N balance as an indicator of N leaching in an oilseed rape – winter wheat – winter barley rotation

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Abstract

The nitrogen (N) balance (N input – N export by the grain) is often used to estimate the risk of N leaching from arable land. In a nine year study during the leaching seasons 1991/1992 to 1999/2000, the relationships between N fertilization, N balance and N leaching in the subsequent percolation period were investigated in a multifactorial field experiment near Kiel in NW Germany at the Hohenschulen Experimental Station. The crop rotation was oilseed rape (OSR) – winter wheat – winter barley, while soil tillage (minimum tillage without ploughing, conventional tillage), application of pig slurry (none, application in autumn, application in spring, application in autumn plus in spring), mineral N fertilization (none, 120 or 240 kg N ha\(^{-1}\) to cereals), and application of fungicides (none, intensive) were all varied. In each year the rotation and the treatments were located on the same plots. N leaching was calculated by multiplying the drainage volume with the respective N concentration obtained using ceramic suction cups. In all crops, N fertilization significantly increased the N balance in the order mineral N < spring slurry < autumn slurry. N leaching significantly correlated with the amount of percolation (\(P < 0.05\)). Highest annual N losses occurred with wheat following OSR (73 kg N ha\(^{-1}\)) compared to the situation with OSR following barley (44 kg N ha\(^{-1}\)). Without slurry, mineral N fertilization increased N leaching only slightly, whereas slurry, especially if applied in autumn, boosted N losses. Soil tillage and fungicide application had no significant effect on N leaching, although the latter showed a large influence on N balance. Increasing N balance progressively raised N leaching in the subsequent period with all crops, however, only 13–25% of the N balance surpluses originating from the preceding crop seem to leave the system via this pathway. The results indicate only a poor correlation between N balances and N leaching. In the short-term, therefore, the N balance is not an appropriate indicator for the environmental impact of N fertilization. However, if set up over a longer period, N balances may still give good estimates of the leaching potential arising from different management systems.

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Keywords: N balance; N leaching; Mineral N fertilization; Slurry application; Oilseed rape; Wheat; Barley

1. Introduction

Agriculture is the major contributor to nitrate contamination of groundwater (Fraters et al., 1998). Therefore, farmers are asked to reduce the impact of nitrogen (N) on the environment. Increased nitrogen supply to crops may increase yield but decreases N use efficiency (Kuhlmann and Engels, 1989; Sieling and Hanus, 1997). If it has not been volatilised or denitrified, N amount not utilized by the crop can accumulate in the soil and, in consequence, escalates the risk of leaching with corresponding environmental consequences.

N leaching depends on the amount of water percolating through the soil (mainly affected by winter rainfall; Webb et al., 2000) and the N concentration in the leachate. The latter is closely related to the mineral N pool in the soil at the beginning and/or during the leaching period (Goss et al., 1991). Most of the N leached from arable soils originates from inorganic N present in late summer, autumn or early winter when soils start to drain and plant demand is low or non-existent. Generally, N leaching positively correlates with the N supply. With mineral N application it has been shown that only N rates exceeding the economic optimum progressively increase N losses (e.g. Engels and Kuhlmann, 1993; Davies and Sylvester-Bradley, 1995; Goulding et al., 2000). Results from the Broadbalk Wheat
Experiment at Rothamsted (UK) indicated that in most years only a little fertilizer-derived N remained in inorganic form at harvest from applications of up to 192 kg N ha\(^{-1}\) (Glendining et al., 1996). In the short term, therefore, reduction of N fertilization below optimum had only small effects on autumn soil mineral N and, in consequence, on N losses over winter (Macdonald et al., 1989; Lickfett, 1993; Zerulla et al., 1993; Shepherd and Sylvester-Bradley, 1996). More serious problems may arise from the use of organic manures and slurries, which are often applied to onto the stubbles after harvest on arable land, when no plant uptake occurs. Compared with mineral N fertilizers, crops utilize slurry N poorly, due to overwinter losses by leaching or denitrification (Smith and Chambers, 1992; Sieling, 2005).

