry and slurry gave a higher yield than artificial fertilizer, with 2008 and 2010 as exceptions. In 2008 salsify was grown, which is known to have a weak response on fertilizer application. This explains the sudden decrease in relative yield of the deep stable manure treatment. In 2010 however squash showed this same decrease in relative yield. This year no fertilizer was applied, and squash is generally known as a crop with a strong response on nitrogen availability. Overall there is a considerable yearly variability. If the period before 2002 is compared with the period after 2002, a diverging trend is visible. Between 2003 and 2011 such a diverging trend is not visible. From our four hypothesis, the fourth is supported to a limited extend: increased yield differences in later years, correlated to the decomposition rates.

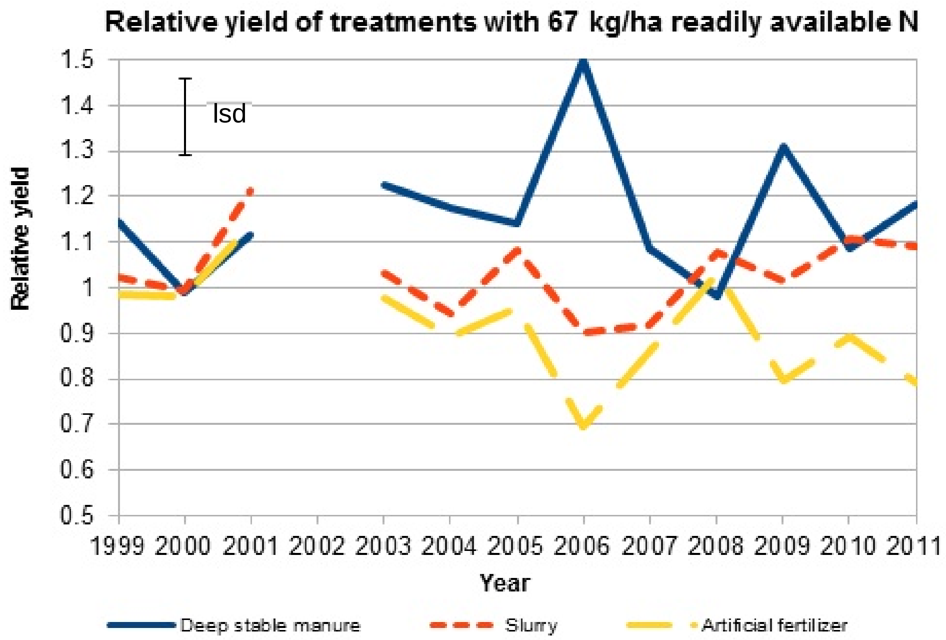

Figure 2 Relative yield of deep stable manure, slurry and artificial fertilizer in the years 1999 until 2011.

3.1.2 Relative yield of treatments with similar total nitrogen

In Figure 3 the relative yield from the treatments deep stable manure and nature compost are shown. Except for in 2001 there were no significant differences. The yield of the nature compost treatment was generally lower than that of deep stable manure. However, there is a number of years in which yields in both treatments were nearly equal. In two of the four years in which this was the case there was no fertilization. The years without fertilization are expected to show a more pronounced effect of soil organic matter and soil N build-up since without fertilization the crops fully depend on mineralization of soil organic matter. However, in 2010 there was no fertilization either and this year the yield was just like in the years in which there was fertilization. So there seem to be multiple factors of effect. In general there is no clear trend. We would have expected the yield of nature compost to increase relative to deep stable manure. Within this time lapse, these two treatments give no support for the fourth part of our hypothesis.

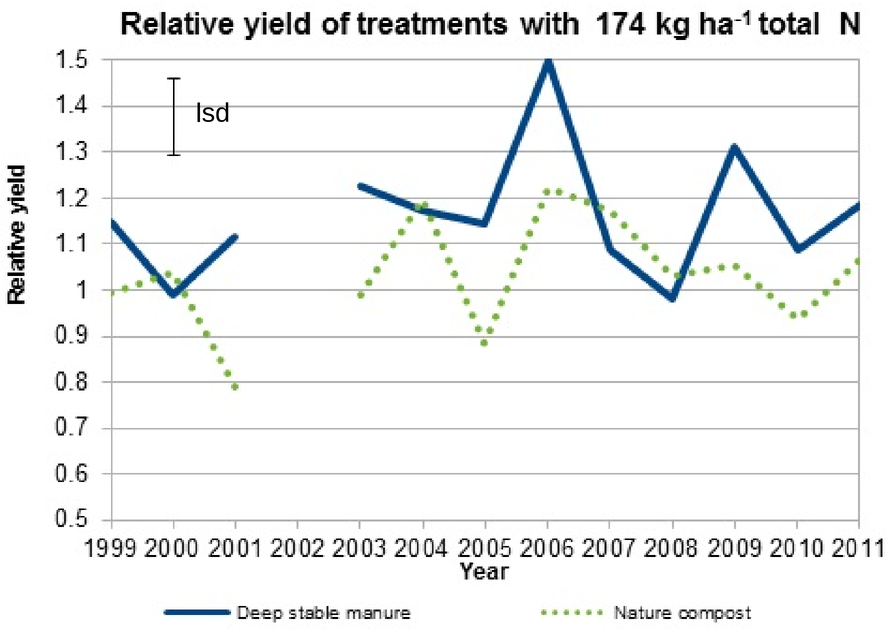

Figure 3 Relative yield of deep stable manure and nature compost in the years 1999 until 2011.

Figure 4 shows that the relative yield of crops grown in treatments with plant compost and with artificial fertilizer are fluctuating. Plant compost tends to have a lower yield in the first half of the trial, and a slightly higher yield towards the end of the trial, but significant differences are absent in most years. Even without differences this is interesting since the total nitrogen application of plant compost was lower than that of artificial fertilizer (58 kg ha^{-1} and 67 kg N $ha-^{1}$ respectively). Assuming that nitrogen availability was a limiting factor this means that the yield of plant compost can only be this high due to mineralization from fertilizer applied in former years. This again would give support to the fourth part of our hypothesis. Another explanation could be the overall positive effect of organic matter, leading to a more efficient use of nitrogen.

