# Denitrification in agricultural soils in the Netherlands

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#### Introduction

Dutch agriculture is characterized by high production levels, which are at least partly the result of high input rates of fertilizer nitrogen. The average annual input of nitrogen per ha agricultural land (70% of the Dutch land area) is approximately 200 kg higher than the amount that is removed by agricultural harvest products (OECD, 2001). One may reasonably well assume that ultimately, all this nitrogen will be transformed into molecular nitrogen gas as a result of denitrification and other processes (Wrage et al., 2001). However, in annual field balance sheets, the amount of nitrogen that is accounted for by denitrification is much lower than 200 kg per ha. Consequently, on the short term part of the excess nitrogen will be lost by other pathways than denitrification, of which leaching to ground and surface water, ammonia volatilization and sequestration into the soil organic matter (SOM) pool probably are the most predominant(e.g. Van Beek et al., 2003a&b). The high surplus of agricultural nitrogen indeed leads to increased nitrate concentrations in both the upper <sup>1</sup> (Fraters et al (2002), Figure 1) and deeper ground water as a result of leaching. The lowest nitrate concentrations are found in those areas of the Netherlands with deep layers of clay or peat in the soil and high ground water levels, i.e. the Western and central parts of the country, whereas the highest concentrations are found in the Eastern and South-Eastern areas (Fig. 1), with sandy soils with generally deeper ground water levels and very intensive agricultural activities (pig and poultry breeding and dairy cattle farming). In these areas the nitrate concentrations exceed the EU nitrate directive maximum concentration level of 50 mg nitrate per L. Apparently the sequestration and volatilization capacity of the soils in the Western and central areas are sufficient to prevent nitrate leaching to concentrations above the 50 mg per L, whereas in the Eastern and South Eastern parts this is not the case.

# The impact of denitrification on field nitrogen balances

The impact of denitrification on the total nitrogen balance can be obtained using several methods, including measurements of ground water nitrate concentrations, potential and

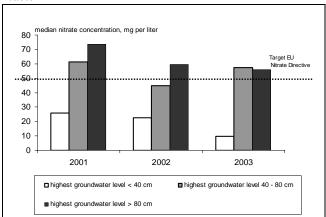
<sup>&</sup>lt;sup>1</sup> Groundwater levels in the Netherlands are very shallow in comparison to other countries. During the winter groundwater level in most soils are within 1 meter below the soil surface and often within the upper 50 cm

actual denitrification rates and computer modeling. This paper describes the results of recent studies in the Netherlands of such measurements in agricultural fields. The results described in this paper have been reported at a workshop on denitrification held at Alterra, Wageningen on April 21<sup>st</sup>, 2004 (see www.mestenmineralen.nl)

#### Ground water nitrate concentration

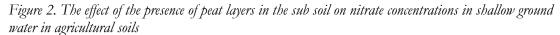
The concentration of nitrate in the upper ground water (0-1 m below the ambient ground water level) of sandy soils varies with the ground water level (Figure 2).

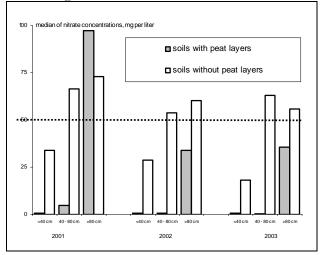
Figure 2. Nitrate concentrations in shallow groundwater of agricultural soils in relation to the groundwater table



On sandy soils where the highest ground water level (HGL) is higher than 40 cm below the surface (HGL < -40 cm), the average nitrate concentrations are far below the value of 50 mg per L. In soils with HGL > 80 cm, the average nitrate concentrations are on average far above this value. In the intermediate ground water levels, the nitrate concentrations vary annually. On average the nitrogen surplus in these three situations are comparable. One may therefore conclude that high ground water levels stimulated denitrification as a result of the presence of (degradable) organic matter in the upper soil layers and anoxic conditions due to high ground water levels (Burgers et al, 2004]. On a somewhat more detailed scale, the presence of peat layers (> 15% SOM) deeper in these sandy soils had a marked effect on the ground water nitrate concentration (Figure 3). In the presence of a peat layer in the sub soil the ground water nitrate concentrations were always lower than in its absence, except for the HGL > 80 cm soils in 2001 (Velthof et al., 2004b).

