Nitrate leaching in intensive agriculture in Northern France: Effect of farming practices, soils and crop rotations

N. Beaudoin\textsuperscript{a,}\textsuperscript{*}, J.K. Saad\textsuperscript{a}, C. Van Laethem\textsuperscript{b}, J.M. Machel\textsuperscript{a}, J. Maucorps\textsuperscript{a}, B. Mary\textsuperscript{a}

\textsuperscript{a}INRA Unité d’Agronomie LRM, rue Fernand Christ, 02007 Laon Cedex, France
\textsuperscript{b}Chambre d’Agriculture de l’Aisne, Bd de Lyon, 02000 Laon Cedex, France

Received 4 August 2004; received in revised form 10 June 2005; accepted 17 June 2005
Available online 1 September 2005

Abstract

The efficacy of ‘Good Agricultural Practices’ (GAP) for reducing nitrate pollution is tested on the scale of a small catchment area (187 ha) which is almost entirely under arable agriculture. GAP have been introduced on all fields since 1990. They consist in applying carefully planned N fertiliser recommendations, establishing catch crops (CC) before spring crops and recycling all crop residues. Soil water and mineral nitrogen (SMN) were measured three times each year on 36 sites representative of crops (wheat, sugarbeet, pea, barley, oilseed rape) and soil materials (loam, loamy clay and rocks, sand loam and limestone, sand) during 8 years (1991–1999). These measurements (about 3600 soil samples) were used in LIXIM model to calculate water and nitrogen fluxes below the rooting zone. The model could reproduce satisfactorily the water and SMN contents measured at the end of winter. It simulated reasonably well the nitrate concentration measured in the subsoil (3–10 m deep) of nine fields. The mean calculated amounts of drained water and leached nitrogen below the rooting depth were 231 mm year\textsuperscript{-1} and 27 kg N ha\textsuperscript{-1} year\textsuperscript{-1}, corresponding to a nitrate concentration of 49 mg L\textsuperscript{-1}. Leached N varied by a five-, four- and three-fold factor according to the year, crop and soil type, respectively. Nitrate concentration was primarily affected by soil type: it varied from 31 mg L\textsuperscript{-1} in deep loamy soils to 92 mg L\textsuperscript{-1} in shallow sandy soils, and was linked to the soil water holding capacity. The sugarbeet–wheat rotation gave the lowest concentration (38 mg L\textsuperscript{-1}) and the pea–wheat rotation the highest one (66 mg L\textsuperscript{-1}). In spite of their moderate growth (mean biomass = 0.8 Mg ha\textsuperscript{-1}), the catch crops allowed to reduce the mean concentration by 50% at the annual scale and 23% at the rotation scale. Straw incorporation was also beneficial since net mineralisation between harvest and late autumn was reduced by 24 kg N ha\textsuperscript{-1} when straw residues were incorporated. Reducing fertilisation below the recommended rate did not significantly reduce further nitrate leaching. Although GAP were not all optimal and therefore less efficient than in well controlled experiments, they appear essential in intensive agriculture in order to comply with the EU standard for nitrate concentration.

\textsuperscript{*} Corresponding author. Tel.: +33 3 23 23 99 42; fax: +33 3 23 79 36 15.
E-mail address: nicolas.beaudoin@laon.inra.fr (N. Beaudoin).

Keywords: Agricultural practices; Nitrate leaching; Nitrogen fertilisation; Catch crops; Catchment
1. Introduction

Nitrate pollution of groundwater from agriculture is a common fact (Addiscott et al., 1991; Guillemin and Roux, 1992; Datta et al., 1997). The European Union has implemented a procedure aiming at recovering a good quality of water resources in 2015 (Directive 2000/60/EC; Letcher and Giupponi, 2005). The challenge is particularly hard in intense farming systems with high N excess as well as in arable cropping systems with low drainage (Machet et al., 1997; Hall et al., 2001; Di and Cameron, 2002). Moreover, in regions with large sedimentary basins and deep groundwater, such as Paris basin, the impact of present practices may be hidden due to the long response time of the aquifers. The complexity of the problem rules out apparently simple solutions such as taxation of nitrogen fertilisers (Haruvy et al., 1997). It raises the question as to whether the standard is achievable (Addiscott et al., 1991). Alternative agricultural practices have been encouraged since the 1990s under the generic term ‘Good Agricultural Practices’ (GAP) or ‘Best Management Practices’ (Hubbard and Sheridan, 1994). This trade-off is not entirely concerned with sustainability but it does appear to be economically achievable (Lacroix, 1995).