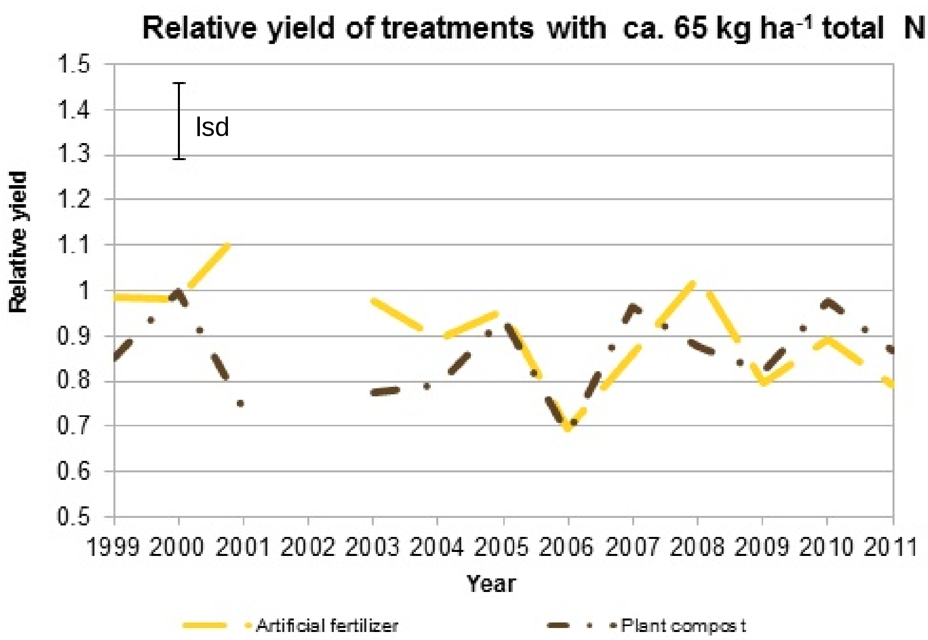

Figure 4 Relative yield of artificial fertilizer and plant compost in the years 1999 until 2011.

3.2 Nitrogen availability

The results of the regression analysis of nitrogen availability to cop yield are presented in Table 6. Graphical representation of the results can be found in Annex 2.

Nitrogen availability is positively correlated to yield in 7 of 11 years ($p<.05$). In those years, between 44% and 80% of the variability in yield can be explained by nitrogen availability (Table 6, r^2-value). In the majority of the years considered, nitrogen availability is an explaining factor for crop yield in this system. In the remaining years, other factors were more important. The slope ranges approximately from 0.03 to 0.1, which means that in this system 1 kg ha^{-1} of available nitrogen results in 30 to 100 kg ha^{-1} yield.

The third part of the hypothesis, nitrogen availability being an important factor in explaining yield performance, is supported by these results. As an integral part of this it has become clear that nitrogen is an important limiting factor in this type of certified organic production system. This was also concluded in other studies (Van der Burgt et al, 2010; Van der Burgt and Staps, 2010). Nitrogen availability is nevertheless not the only factor determining yield.

Table 6 Results of the regression of nitrogen availability to crop yield. Significant relationships are shown in grey.

Year	P-value	R2	Slope	Intercept
2000	0.655	0.02	-0.01	37.75
2001	<0.001	0.80	0.12	6.73
2002	no yield data available			
2003	0.088	0.24	0.06	28.21
2004	<0.001	0.70	0.05	2.49
2005	0.011	0.46	0.03	12.17
2006	0.300	0.10	0.03	9.55
2007	0.002	0.60	0.07	14.18
2008	0.013	0.44	0.03	14.05
2009	0.002	0.58	0.10	19.48
2010	0.184	0.15	0.03	17.70
2011	0.004	0.54	0.06	23.93

3.3 Mineralization

For some of the selected treatments, yearly mineralization of nitrogen differed considerably from year to year (Figure 5). The peaky character of some of the lines occurs because in some years no fertilizer was applied (2002, 2004, 2007 and 2010). The fertilizers with, combined, the highest amount of directly available inorganic nitrogen and the lowest decomposition rate of the organic nitrogen, showed the strongest reaction to this. Both compost treatments, with only a small amount of inorganic nitrogen and a low decomposition rate, show only a week annual variation..

In general, over the first five years of the trial, there was a decline in mineralization. Nitrogen levels of the fertilizer application before the start of the trial were higher than during the trial, which might explain this decline..

The mineralization of the nature compost treatment gradually picked up with that of deep stable manure. The mineralization of the plant compost treatment superseded that of artificial fertilizer in the non-fertilized years 2007 and 2010.

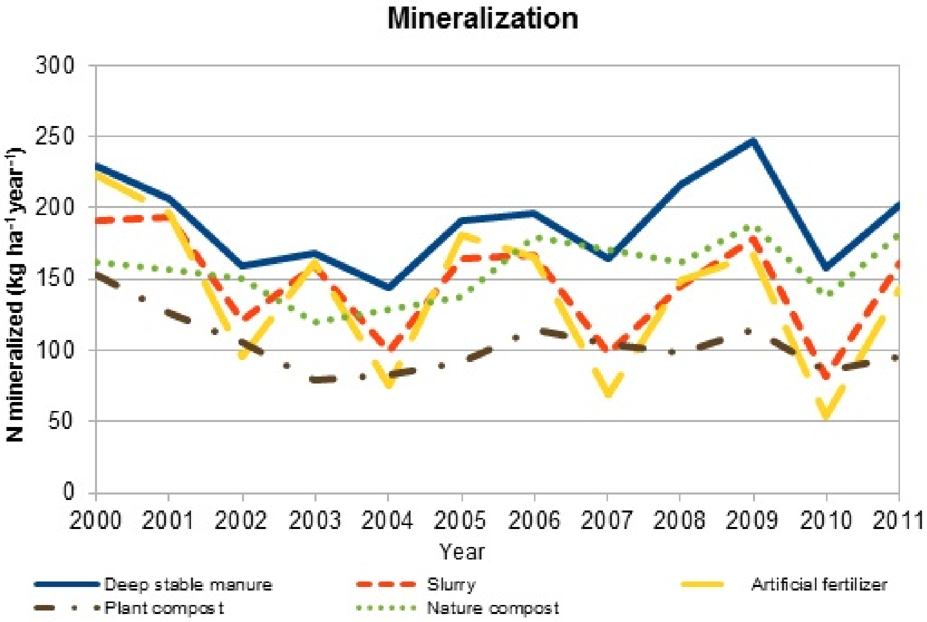

Figure 5 Mineralization for the whole year as calculated by NDICEA for the five selected treatments.

In 2010 there was a strong dip in mineralization over more or less all treatments. The environmental data collected by NDICEA show that 2010 was indeed a relatively cold year (Table 7). This is likely to be the cause of the decrease in mineralization.

Table 7 Average temperature in the years of non-fertilization

Year	Average temp (°C)
2002	10.8
2004	10.4
2007	11.2
2010	8.7

Due to the peaks in the curves it is hard to see a trend in this graph. We therefore look at the years in which there was no fertilizer application. This shows us per definition mineralization from former years (Figure 6).