The effects of excess nitrogen from agriculture are also evident at greater groundwater depth. Figure 4 shows the nitrate concentration at 5-15 and 15-35 m depth respectively in two areas in the Netherlands. Drenthe in the North Eastern part has relatively extensive agriculture, whereas agriculture in Brabant in the Southern part is very intensive. Yet nitrate concentrations in Drenthe in the deep subsoil are higher than in Noord-Brabant as a result of lower contents of the mineral FeS<sub>2</sub>, pyrite and/or of reactive organic matter. Pyrite acts as an electron donor for denitrifying bacteria and due to pyrite oxidation a large part of the nitrate that leaches into deep soil layers is denitrified in Noord-Brabant but not in Drenthe.





The different nitrate concentrations in shallow ground water indicate different denitrification rates. Further by comparing nitrate concentrations in both upper and deeper groundwater under sandy soils, one may conclude that part of the excess of nitrogen originating from agricultural activities disappears as a result of pyrite driven denitrification. However, it remains difficult to quantify this amount exactly, reaction products of pyrite are possibly more harmful to ground water quality than nitrate and, more important, the quantities of nitrate that appear in the ground water exceed critical concentrations in large areas.

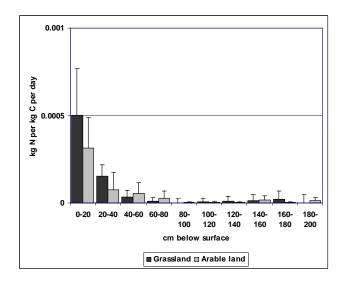
### Denitrification rates in agricultural soils

Denitrification rates can be expressed as potential or actual rates. Potential denitrification is measured under anaerobic conditions, at a fixed reference temperature and in the presence of excess nitrate. Acetylene is often used to inhibit the last step of the denitrification reaction (Yoshinara et al 1977). As such, potential denitrification rate is an indication of the maximum denitrification capacity of a soil at the reference temperature. The actual denitrification is generally much lower than the potential denitrification due to lower temperatures, incomplete anoxic situations and (much) lower nitrate concentrations.

#### Potential denitrification rates

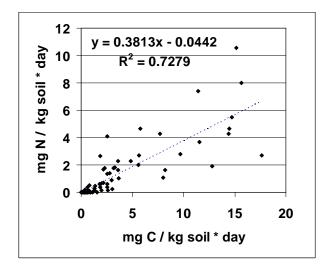
In a recent study Zwart (2003, 2004) measured the potential denitrification rates of grass land and arable fields in soil profiles up to 2 m depth. The results showed that denitrification rates declined rapidly with depth, even if organic carbon was available. Velthof & Oenema (1995) also found a strong decrease in potential denitrification rates in grassland soils. The potential denitrification in the upper 5 cm of grassland was a factor 2 to 5 higher than in the 5-10 cm layer, indicating that grass roots and the addition of manure have a strong effect on the potential denitrification rate. The amount of nitrate that can be denitrified per kg organic carbon decreased rapidly with depth (Figure 5, Zwart, unpublished results). The results suggested that the probability of denitrification in many sub soils is low due to the quality of the organic carbon source in these deeper layers.

Figure 5 Relative denitrification rate (kg N per kg total soil carbon per day) in relation to soil depth of grassland and arable land



There was a good correlation between potential denitrification rates and soil respiration rates (Figure 6), which is not really surprising, since denitrification is in fact soil respiration using nitrate instead of oxygen as an electron acceptor. Actual denitrification rates were between 0.5 and 5% of the potential denitrification rates if measured in comparable samples.

Figure 6. Relation between respiration and potential denitrification



For a number of the sandy soils with a peat layer in the sub soil (see Figure 3), the potential denitrification rate was measured above, inside and below the peat layer and was compared to the rates in soils without peat. Soils with peat layers had much higher potential denitrification rates (Figure 7), especially inside the peat layers than soils without peat at similar depths. However the variation within the peat was considerable, indicating that the presence of peat will not invariably leads to low nitrate concentrations in the ground water.

Addition of pig slurry strongly increases the potential denitrification of the top soil (Velthof et al., 2004a). Regression analyses with the 10 slurries of different composition showed that

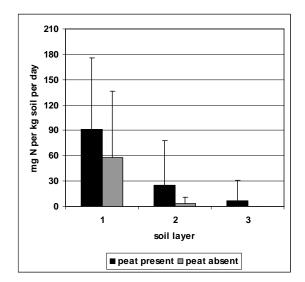


Figure 7. Effect of the presence op peat layers in the sub soil on potential denitrification

the potential denitrification was statistically significantly related to the amounts of added Volatile Fatty Acids and total C, but it was not significantly related to the amount of dissolved organic C. The potential denitrification rate in this study was also significantly related to the respiration rates.