N balances (N fertilization minus N offtake by the harvest products) at field scale or in larger areas are often used to estimate the leaching risk (Doluschitz et al., 1992; Lord et al., 2002; Jansons et al., 2003; Sacco et al., 2003). However, there is much evidence that, in the short-term, the link between fertilizer use (except excessive amounts) and nitrate in water is not very direct. A nutrient surplus in itself may not be sufficient to quantitatively determine the amount of nutrient lost via various pathways, because of the interaction with other environmental parameters. For example, the large reserve of organic N in soils and vegetation will inevitably contribute nitrate to leaching once the land is tilled (Macdonald et al., 1989; Sylvester-Bradley and Chambers, 1992). On the other hand, however, N balances can give an indication of the risks that are associated with specific farming practices, especially in the wider environment and if integrated over a relatively long period (Öborn et al., 2003). Even if N fertilization meets plant N requirement in time and rate, long-term application of inorganic N fertilizer and, to a greater extent, of organic manures, they may build up soil organic matter. This is due to a larger amount and higher N concentration of crop residues being returned to the soil at harvest and, in consequence, may increase N mineralization of soil organic N (Glendining et al., 1996).

The objective of this paper therefore, is to quantify the effect of different crop management measures (soil tillage, slurry application, mineral N fertilization, and application of fungicides) on the N balance of oilseed rape (OSR) (cv. Falcon) – winter wheat (cv. Orestis) – winter barley (cv. Alpaca). Practical constraints required the field trial design to be a single-replicate split–split-plot design, with three levels of splitting. The tillage treatments were main plots, the slurry treatments were sub-plots split within main plots. The fungicide treatments were sub-sub-plots split within sub-plots and the mineral N fertilizer treatments were sub-sub-sub-plots split within sub-sub-plots. Each crop was grown in each year and each main plot finished a complete rotation after three years. The same treatment regimes were applied to the same sub-plots, the same sub-sub-plots, and the same sub-sub-sub-plots in each year so that the cumulative effects of each treatment were included in the balance both for years and for previous crops.

In spring, mineral nitrogen fertilizer (calcium ammonium nitrate with 27% N) was applied as a split-dressing at the beginning of spring growth, at the start of stem elongation, and at ear emergence of cereals or at bud formation of OSR. Pig slurry (80 kg total N ha\(^{-1}\)) was applied in autumn on the stubble of the preceding crop and immediately incorporated into the soil by cultivator. Spring application (80 kg total N ha\(^{-1}\)) was made within one week around the second mineral N fertilizer application, e.g. at the end of March to OSR and in April to cereals, when soil and weather conditions were suitable. At both dates drag hoses were used. A subsample of each application was taken and analysed photometrically for its ammonium N content and for its total N content using the Kjeldahl method. Total N content was multiplied by the amount of applied slurry to give the rate of N applied.

### Table 1

<table>
<thead>
<tr>
<th>Percolation period</th>
<th>Estimated amount of percolation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991/1992</td>
<td>210</td>
</tr>
<tr>
<td>1992/1993</td>
<td>310</td>
</tr>
<tr>
<td>1993/1994</td>
<td>360</td>
</tr>
<tr>
<td>1994/1995</td>
<td>420</td>
</tr>
<tr>
<td>1995/1996</td>
<td>0</td>
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<tr>
<td>1996/1997</td>
<td>130</td>
</tr>
<tr>
<td>1997/1998</td>
<td>330</td>
</tr>
<tr>
<td>1998/1999</td>
<td>490</td>
</tr>
<tr>
<td>1999/2000</td>
<td>380</td>
</tr>
</tbody>
</table>

2. Materials and methods

2.1. Site and soil

The experiment was carried out on a pseudogleyic sandy loam (Luvisol: 170 g kg\(^{-1}\) clay, pH 6.7, 9 mg kg\(^{-1}\) P, 15 mg kg\(^{-1}\) K, 13 g kg\(^{-1}\) C\(_{\text{org}}\), 1.13 g kg\(^{-1}\) N\(_{\text{total}}\)) at the Hohenschulen Experimental Farm (10.0°E, 54.3°N, 30 m a.s.l.) of the Kiel University, located in NW Germany 15 km west of Kiel (Schleswig-Holstein). In the humid climate of NW Germany, total rainfall averages 750 mm annually at the experimental site. Average percolation volume during autumn and winter varied between 0 mm in 1995/1996 and 490 mm in 1998/1999 (Table 1).

2.2. Treatments and design

Table 2 shows the factors and the factor levels tested in the field trial, which was based on the rotation oilseed rape (OSR) (cv. Falcon) – winter wheat (cv. Orestis) – winter barley (cv. Alpaca). Practical constraints required the field trial design to be a single-replicate split–split-plot design, with three levels of splitting. The tillage treatments were main plots, the slurry treatments were sub-plots split within main plots. The fungicide treatments were sub-sub-plots split within sub-plots and the mineral N fertilizer treatments were sub-sub-sub-plots split within sub-sub-plots. Each crop was grown in each year and each main plot finished a complete rotation after three years. The same treatment regimes were applied to the same sub-plots, the same sub-sub-plots, and the same sub-sub-sub-plots in each year so that the cumulative effects of each treatment were included in the balance both for years and for previous crops.