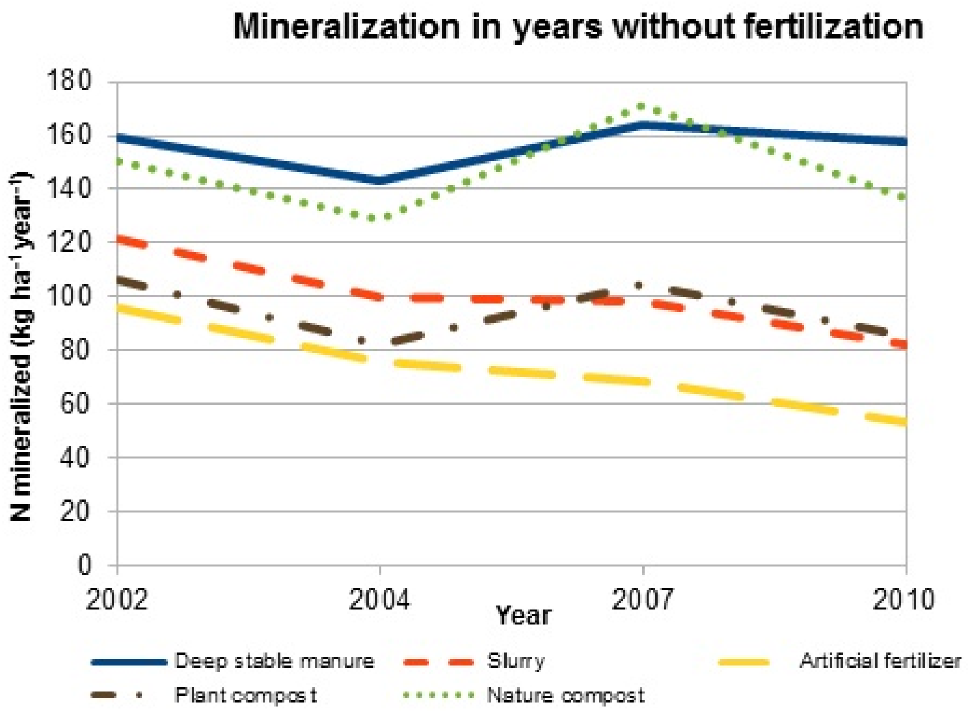

Figure 6 Nitrogen mineralization per year for the years in which there has been no fertilizer application.

The mineralization of the deep stable manure treatment was almost twice as large as that of artificial fertilizer. The lines are divergent. This is in line with our expectation that in some treatments there is a building-up of soil organic matter and soil organic nitrogen during time, leading to extra mineralization. None of the fertilizers showed an increase in mineralization over the years. The graph shows a decrease in mineralization for slurry (regression, p-value: 0.067, slope:-4.851 kg ha^{-1} (SE:0.910)) and artificial fertilizer (regression, p-value: 0.033, slope:-4.30 kg ha^{-1} (SE:1.18)).
By using the mineralization of artificial fertilizer with a decomposition rate of 100% as a reference we can see what part of the mineralization of deep stable manure and slurry is generated by decomposition of build-up soil organic nitrogen. So the difference in mineralization between deep stable manure and artificial fertilizer in 2010 – about 100 kg ha^{-1} – was predominantly realized by decomposition of manure that was applied in earlier years.. Figure 5 shows that mineralization in the deep stable manure treatment in the last few years of the experiment averages around 200 kg ha^{-1}. This means that towards the end of the trial total mineralization in the deep stable manure is for about 50% derived from organic matter input in former years. For slurry this difference in 2010 was 20 kg N ha^{-1}, which is about 15% when related to a mineralization of 150 kg N ha^{-1}.

3.4 Soil nitrogen content and nitrogen balances

In this part the nitrogen balances are presented. Three comparisons are discussed: treatments with similar available nitrogen applications; treatments with similar total nitrogen applications, both high-input and low-input; treatments with a more or less stable soil nitrogen content.