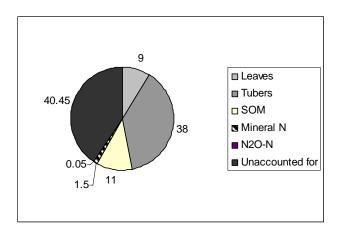
## Actual denitrification rates

Actual denitrification on a field scale basis is mostly established using the acetylene inhibition method (AIM). Measurements with AIM show that both spatial and temporal variability of denitrification are very high (e.g. Velthof et al., 1996 en 1997) and this hampers an accurate estimation of denitrification. The results of 23 different studies in the Netherlands are summarized in Table 1 for grass land on three different soil types and for arable crops on loamy soil. Most of the measurements carried out in the Netherlands were restricted to the upper soil layers. Most fields had a measured denitrification rate below 20 kg N per ha per year with a maximum of 52 kg N per ha per year (note that the thickness of the sampled soil layer differs from study to study). These values represented less than 10% of the nitrogen applied and they are in good agreement with the amounts reported in the international literature (Barton et al, 1999). Although measured values using both techniques often differ, there is no systematic difference. It can therefore be assumed that measured values using AIM are unbiased, though not precise. In a recent study on sandy soils Van Groenigen et al ( 2004) showed that less than 5% of the applied nitrogen was denitrified. The fraction not accounted for in this study was 41%, resulting in a large gap in the N-balance sheet (Figure 8). So, the reported amounts of nitrogen that can be denitrified annually are considerably lower than the excess amounts of 200 kg nitrogen that are applied. Since the annual amounts of nitrogen that can be accounted for by leaching and ammonia emission are also much lower than 200 kg per ha, most studies on the nitrogen balance of agricultural fields show a

Table 1. Denitrification on a field scale using acetylene inhibition on pasture on sandy soils (A); clay soils (B) and peat soils (B) and in arable crops on loamy soils (D), n.a. not available.

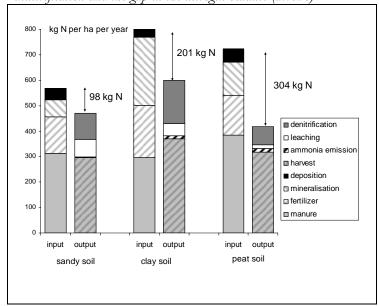
	Measurement period	Layer,	Fertilization, kg N · ha-1	denitrification, kg N · ha-1	denitrification, % of applied N	Reference
A	Full year	0 - 20	298	14	5	Corré (1996)
	Full year	0 - 20	327	31	9	
	April - September	0 - 11	250	5	2	De Klein et al (1994)
	April - September	0 - 11	400	7	2	
	March - June	0 - 11	160	18	11	Velthof et al (1997)
	March - June	0 - 10	260	< 1	0	
	March - June	0 - 10	260	< 3	1	
	March - June	0 - 10	30 t slurry	< 1	< 1	
	January - May	0 - 30	67 t slurry	14	5	De Klein et al (1996)
	January - May	0 - 30	67 t slurry	4	1	
	January - May	0 - 30	0	1	n.a.	
В	March - October	0 - 15	250	30	12	Corré et al (1990)
	March - October	0 - 15	600	52	9	
	August (17 days)	0 - 15	25 t slurry	6	5	
	April - October	0 - 11	250	25	10	De Klein et al (1994)
	April - October	0 - 11	400	20	5	
С	April - October	0 - 11	93	11	12	
	April - October	0 - 11	193	6	3	
	Avg. over 2 full years	0 - 40	0	27	n.a.	Koops et al (1996)
	Avg. over 2 full years	0 - 40	365	41	11	
	Avg. over 2 full years	0 - 40	365	75	21	
	Avg. over 2 full years	0 - 40	0	24	n.a.	
	Avg. over 2 full years	0 - 40	242	44	18	
	14 days	0 - 10	50	2	4	Jarvis et al (1994)
D	April - June	0 - 20	0	7	n.a.	Postma & van
	April - June	0 - 20	300	7	2	Loon (1996)
	May - January	0 - 120	220	35	16	Corré (1995)

Figure 8. Effect of denitrification on the nitrogen balance of potatoes using <sup>15</sup>N nitrogen



gap in the balance sheet. The quantity represented by this gap may vary between agricultural systems; for managed grass land it depends e.g. on the soil type (Velthof & Oenema, 1995, Figure 9).