In spring, mineral nitrogen fertilizer (calcium ammonium nitrate with 27% N) was applied as a split-dressing at the beginning of spring growth, at the start of stem elongation, and at ear emergence of cereals or at bud formation of OSR. Pig slurry (80 kg total N ha\(^{-1}\)) was applied in autumn on the stubble of the preceding crop and immediately incorporated into the soil by cultivator. Spring application (80 kg total N ha\(^{-1}\)) was made within one week around the second mineral N fertilizer application, e.g. at the end of March to OSR and in April to cereals, when soil and weather conditions were suitable. At both dates drag hoses were used. A subsample of each application was taken and analysed photometrically for its ammonium N content and for its total N content using the Kjeldahl method. Total N content was multiplied by the amount of applied slurry to give the rate of N applied.
Ammonia losses during application, measured in the first 3 years by using wind tunnels (according to Lockyer, 1984), averaged $<10$ kg N ha$^{-1}$ and were taken into account in calculating the N supply. Crop management not involving the treatments (e.g. seed date, application of herbicides and insecticides) was according to standard farm practice. The straw remained on the plots.

The sub-sub-sub-plot size was $12$ m$^2$. At harvest an area of 9 m$^2$ was harvested by combine and yield was standardized to t ha$^{-1}$ total dry matter (TDM) based on the moisture content of a grain subsample. The N uptake of the harvested grain was obtained by multiplying the TDM by the total N content of the grain determined by the NIRS method.

Beginning with the leaching period 1991/1992, N loss was calculated in three slurry (S1, S2, S4) and all mineral N treatments (0, 120 and 240 kg N ha$^{-1}$) by multiplying the drainage volume with the respective nitrate concentration (see also Sieling et al., 1997). Soil water at 90 cm depth was obtained using porous ceramic suction cups (two per plot, averaged to one sample) and analysed for nitrate photometrically. During the leaching period, the cups were sampled at approximately fortnightly intervals. The vacuum of 65 kPa was maintained for 1–2 days depending on the soil water content. The drainage volume was estimated from daily meteorological observations and evapotranspiration equations. It was assumed that after the soil water content has reached field capacity in autumn, daily drainage is equal to the difference of rainfall less the evapotranspiration calculated by the Haude equation. The return to field capacity was identified by tensiometers. During winter 1995/1996 no N leaching occurred because the amount of rainfall from October until March was very small (102 mm), compared to the 30-year average of 363 mm. In addition, the soil was frozen from the end of November 1995 until the end of March 1996.

Assuming a similar N deposition in all plots, the N balance was calculated from the difference between N input and N output and was defined as

\[
N \text{ balance} = N \text{ fertilization (mineral and slurry)} - N \text{ uptake by the grain}
\]

### 3. Statistical analysis

Analyses of variance were done separately for each crop, using the GLM procedure of the SAS statistical package. The year was used as a blocking factor. LSD$_{0.05}$ for tillage treatments are based on year $\times$ tillage interaction, those for slurry treatments are based on year $\times$ tillage $\times$ slurry interaction effects, those for the fungicide treatments are based on year $\times$ tillage $\times$ slurry $\times$ fungicide interaction effects, those for the mineral N treatments are based on year $\times$ tillage $\times$ slurry $\times$ mineral N interaction effects. The LSD$_{0.05}$ apply only to individual treatment means.

In order to relate N leaching to the N balance, a linear-plateau model was fitted to the crop data for each crop separately on average values across the years:

\[
Y = \begin{cases} 
  P - a(C - NB), & \text{if } NB > C \\
  P, & \text{if } NB \leq C 
\end{cases}
\] (1)
where \( Y \) is the N leaching (kg N ha\(^{-1}\)) or N leaching per unit grain (kg N t\(^{-1}\)), NB the N balance (kg N ha\(^{-1}\)), \( C \) the N balance at the intersection of the plateau and the linear model, \( P \) describes the plateau and \( a \) is a constant, which were estimated using the NLIN procedure of SAS and are shown in Tables 3 and 4.