3.4.1 Nitrogen balances for treatments with similar available nitrogen-applications

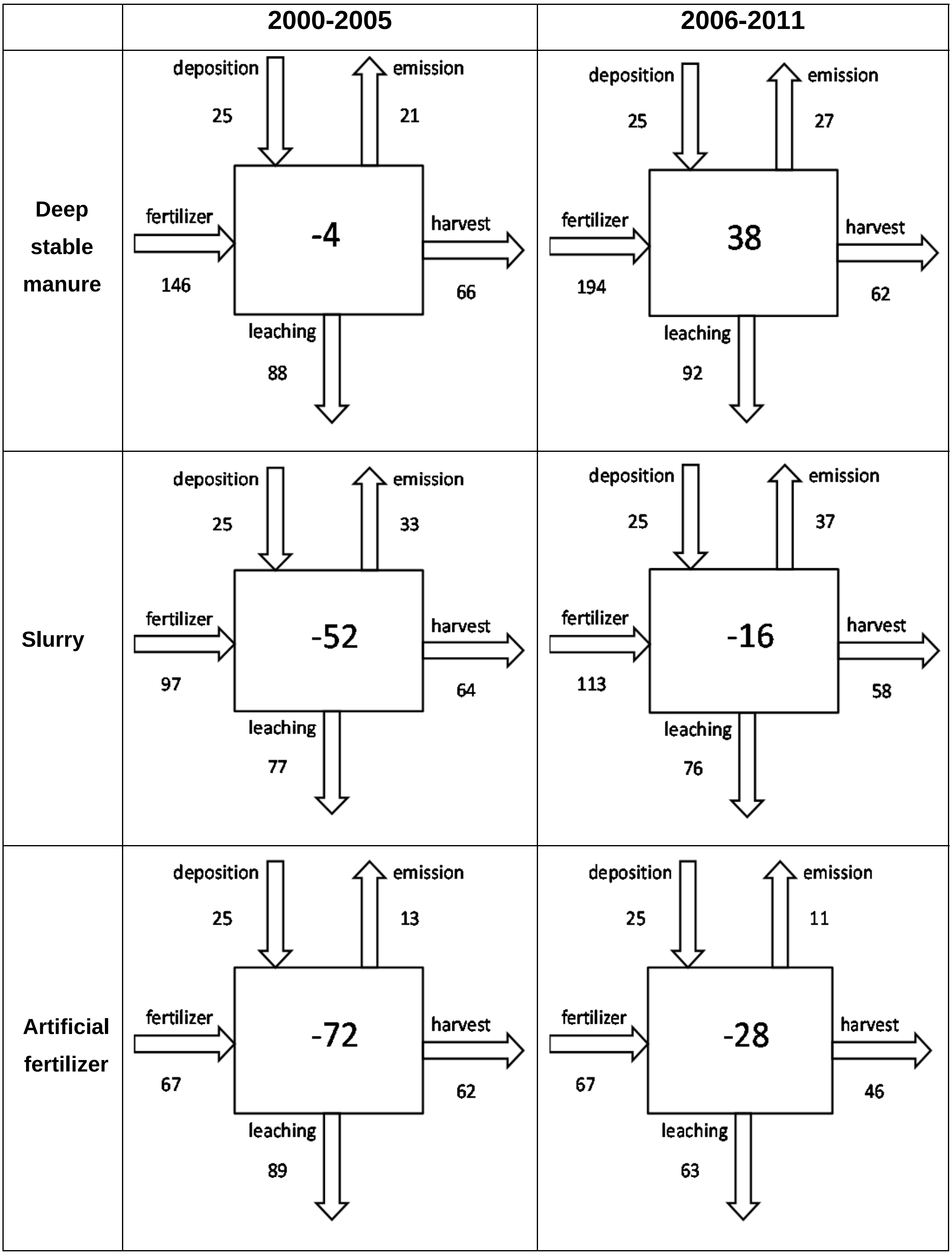

Figure 7 Nitrogen balances for the treatments deep stable manure, slurry and artificial fertilizer. All units are kg ha^{-1} year^{-1}. Within the square: change in soil nitrogen. Emission: sum of denitrification and volatilization.

In Figure 7, it can be seen that only in the case of deep stable manure there was build-up of nitrogen in the soil. However, nitrogen was only built up in the second half of the trial. This may be explained by the fact that from 2008 onwards the nitrogen application – incidentally - increased. Artificial fertilizer showed a stronger decrease in soil nitrogen content than slurry, which is expected since artificial fertilizer had a lower total nitrogen and no organic nitrogen application. Both artificial fertilizer and slurry showed a stronger decrease during the first half of the trial than during the second half of the trial. This suggests that the systems tend to go towards equilibrium. This turns out to be a slow process, for this equilibrium is clearly not reached within 6 years.
The losses of nitrogen to the environment were considerable. In most treatments, around 60 kg N ha^{-1} was collected in the harvest per year, and between 63 and 92 kg N ha^{-1} leached annually from the soil (Figure 7). The other emissions, being the sum of denitrification and volatilization, were highest for the slurry treatment. This is mainly due to the volatilization when the manure was spread
In the treatment with artificial fertilizer, a high amount of nitrogen was lost by leaching compared to the nitrogen input. In the first 6 years the leaching was higher than in the treatment with slurry, whereas the treatment with slurry had a higher nitrogen input. Leaching in the treatment with artificial fertilizer was similar to that in the treatment with deep stable manure, although the nitrogen input of deep stable manure was more than twice as high. This can partly be explained by leaching during crop growth, which can be higher in case of a fertilizer with a high mineral nitrogen content. During the second half of the trial leaching from the treatment with artificial fertilizer decreased from 89 kg ha^{-1} to 63 kg ha^{-1}, while the nitrogen input stayed the same. This is not hard to explain: a decrease in soil organic matter will imply a decrease in mineralization and so in leaching.

3.4.2 Nitrogen balances for treatments with similar total nitrogen applications: high and low nitrogen input

In this section the results for deep stable manure versus nature compost (Figure 8) and artificial fertilizer versus plant compost (Figure 9) are compared. Within the pairs the total nitrogen input is more or less the same, but they differ in decomposition rate. The first pair is high-input and the second pair is low-input.

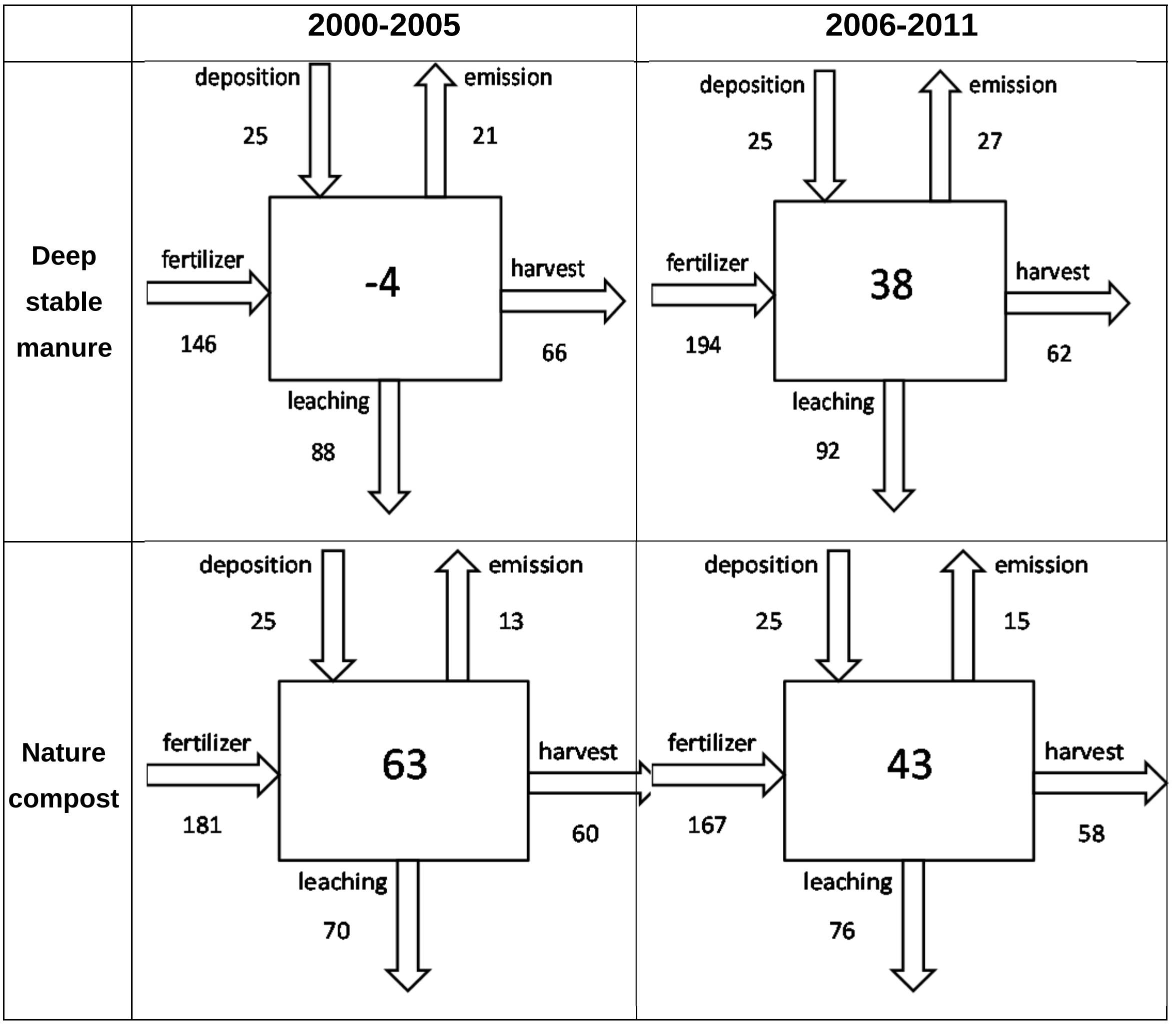

Figure 8 Nitrogen balances for the treatments deep stable manure and nature compost. All units are kg ha^{-1}year^{-1}. Within the square: change in soil nitrogen. Emission: sum of denitrification and volatilization.