Figure 9 Nitrogen balance sheet of grassland on three different soil types indicating the impact of denitrification and the gap in the nitrogen balance (arrows)



# Modelling denitrification rates

Denitrification is a complex process that is influenced by temperature, the availability of an electron donor, the redox status and the nitrate concentration in soil. These conditions fluctuate largely both spatially and temporarily. Several computer models with a wide range of complexity have been developed to deal with such fluctuating conditions in order to calculate annual soil denitrification rates. These have been reviewed by Heinen (2003). Simple process models are most widely used. These generally convert potential

denitrification rates into actual rates by using reduction functions for nitrate content  $(f_N)$ , anoxic conditions (as water filled pore space,  $f_S$ ) and temperature  $(f_T)$ . Such a model was applied to experimental datasets from which both potential and actual denitrification rates could be derived and for which soil nitrate contents, soil water contents and soil temperatures were available (eight from the Netherlands and one from the UK). For each individual data set the parameters in the model were optimized. Except for peat soils, there appears to be a good correlation between measured and calculated average actual denitrification rates (Figure 10). However, the model is not able to predict the individual observations (Figure 11). For each data set different sets of parameters were obtained, indicating that these parameters are site specific. Even when grouped into main soil types (sand, clay, peat) the reduction functions differed within such a group.

Figure 10. Comparison between measured and computed (after parameter optimization) average actual denitrification rates for eight Dutch data sets and one UK data set.

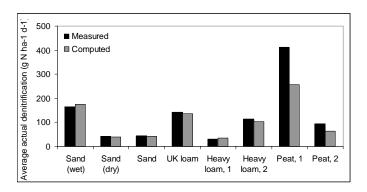
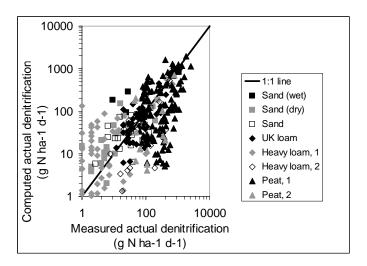


Figure 12. Comparison between measured and computed (after parameter optimization) actual denitrification rates for eight Dutch data sets and one UK data set



## **Summary and Conclusions**

The nitrate concentrations in shallow and deeper ground water in agricultural soils in the Netherlands depend on the ground water depth and on the presence of organic matter or pyrite. Measured actual denitrification rates are always (far) too low to compensate for the excess of nitrogen that is applied. The potential denitrification rate decreases with soil depth, as a result of lower SOM contents at greater depths. Moreover, the quality of the organic matter, expressed as the amount of nitrate which can be denitrified per kg SOM, decreases with soil depth. The complex nature of soil denitrification requires computer simulation models in order to estimate annual denitrification rates. A widely used simple process model for denitrification, predicts average denitrification rather well, after optimization. This means that such a model can be used to predict cumulative denitrification. However, site specific properties should always be kept in mind.

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nitrate (mg/l)

not relevant or no data

0 - 25

25 - 50

50 - 100

100 - 150

> 150

Figure 1 Nitrate concentrations in shallow ground water in the Netherlands (source RIVM)

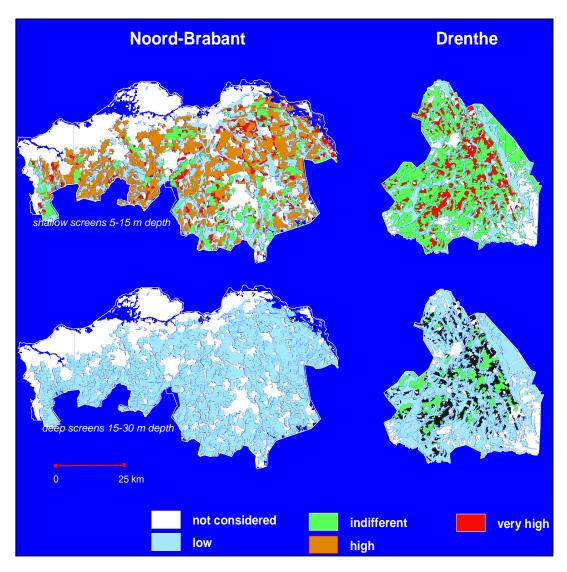


Figure 4 Nitrate concentrations in deeper groundwater in two areas in the Netherlands (Source TNO)