To distinguish between slurry and mineral N fertilizer effects on N leaching, the following approach was used

\[
Y = a + b(mN + cSA + dSS - eNU)^2
\]

(2)

where \( Y \) is the N leaching (kg N ha\(^{-1}\)) or N leaching per unit grain (kg N t\(^{-1}\)), \( m \) the mineral N fertilization (kg N ha\(^{-1}\)), \( SA \) the amount of slurry N applied in autumn (kg N ha\(^{-1}\)), \( SS \) the amount of slurry N applied in spring (kg N ha\(^{-1}\)), \( NU \) the N uptake by the grain (kg N ha\(^{-1}\)) and \( a - e \) are the constants, which were estimated using the NLIN procedure of SAS and are shown in Table 5.

### 3. Results

#### 3.1. Husbandry effects on N balance

On average, N balances were positive in all crops (Table 6). Due to higher grain yields and N uptake by the grain, wheat (52 kg N ha\(^{-1}\)) left significantly less N in the soil than barley (88 kg N ha\(^{-1}\)) or OSR (97 kg N ha\(^{-1}\)) with a similar N supply. Slurry and mineral N application increased N balance \((P < 0.001)\). In OSR and barley,

### Table 4

Estimates of parameters in Eq. (1) relating N leaching per unit grain (kg N t\(^{-1}\)) in different preceding crop–crop combinations to the N balance \((NB = N \text{ fertilization minus } N \text{ uptake by the grain, kg N ha}^{-1})\)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimates</th>
<th>Standard error of the estimates</th>
<th>( P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Under OSR following barley</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P ): plateau</td>
<td>8.3</td>
<td>0.59</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>( C ): intersection</td>
<td>112.6</td>
<td>36.01</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>( a ): C – NB</td>
<td>0.046</td>
<td>0.0166</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>RMSE</td>
<td>2.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( N )</td>
<td>36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.39</td>
<td></td>
<td>0.0003</td>
</tr>
<tr>
<td>Under wheat following OSR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P ): plateau</td>
<td>23.0</td>
<td>1.61</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>( C ): intersection</td>
<td>126.0</td>
<td>37.70</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>( a ): C – NB</td>
<td>0.113</td>
<td>0.0509</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>RMSE</td>
<td>7.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( N )</td>
<td>36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.26</td>
<td></td>
<td>0.0066</td>
</tr>
<tr>
<td>Under barley following wheat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P ): plateau</td>
<td>6.86</td>
<td>0.529</td>
<td>&lt;0.05</td>
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<tr>
<td>( C ): intersection</td>
<td>47.0</td>
<td>19.09</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>( a ): C – NB</td>
<td>0.051</td>
<td>0.0085</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>RMSE</td>
<td>2.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( N )</td>
<td>36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.66</td>
<td></td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

### Table 5

Estimates of parameters in Eq. (2) relating N leaching (kg N ha\(^{-1}\)) in different preceding crop–crop combinations to the N balance \((NB = N \text{ fertilization minus } N \text{ uptake by the grain, kg N ha}^{-1})\)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimates</th>
<th>Standard error of the estimates</th>
<th>( P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Under OSR following barley</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( a ): intercept</td>
<td>28.4</td>
<td>2.01</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>( b ): total N fertilization</td>
<td>(1.2 \times 10^{-4})</td>
<td>(0.52 \times 10^{-4})</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>( c ): autumn slurry (AS)</td>
<td>3.12</td>
<td>0.690</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>( d ): spring slurry (SS)</td>
<td>1.71</td>
<td>0.406</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>( e ): N uptake (NU)</td>
<td>-0.082</td>
<td>0.5687</td>
<td>n.s.</td>
</tr>
<tr>
<td>RMSE</td>
<td>6.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( N )</td>
<td>36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.84</td>
<td></td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Under wheat following OSR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( a ): intercept</td>
<td>37.3</td>
<td>3.84</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>( b ): total N fertilization</td>
<td>(1.8 \times 10^{-4})</td>
<td>(1.06 \times 10^{-4})</td>
<td>n.s.</td>
</tr>
<tr>
<td>( c ): autumn slurry (AS)</td>
<td>4.30</td>
<td>1.051</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>( d ): spring slurry (SS)</td>
<td>1.50</td>
<td>0.412</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>( e ): N uptake (NU)</td>
<td>0.091</td>
<td>0.967</td>
<td>n.s.</td>
</tr>
<tr>
<td>RMSE</td>
<td>11.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( N )</td>
<td>36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.86</td>
<td></td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Under barley following wheat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( a ): intercept</td>
<td>28.8</td>
<td>3.10</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>( b ): total N fertilization</td>
<td>(2.4 \times 10^{-4})</td>
<td>(0.91 \times 10^{-4})</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>( c ): autumn slurry (AS)</td>
<td>2.13</td>
<td>0.459</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>( d ): spring slurry (SS)</td>
<td>1.61</td>
<td>0.337</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>( e ): N uptake (NU)</td>
<td>0.1105</td>
<td>0.3922</td>
<td>n.s.</td>
</tr>
<tr>
<td>RMSE</td>
<td>9.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( N )</td>
<td>36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.86</td>
<td></td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>
already 120 kg N ha\(^{-1}\) applied as CAN led to a surplus of 29 and 11 kg N ha\(^{-1}\), respectively. Increasing mineral N fertilization from 120 to 240 kg N ha\(^{-1}\), however, had more pronounced effects on the N balance. The effect of spring slurry on the N balance was smaller compared to autumn slurry. In the treatments with slurry application in the autumn and in spring, combined with 240 kg mineral N ha\(^{-1}\), N surplus varied between 192 kg N ha\(^{-1}\) (in wheat) and 247 kg N ha\(^{-1}\) (in OSR). Due to higher yield levels, application of fungicides decreased the N balance significantly by 6 kg N ha\(^{-1}\) in OSR, 17 kg N ha\(^{-1}\) in barley and 23 kg N ha\(^{-1}\) in wheat (data not shown). In contrast, soil tillage had no effects on the N balance.