In the treatment with nature compost, more nitrogen was build up in the soil than in the treatment with deep stable manure (Figure 8). Because nature compost has a lower decomposition rate than deep stable manure (0.1 resp.0.45) the readily available nitrogen was generally lower, so less leaching was expected. This corresponds with what we see in Figure 8. In the second half of the experiment leaching increased a bit compared to the first half, being in accordance with an increased mineralization after harvest due to build-up of soil nitrogen.

Interestingly, the amount of nitrogen in the yield was about the same in both treatments. This suggests that with nature compost as fertilizer the crops can obtain the same yield with lower available nitrogen than with deep stable manure. Possibly, other soil processes such as enhanced soil life, enhanced rooting capacity or better water drainage contribute to this effect.

In the treatment with nature compost, less nitrogen was lost by emission and leaching, per kg of nitrogen in the crop, than in the treatment with deep stable manure. Nature compost thus seems more efficient. However, in the nature compost treatment the process of nitrogen build-up is still going on, and values for leaching may change. Leaching increased from 70 kg N ha^{-1} to 76 kg N ha^{-1} in the second half of the trial. This may further increase in future if the same fertilizer application is maintained.

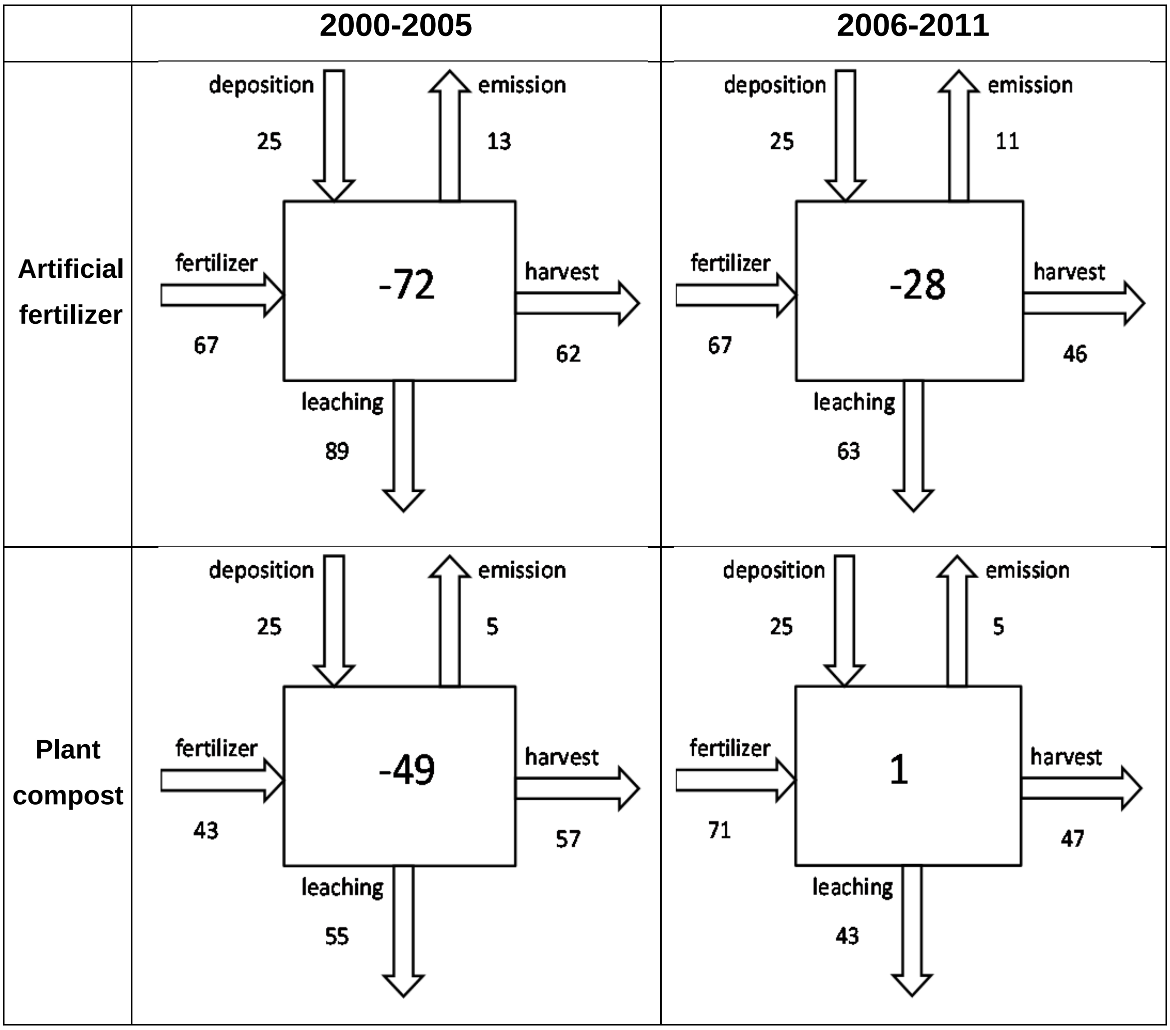

Figure 9: Nitrogen balances for the treatments artificial fertilizer and plant compost. All units are kg ha^{-1} $year^{-1}$. Within the square: change in soil nitrogen. Emission: sum of denitrification and volatilization.

The differences between artificial fertilizer and plant compost (Figure 9) are similar to the differences between deep stable manure and nature compost (Figure 8). In the treatment with plant compost, much more nitrogen was maintained in the soil than in the treatment with artificial fertilizer, whereas nitrogen input was even a bit smaller. The yields were comparable although directly available nitrogen was lower for the plant compost treatment. The soil nitrogen content in the treatment with plant compost has decreased less than that in the treatment with artificial fertilizer. Despite the higher directly available nitrogen and the higher soil nitrogen content in the plant compost treatment, leaching was lower for this treatment than for the artificial fertilizer treatment (Figure 8).