In arable systems, the main rules to prevent nitrate pollution rest on better management of the nitrogen cycle during crop succession. Dehéain (cited by Morlon et al., 1998) explained the principles as early as 1902: “since the major losses of nitrogen from ploughed soils take place in autumn, one must reduce as far as possible the area of bare soil in winter by using green manures, incorporate crop residues and avoid applying nitrogen fertiliser greatly in excess of crop requirements”. These principles seem essential to prevent nitrate pollution of groundwater (Laurent and Mary, 1992; Hansen et al., 2001). However, applying GAP in actual farming conditions may be more or less successful because there are uncertainties on N predictions and farmers may not follow the recommendations at the optimum due to lack of information, technology or time (Meynard et al., 2002).

Few studies have quantified precisely the efficiency of GAP applied in farming conditions with regard to the EU guideline for nitrate in drinkable water. The relevant spatial and temporal limits for this quantification are the loading aquifer perimeter and the renewal time of the aquifer. At this scale, the results are hampered by uncertainties but can be smoothed using a relevant aggregation (Kersebaum and Beblik, 2001). The objectives of this work are to quantify nitrogen leaching below the rooting zone in different soil types, crop rotations and farming practices, and to evaluate GAP efficacy for reducing nitrate leaching in actual farm conditions in Northern France. The method chosen has consisted in using measurements and simple modelling rather than using a pure simulation model which requires many parameters and local testing. The data presented here concern the first 8 years of the study. A large number of measurements were realized on crops (700) and soils (3600) in order to estimate the water and nitrogen fluxes below the rooting zone. The comparison with the fluxes measured at the catchment outlet will be presented in a next paper.

2. Materials and methods

2.1. Experimental site

2.1.1. General characteristics

The site investigated is located in Bruyères, near Laon, in Northern France. It is a tertiary sedimentary plateau, typical of the Paris Basin. The main characteristics of this site are: (i) a small (187 ha) and well defined loading perimeter for the aquifer (Mary et al., 1997), (ii) an aquifer showing increasing nitrate pollution with a faster response time than the surrounding chalk aquifers and (iii) an important variability of soils. Due to the concern of nitrate pollution, GAP have been adopted by farmers since 1990 and applied to all cultivated fields present in the catchment area: 21 fields composing 145 ha. The period of study described here begins in autumn 1991 and ends in autumn 1999. A set of 36 sampling sites was defined to assess the variability of crop yields, water and N losses. The sites represent the main soil types within each field (Fig. 1).

2.1.2. Soil properties

A 1:7500 soil map was established (Fig. 1). Four main soil types were defined according to their parent material (Table 1): deep loam (DL) or neoluviosols...
developed on decarbonated loess; shallow loamy clay (SLC) or calcosols developed on marl and rocks; shallow sandy loam (SSL) or calcaric rendosols developed on coarse limestone; shallow loamy sand (SLS) or redoxic arenosols overlying sand (taxonomy according to AFES, 1995). They represent 43, 21, 14 and 6% of the agricultural area, respectively. All soils are fairly porous, well structured and allow good drainage. The maximum rooting depths of wheat were measured at flowering in 1993 and appeared to be strongly related to soil type. Percentage of coarse fractions and bulk densities of the main materials were measured by mechanical analysis and gamma density probe, respectively.
2.1.3. Climatic characteristics

Rainfall and air temperature have been measured continuously in two locations on the site. Potential evapotranspiration (Penman) was provided by the nearest meteorological station. The annual mean temperature is 9.7°C over the last 40 years. Annual precipitation (R) reaches 701 mm and is distributed evenly throughout the year. Mean potential evapotranspiration (PET) calculated by the Penman formula (1948) is 664 mm.

2.1.4. Land use and agronomic management

The main crops grown are winter wheat (Triticum aestivum, 39% of the cropped area), sugarbeet (Beta vulgaris, 19%), spring pea (Pisum sativum, 16%), winter barley (Hordeum vulgare, 12%) and winter rapeseed (Brassica napus, 7%). Autumn crops represent 58% and spring crops 40% of the area. Soil type has no significant influence on the nature of crop (p < 0.05). The duration of the fallow period varies from 31 to 218 days (mean = 118); it determines together with the date of harvest the possibility to establish or not a catch crop.

GAP were introduced in 1990, which consist in reducing the recommended rate of fertiliser-N by 20% to obtain a suboptimal N fertilisation. GAP and AEP both aim at reducing the amount of mineral nitrogen present in soil when water drainage starts again in autumn. Fertilisation is calculated using the balance-sheet method AZOBIL (Machet et al., 1990). The method involves the measurement of soil mineral nitrogen in February and establishes a predictive mineral N balance.

The catch crops sown were rye (Secale cereale) until 1995 and then nematocidal mustard (Sinapis alba) or radish (Raphanus sativus). Rapeseed and barley volunteers were encouraged and had a growth comparable to CC. CC were always ploughed in, at the earliest on December 1 and at the latest on January 15. Volunteers were either destroyed in September when they preceded an autumn-sown cereal or at the same time than CC. Crop residues were first mixed with the soil by superficial disking after the summer harvest and then incorporated by deep ploughing in December.