### 3.2. Husbandry effects on N leaching

N leaching in the plots without N fertilization since autumn 1990 varied considerably between years, from 0 kg N ha\(^{-1}\) in 1995/1996 to 59 kg N ha\(^{-1}\) in 1998/1999 (Fig. 1). This is due to differences in the amount of percolation. Due to the experimental design, no error estimate is possible for the effect of the year. However, despite the lacking N supply (except for ca. 25 kg N ha\(^{-1}\) as deposition), no decline in N leaching occurred \((P > 0.05)\).

Taking an average of the treatments, the preceding crop–crop combination significantly affected N leaching (Table 7). Under wheat following OSR, N losses were highest with 73 kg N ha\(^{-1}\), where OSR followed barley, 44 kg N ha\(^{-1}\) were displaced beneath 90 cm soil depth. In each crop, application of pig slurry in autumn and in autumn plus in spring increased N leaching. Also mineral N fertilization led to higher N losses during the percolation period. The slurry by mineral N interaction revealed only small effects of the mineral N fertilization in the treatments without slurry (except 240 kg N ha\(^{-1}\) under wheat). Highest values occurred, if 240 kg N ha\(^{-1}\) combined with slurry in

### Table 6

Effect of slurry and mineral N fertilization on N balance (kg N ha\(^{-1}\)) of barley, OSR and wheat (with fungicides, 1991–1999)

<table>
<thead>
<tr>
<th>Crop</th>
<th>Barley</th>
<th>OSR</th>
<th>Wheat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slurry application</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None (S1)</td>
<td>21</td>
<td>32</td>
<td>-12</td>
</tr>
<tr>
<td>In autumn (S2)</td>
<td>98</td>
<td>100</td>
<td>64</td>
</tr>
<tr>
<td>In autumn plus in spring (S4)</td>
<td>143</td>
<td>158</td>
<td>104</td>
</tr>
<tr>
<td>LSD(_{0.05})</td>
<td>4.8</td>
<td>6.8</td>
<td>6.4</td>
</tr>
<tr>
<td>Mineral N fertilization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 kg N ha(^{-1}) (N1)</td>
<td>20</td>
<td>21</td>
<td>-6</td>
</tr>
<tr>
<td>120 kg N ha(^{-1}) (N2)</td>
<td>75</td>
<td>89</td>
<td>39</td>
</tr>
<tr>
<td>240 kg N ha(^{-1}) (N9)</td>
<td>166</td>
<td>182</td>
<td>124</td>
</tr>
<tr>
<td>LSD(_{0.05})</td>
<td>4.1</td>
<td>5.1</td>
<td>7.5</td>
</tr>
<tr>
<td>Slurry × mineral N interaction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1 × N1</td>
<td>-43</td>
<td>-43</td>
<td>-60</td>
</tr>
<tr>
<td>S1 × N2</td>
<td>11</td>
<td>29</td>
<td>-22</td>
</tr>
<tr>
<td>S1 × N9</td>
<td>87</td>
<td>114</td>
<td>46</td>
</tr>
<tr>
<td>S2 × N1</td>
<td>34</td>
<td>31</td>
<td>11</td>
</tr>
<tr>
<td>S2 × N2</td>
<td>80</td>
<td>88</td>
<td>50</td>
</tr>
<tr>
<td>S2 × N9</td>
<td>181</td>
<td>180</td>
<td>134</td>
</tr>
<tr>
<td>S4 × N1</td>
<td>61</td>
<td>75</td>
<td>33</td>
</tr>
<tr>
<td>S4 × N2</td>
<td>138</td>
<td>152</td>
<td>88</td>
</tr>
<tr>
<td>S4 × N9</td>
<td>231</td>
<td>247</td>
<td>192</td>
</tr>
<tr>
<td>LSD(_{0.05})</td>
<td>7.1</td>
<td>8.9</td>
<td>13.1</td>
</tr>
<tr>
<td>Mean</td>
<td>88</td>
<td>97</td>
<td>52</td>
</tr>
<tr>
<td>LSD(_{0.05})</td>
<td>20.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>159</td>
<td>159</td>
<td>160</td>
</tr>
</tbody>
</table>