3.4.3 A stable soil nitrogen content

There are two treatments that have had a stable soil nitrogen content for at least some of the time. These are the fertilization of about 150 kg N ha^{-1} deep stable manure from 2000 to 2005 and the application of about 70 kg N ha^{-1} plant compost in 2006 to 2011. This is an interesting comparison, for the deep stable manure treatment has a relatively high nitrogen input within the context of this experiment, whereas plant compost has reached equilibrium with a much lower input.

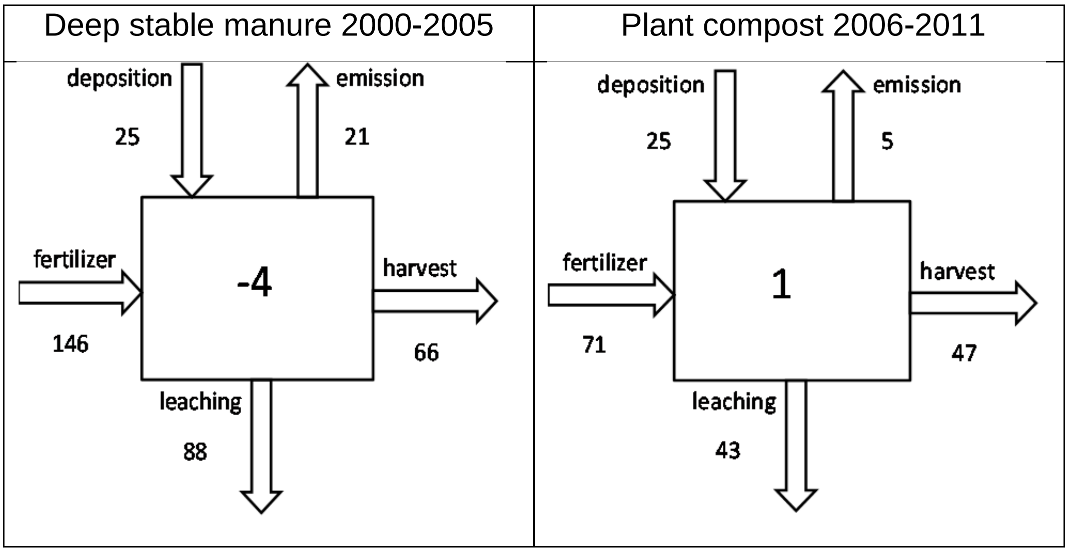

Figure 10 Two nitrogen balances that have a more or less stable soil nitrogen content. All units are kg ha^{-1} $year^{-1}$.

The yield in the treatment with plant compost was approximately 30% lower, whereas nitrogen input was more than 50% lower (Figure 10). So the low-input system is more efficient. This is related to less leaching and lower emissions. Moreover, the deposition of 25 kg N ha^{-1} is of relatively larger contribution when the fertilizer application is low. However, a harvest of 47 kg N ha^{-1} as in the low-input system is hard to make economically viable.

4 Conclusion

A higher total nitrogen input tends to lead to higher yields, when the amount of applied readily available nitrogen is similar. This difference becomes visible after 4 to 5 years. (chapter 3.1.1). At the same time, total nitrogen applied seems to be a more important factor in determining yield than readily available nitrogen. The yields of the low and high input treatments with different decomposition rates do, within the time-span of this research, not tend to diverge in time. (chapter 3.1.2.)

Nitrogen availability plays a dominant, although not exclusive role in yield. This is shown in the regression analysis of nitrogen availability and yield of all treatments (chapter 3.2).

Nitrogen mineralization of soils receiving fertilizers with a high decomposition rate, such as slurry or artificial fertilizer, decreases over time, especially in years without fertilization. In contrast, mineralization stays at a constant level in plots receiving fertilizers with a medium decomposition rate, such as deep stable manure, or with a low decomposition rate, such as nature or plant compost. Plots receiving less total nitrogen show lower mineralization levels than plots receiving more total nitrogen (chapter 3.3).

The soil nitrogen stock decreased in most of the five selected treatments during the time lapse of this experiment. The changes in soil nitrogen are less negative or a bit positive in the second half of the studied time lapse compared to those in the first part. There are substantial differences between the three treatments with the same application of readily available nitrogen. The soil nitrogen balances in case of deep stable manure (positive balance), slurry and artificial fertilizer (most negative balance) are according to our expectations. The differences between deep stable manure and nature compost are less easy to interpret because of interaction with other processes such as substantial changes in input.

Overall we conclude that the process as described in our hypothesis (build-up of soil nitrogen -> increased mineralization -> increased nitrogen availability -> increased yield) are shown in our results. Some effects are visible within a few years, some effects may last longer than the time lapse studied to become visible.

5 Discussion

Extra nitrogen application to compensate for low decomposition rate is common practice in The Netherlands. In the long run, this has a major impact on nitrogen dynamics in the soil and hence, potentially, on the yield. This makes it interesting to study this process in detail. Within the MAC long term field trial there are differences in yield of around 30%. We showed that treatments with fertilizers with a low decomposition rate may obtain 50% or more of the mineralization during crop growth from organically bound nitrogen applied in former years, compared to the treatment with artificial fertilizer only. This is substantial and makes it well worth taking into account in nitrogen management. However, this is not easy. As we have seen, these processes may well last for over 10 years. Also, although crop yield correlated with nitrogen availability rather well, the results of the crop yield alone were quite variable, since different crops were grown. This means that within the context of this study conclusions cannot be based on crop yield alone. Further knowledge on the soil processes is needed, such as changes in soil nitrogen.

In this long-term experiment fertilizer is applied in a quantity independent from the crop that was grown. In agricultural practice other choices will be made. One will usually adapt the nitrogen application to the crop grown, which may help to limit leaching. Although in this case there was generally a decrease in soil nitrogen rather than a build-up it is advisable to level off fertilizer application when a sufficiently high soil nitrogen content level and, correlated to that, a certain level of mineralization has been reached. Also, combinations of different fertilizers can be used. Especially using a combination of a fast decomposing and a slowly decomposing fertilizer is advisable because of their complementary characters.

The amount of nitrogen leaching was quite high in this trial, even though the nitrogen applications were generally low. Apart from fertilization management there are other options to limit leaching. The most effective might be inserting catch crops in the rotation. We expect that this change in the rotation will have major impacts on the nitrogen dynamics. It is possible to get an impression of the influence of catch crops on the nitrogen dynamics by using the existing NDICEA files, but there is a limitation. NDICEA is target-oriented, and there is no feedback between nitrogen availability and crop yield. Increase of yield due to increased nitrogen availability has to be estimated by interpolation or extrapolation of the relation between nitrogen availability and crop yield. This could be subject for a next study.

This study was limited to the effect of nitrogen on crop yield. However, it is well known that organic matter has additional positive effects on yield through amelioration of soil life, improved rooting density and water retention and other aspects. It is interesting to study these factors as well to shed more light on their relative importance.

The soil conditions in the MAC trial field are in general favourable for decomposition: a low clay content, a pH > 7, well-drained soil, regular soil cultivation. Under a fertilizer applications of around 67 kg ha^{-1}readily available nitrogen, a build-up in the soil is only achieved with the use of compost and of deep stable manure. In these cases the application of additional nitrogen to compensate for low decomposition rate is no luxury, but needed to maintain the soil nitrogen content at a constant level. This coincides with a surplus in the phosphorus balance (data not given here). Under the new Dutch regulations for phosphorus application in agriculture these levels of phosphorus are not allowed. This invokes a new urgent question: how to maintain soil fertility and soil organic matter within the new regulations?

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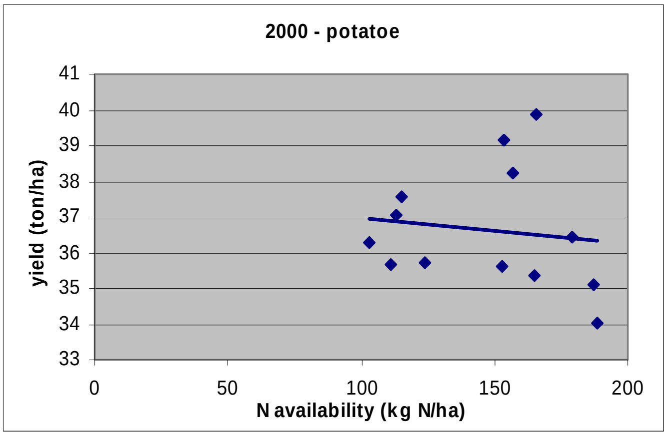
Annex 1: RMSE values of NDICEA predictions against mineral nitrogen measurements

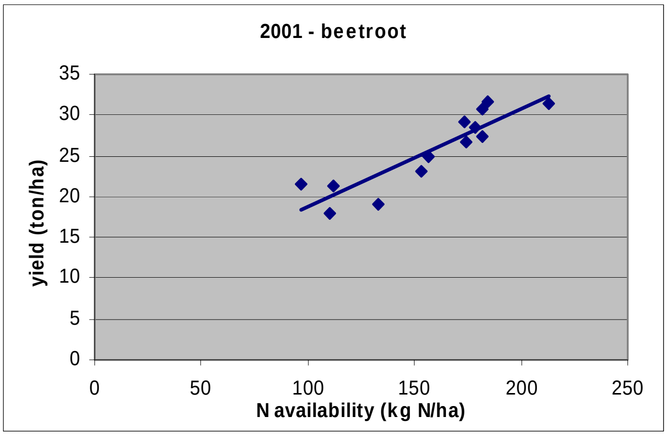
The RMSE (root mean square error) is a measure to evaluate whether model predictions fit experimental data well enough. In this case the technique is used to evaluate the NDICEA predictions on the nitrogen fluxes in the soil with data on mineral nitrogen content. A RMSE of 20 kg ha^{-1} is considered to be within range of allowable deviation. The following table shows the RMSE for each treatment.

Treatment	Fertilizer	RMSE
1	Deep stable manure, fresh	13.53
2	Slurry	12.27
3	Artificial fertilizer	10.46
4	Household compost with slurry	12.05
5	Poultry manure with slurry	13.08
6	Deep stable manure, lightly composted	14.82
7	Deep stable manure, heavily composted	10.75
8	Pig manure	11.83
9	Poultry manure	15.79
10	Nature compost	12.41
11	Household compost	12.69
12	Plant compost, lightly composted	13.08
13	Plant compost, heavily composted	11.79

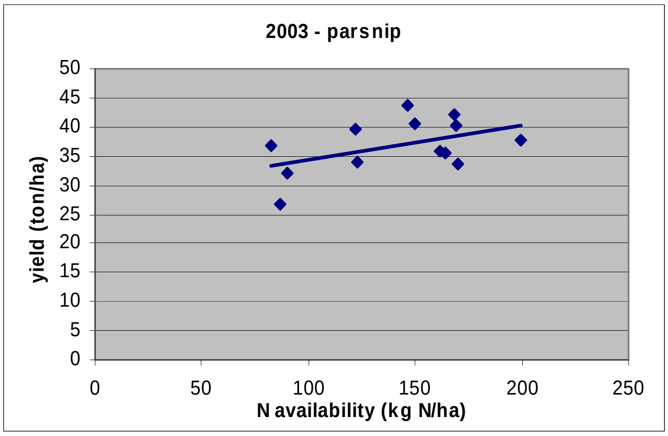
Annex 2: Crop yield versus nitrogen availability

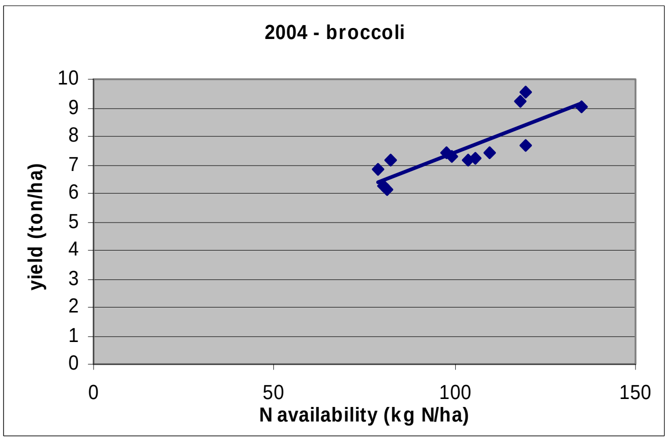
The following table shows the graphs of the correlations of the yield against the nitrogen availability for each year. The slope, intercept, R^2-value and the significance are given in Table 5 of the main text.