\(^a\) LSD\(_{0.05}\) for crops is based on year × crop interaction.
autumn or in autumn plus in spring were applied. Soil tillage and fungicide application did not alter N leaching (data not shown).

3.3. Relationship between N leaching and N balance or N fertilization

Increasing N balance boosted N leaching in all preceding crop–crop combinations (Fig. 2). Under wheat following OSR, the level of N losses was higher than under OSR following barley. In addition, N leaching started to increase at a lower N balance (under wheat: −45 kg N ha\(^{-1}\); under OSR: 100 kg N ha\(^{-1}\)). Assuming a percolation of 300 mm, the EU threshold for drinking water of 50 ppm nitrate (=11.4 mg nitrate-N kg\(^{-1}\) water) will be reached if 34 kg N ha\(^{-1}\) are leached. Growing wheat following OSR or barley following wheat, even a negative N balance resulted in reaching or exceeding the threshold.

Values of the N balances ranged from −50 to +275 kg N ha\(^{-1}\), with the corresponding figures for N leaching varying from 30 to 120 kg N ha\(^{-1}\) (Fig. 2). The difference between the smallest and largest N balances of about 325 kg N ha\(^{-1}\) resulted in increasing N leaching by 42 kg N ha\(^{-1}\) (under OSR) to 82 kg N ha\(^{-1}\) (under wheat). With OSR therefore 13% and with wheat 25% of the N balance surplus originating from the preceding crop were lost by leaching.

Eq. (1) implies a similar N efficiency of both slurry (applied in autumn and/or in spring) and mineral N fertilizers. In order to differentiate between the N types as well as between the dates of slurry application, an approach was used where the N balance was subdivided into N input (mineral N, slurry in autumn, slurry in spring) and N output (N uptake by the grain) (Eq. (2)). N leaching in the spring slurry plots was not measured, but estimated from results of the autumn slurry and autumn + spring slurry treatments. A possible interaction between the two slurry applications on N leaching was neglected.

The effect of mineral N or slurry supply on N leaching was smaller with OSR following barley than in the other preceding crop–crop combinations. Without slurry, mineral N fertilization of 240 kg N ha\(^{-1}\) only slightly affected N leaching with all crops (+8 kg N ha\(^{-1}\) under OSR to +11 kg under cereals) (Figs. 3–5). Compared to autumn slurry, slurry application in spring to a growing crop resulted in less N losses, especially with wheat following OSR. N leaching was increased in the order mineral N fertilizer < spring slurry < autumn slurry. As expected, largest N losses occurred in the treatment with 240 kg mineral N ha\(^{-1}\) combined with two slurry applications each year.

The effects of the different N forms and application dates are reflected in the estimates of the parameters of Eq. (2) (Table 5). Mineral N fertilization was taken as standard of comparison (factor = 1). Autumn slurry increased N leaching by the factor 2.1–4.3, depending on the crop, while slurry applied in spring by the factor 1.5–1.7. N output via harvest products (grain, seed) only slightly affected N losses (P > 0.05).
Intensive production systems with higher yields may allow a reduction in the area needed for cropping and therefore allow alternative usage of the land. Yield-based N leaching values therefore were calculated alternatively to the previous analysis, where N leaching was area-based \( (\text{kg N ha}^{-1}) \). Yield-based N leaching increased if N balances exceeded 50 kg N ha\(^{-1}\) with barley following wheat, 113 kg N ha\(^{-1}\) with OSR following barley and 126 kg N ha\(^{-1}\) with wheat following OSR (Fig. 6). The higher level occurring with wheat was due to the lower OSR yield and the high N losses with wheat.

4. Discussion

The results presented here are based on a 9-year field trial. Due to the experimental design, the same treatment regimes were applied to the same plots so that the effects of the actual fertilization cannot be separated from the residual effects of the preceding fertilization and/or crops. More detailed analysis on this topic (Sieling, 2000) revealed no distinct trends in N leaching or grain yield in the unfertilized plots. The fertilized treatments showed no trends to increase grain yields or N supply for optimal grain yield during the 9 experimental years. However, perhaps such trends might be superimposed by the large year-to-year variation due to the weather conditions.

The literature provides only scarce information about the effects of different crops or crop rotations on N leaching. Our results revealed significant effects of the preceding crop–crop combination on N leaching where there were larger N losses with wheat following OSR than with OSR following barley (Goss et al., 1993). Milford et al. (1993) observed that in one year wheat following oats yielded 0.42 t ha\(^{-1}\) less grain than wheat following rape and the deficit in yield was levelled out by an application of fertilizer N equivalent to the deficit in soil N, suggesting a more intensive N net mineralization after rape compared with oats. Results of a 1 year trial with OSR and wheat following different preceding crops clearly showed that the amount of N taken up in autumn had a larger effect on N leaching than the N balance of the preceding crop (Mackensen, pers. commun.).

Having a crop rotation where each crop is always following the same preceding crop, a differentiation between the preceding crop and the direct crop effects on N leaching is not possible. In autumn, OSR can be a suitable crop to conserve nitrogen throughout the winter, because of its large autumn N uptake of 40–60 kg N ha\(^{-1}\) (Barraclough, 1989; Aufhammer et al., 1994). Due to its early development, oilseed rape often can utilize only a small proportion of the nitrogen mineralized in spring, especially under the weather conditions when there is a slow temperature increase in spring, typical for this site. Additional large amounts of easily mineralizable crop residue (petals and leaves, residues) return to the soil after flowering and at harvest, therefore the harvest index is low (0.35) compared with cereals (Aufhammer et al., 1994). Moreover, OSR leaves the soil in a favourable structure. All these facts result in a considerable increase in the leaching potential following OSR. In most situations the subsequent crop following rape will be winter wheat. Even sown early, N uptake of wheat before winter does normally not exceed 20 kg N ha\(^{-1}\), which is only a small portion of the soil mineral N usually present after OSR.

On average during the 9 experimental years, N leaching when wheat followed OSR exceeded the EU threshold even without fertilization, while N losses with barley and with OSR curtily remained below 34 kg N ha\(^{-1}\), indicating a high potential of the site for N leaching. This might be due to the former land use. Three years before the experiment was set up (1987/1988–1989/1990), the fields were used to establish the crop rotation on the single fields. N fertilization was moderate during this period. Up to harvest 1987, the commercial part of the experimental farm grew an OSR – winter wheat – winter barley rotation with high N rates, however without slurry. Assuming a soil organic N amount
of 5.000 kg N ha\(^{-1}\) (Frey, 1998) in the ploughing layer, an 
nannual mineralization rate of 2% will result in 
100 kg N ha\(^{-1}\) released from the soil organic matter. In 
the unfertilized plots, about 47 kg N ha\(^{-1}\) was taken off with 
the harvest products each year on average across the crops, 
whereas about 50 kg N ha\(^{-1}\) were potentially subject to 
leaching.

Slurry and mineral N fertilization significantly affected N 
losses whereas the effects of soil tillage or application of 
fungicides can be neglected, although the latter had an 
impact on the N balance. Mineral N fertilization without 
additional slurry application increased N leaching only 
slightly. However, despite the higher N amount of mineral N, 
the increase was smaller than slurry. This was presumably 
due to the higher N use efficiency of mineral N fertilizers 
(Sieling et al., 1998a,b). Detailed analysis revealed the 
higher leaching potential of autumn slurry (up to 4.3 times) 
and, to a smaller extent, of spring slurry (up to 1.7 times) 
compared with mineral N fertilizers (Table 5). The larger 
losses from slurry could be caused by its slower rate of N 
mineralization and the release of N when the crop cannot use 
it.