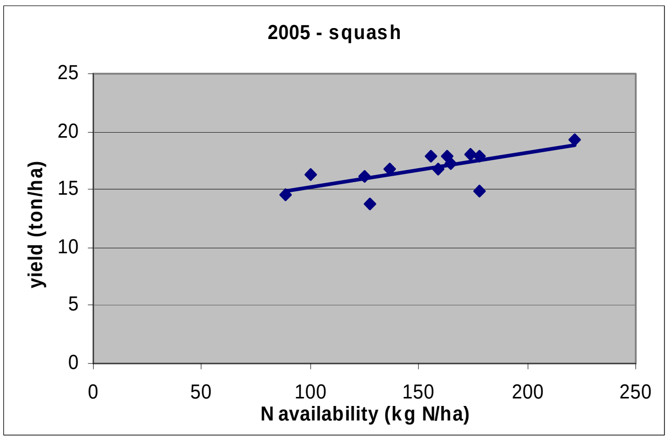


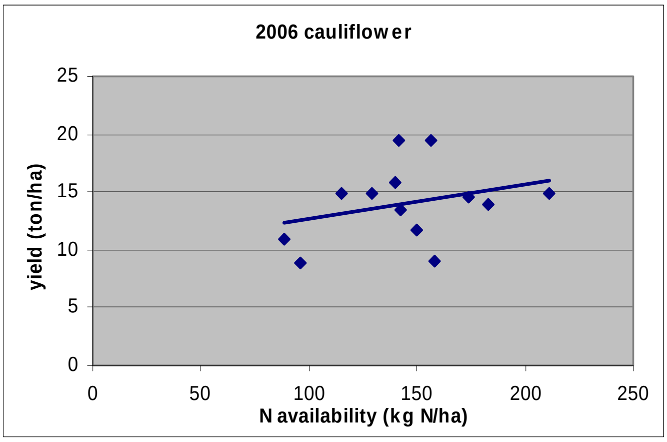


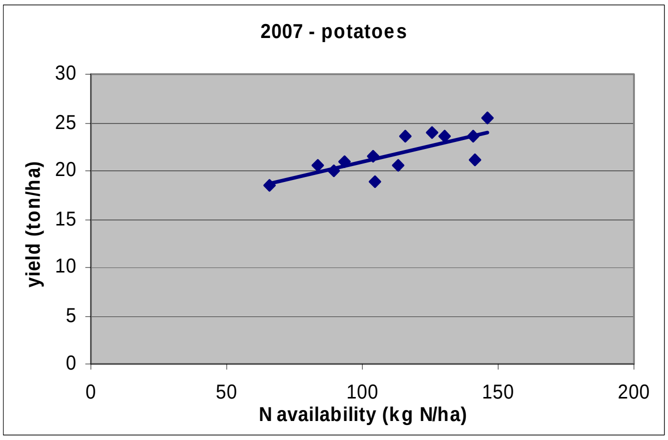
No crop yield data available

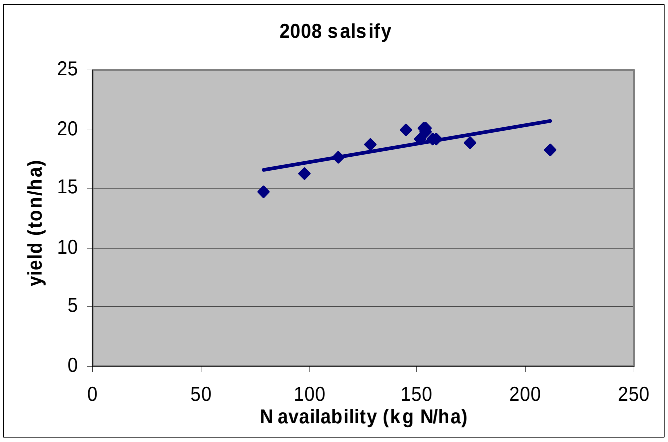


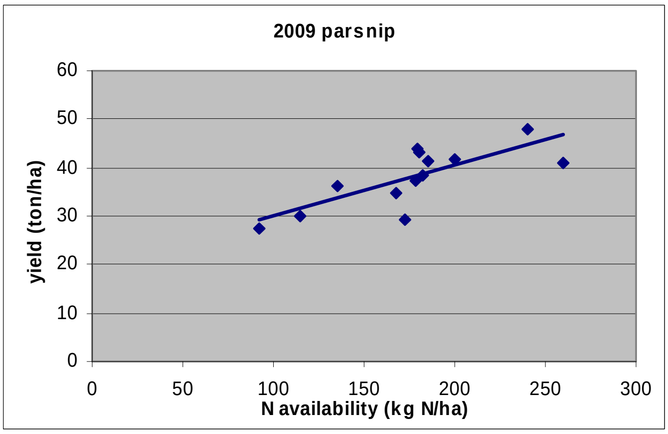


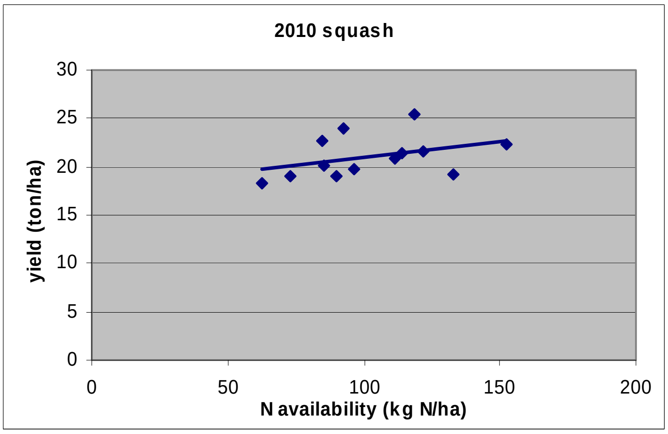


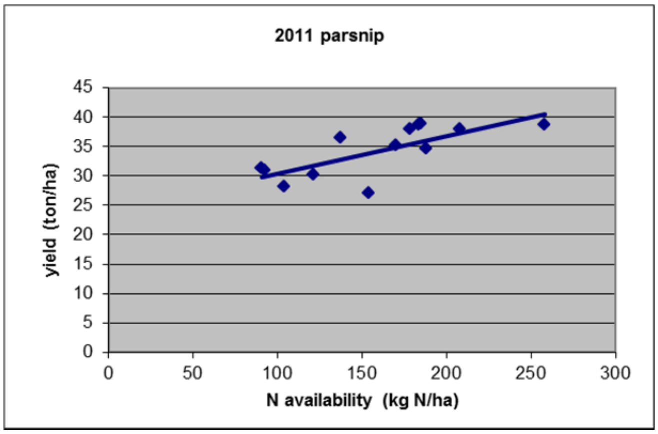

2006 cauliflower
yield (ton/ha)
N availability (kg N/ha)


2007 - potatoes
yield (ton/ha)
N availability (kg N/ha)


2008 salsify
yield (ton/ha)
N availability (kg N/ha)


2009 parsnip
yield (ton/ha)
N availability (kg N/ha)


2010 squash
yield (ton/ha)
N availability (kg N/ha)


2011 parsnip
yield (ton/ha)
N availability (kg N/ha)