N leaching after slurry application only in spring was 
calculated from the ‘slurry autumn’ and ‘slurry autumn + 
spring’ treatments and a possible interaction between these 
two application dates was neglected. The leaching potential 
might be smaller than estimated if slurry application in 
 autumn had caused priming effects resulting in an increase 
in soil N mineralization. Since soil N release was quite high 
even in the unfertilized plots (N leaching just below or 
exceeding EU threshold), we argue that additional N should 
not heavily enhance soil N mineralization.

Yield-based N leaching showed a different picture. Under 
all crops, increasing N supply and corresponding N balance 
slightly decreased N leaching, reaching minimum values at 
25 or 50 kg N ha\(^{-1}\) (Fig. 6). A further rise led to higher N 
losses. As long as N fertilization increases N uptake by the 
 grain more than N leaching, yield-based N leaching 
decreases.

Some authors observed only small effects on area based 
N leaching of spring applied mineral N fertilizers, if the 
needs of the crop were met precisely (timing and amount) 
(e.g. Jenkinson, 1986; Macdonald et al., 1989; Chaney, 
1990). However, drought stress or diseases may reduce N 
utilization. Under such situations, large amounts of fertilizer 
N can remain unused in the soil, being subject to N leaching 
in the subsequent winter.

In contrast, Davies and Sylvester-Bradley (1995) 
provided evidence for a positive relationship between N 
supply and N leaching even when yields were not near their 
maximum. Also, the inclusion of the N output (harvested 
products), in the N balance, was often used to estimate N 
leaching potential. In our trials, we found a positive 
correlation between N balance and N losses; however, only 
15–25% of the surplus left by the preceding crop was lost.

On the other hand, even a negative N balance was not able to 
ensure that the EU threshold of 50 ppm nitrate (resulting in 
34 kg N ha\(^{-1}\) in a leachate of 300 mm) averaged over the 
years was met, especially under cereals. In addition, 
fungicide application had no effect on N leaching despite 
its large influence on yield and N balance. No decline in N 
leaching occurred within 9 years without N supply. Within 
the regression analysis, N uptake by the grain was not a 
significant coefficient (Table 5). Altogether, as mentioned by 
other authors, our results did not indicate a direct relation- 
ship between N balance and (short-term) N leaching (Lord 
et al., 2002; Jansons et al., 2003; Öborn et al., 2003; Sacco 
et al., 2003).

The previous discussion dealt with the husbandry effects 
on N leaching and with the relationship between N balance 
and N leaching, based on average results of a 9-year trial. 
Therefore, this approach must be considered as a short-term 
one. The main source of N leached from arable soils in NW 
Europe is the mineralization of soil organic matter in late 
summer and autumn, when soils become moist and plant 
demand is still low or non-existent. The contribution of 
unused fertilizer applied in spring to the previous crop on the 
other hand seems to be generally quite small. Residues of 
mineral N at harvest time derived from appropriate, well-
timed applications of N to winter wheat tend to be negligible 
(Jenkinson, 1986; Macdonald et al., 1989; Chaney, 1990).

In the short-term, the amount of mineral fertilizer N therefore 
have little effect on N losses over winter; but the long-term 
applications of high rates of inorganic N fertilizer may build 
up soil organic N due to increased amounts of crop residues 
with narrowed C:N-ratios (Glendining and Powlson, 1991; 
Glendining et al., 1996). Adding such organic matter will 
enhance N turnover (MIT) resulting in a larger mineral N 
 pool in autumn and in a higher risk of N leaching. For the 
long-term view (several decades), therefore, N balance 
might be a useful indicator to estimate N leaching potential 
of arable land (Öborn et al., 2003).

5. Conclusion

Slurry, especially if applied in autumn, increased N 
leaching more than mineral N fertilizers. The lower use 
efficiency of slurry N is due to its composition and to the 
often unfavourable application conditions (date, single 
application). In agricultural practice, slurry application in 
autumn is mostly caused by insufficient storage capacities 
on farms. Thus, conserving slurry over winter is a key 
strategy to prevent N leaching. In addition, splitting 
applications according to the crop need and including the 
slurry nutrients into the fertilization strategy may enhance 
crop N uptake and reduce N surplus. Application of 
fungicides enhanced and stabilized yields and therefore 
decreased the N balance.

In the short-term, N balances correlate poorly with N 
leaching, because most of the leached nitrate is not directly 
originating from spring applications, but is mineralized in
autumn. However, if set up over a longer period, N balances may be good indicators of the leaching potential originating from different management systems. In order to minimise the impact on the environment, farmers should improve the efficiency of the N fertilizers, especially that of slurry application, and, in consequence, reduce the N surplus.

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