2.2. Methods

2.2.1. Calculation of nitrate leaching

Several methods are available to assess nitrate leaching: lysimeters, drained perimeters, ceramic cups, soil cores and use of models. Only the first two methods provide direct measurements of water and nitrate fluxes, but they obviously could not be used in our situation. Ceramic cups provide direct

<table>
<thead>
<tr>
<th></th>
<th>Deep soilsa</th>
<th>Shallow soilsb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DL</td>
<td>SLC</td>
</tr>
<tr>
<td>BD (g cm⁻³)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–30</td>
<td>1.49</td>
<td>1.37</td>
</tr>
<tr>
<td>30–LD</td>
<td>1.63</td>
<td>1.42</td>
</tr>
<tr>
<td>WFC (g g⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–30</td>
<td>0.24</td>
<td>0.28</td>
</tr>
<tr>
<td>30–LD</td>
<td>0.22</td>
<td>0.26</td>
</tr>
<tr>
<td>WWP (g g⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–30</td>
<td>0.10</td>
<td>0.11</td>
</tr>
<tr>
<td>30–LD</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>WFC (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–LD</td>
<td>423 (19)</td>
<td>344 (52)</td>
</tr>
<tr>
<td>WWP (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–LD</td>
<td>220 (15)</td>
<td>177 (2)</td>
</tr>
</tbody>
</table>

Values in parenthesis are the standard errors.

a DL: deep loam.
b SLC: shallow loamy clay lying on marl and rocks; SSL: shallow sandy loam lying on limestone; SLS: shallow loamy sand lying on sand.
c LD: depth used for leaching calculations; LD = 120 cm for deep soils and 90 cm for shallow soils.
information on nitrate concentration but not on water fluxes and could not have been installed on all sites. Standard crop models used in a simulation mode allow to predict water and N fluxes below the rooting zone. But they do not consider all farming practices affecting fluxes and require to determine many parameters with good accuracy (Schaffer et al., 2001; Gijsman et al., 2002). We chose to make frequent soil samplings to measure variation of water and mineral N in soils. A classical method to convert mineral N stocks into nitrate leaching fluxes consists in calculating the drainage rate and multiplying it to the mean concentration of the deeper layer (e.g. Duwig et al., 2003). This method is satisfactory if the calculation is made on short time steps, so that mineralisation and transport of nitrate through the profile can be neglected. In the case of longer time steps (in our case 2–3 months), the use of a model which accounts for these phenomena is preferable. We chose to use the ‘calculation’ model LIXIM (Mary et al., 1999) which both simulates these processes and relies on the water and mineral N measurements to calculate the water and nitrate fluxes. The model simply helps to convert these measurements into fluxes. LIXIM has been successfully evaluated in various field experiments with bare soils (Justes et al., 1999; Mary et al., 1999). It simulates the water and nitrate transport in soils using the ‘capacity’ type and the ‘mixing cells’ concepts (Van Ommen, 1985; Van der Ploeg et al., 1995). It calculates the evaporation and the mineralisation rates by fitting the simulated distributions of water and nitrate in the soil profile to the measured ones. The drained water and leached N below the soil depth are then model outputs.

Since LIXIM model was primarily designed for bare soils, we had to make adaptations for using it in cropped soils. The model was modified to account for N uptake versus depth: rooting depth and density were simulated as a function of thermal time and N uptake as a function of soil mineral N and root density, as in STICS model (Brisson et al., 1998). But as opposed to STICS model, the total N uptake measured is imposed in LIXIM model. The results show that the changes in leaching predictions due to crop uptake were small (see discussion in Section 3). This is mainly due to the fact that most drainage occurred throughout the winter period, i.e. between the measurements made in late autumn and mid-February. During this period, temperature was low (average 3.5 °C) so that crop uptake of water and nitrogen was small and mainly affected the upper soil layer.

2.2.2. Soil measurements

Soil samples were randomly taken within a radius of 10 m around each site. The soil water content (SWC) and soil mineral nitrogen (SMN) were measured on each of the 36 sampling sites, three or four times per year. During the first 2 years, soil cores were taken up to 120 cm in deep and 90 cm in shallow soils; then, the sampling depth was extended to 150 and 120 cm, respectively. The measurements were made: (1) at harvest of the main crops; (2) at the end of September in the previously harvested fields; (3) in late autumn (mid-November–early December); (4) in mid-February before growth recommenced. The third date corresponds approximately to the time when water drainage starts again. Six replicate cores were taken in each layer (30 cm thick). They were mixed and deep frozen. After thawing, SWC was determined by gravimetry and mineral nitrogen was extracted in 0.5 M KCl (50 g:100 mL). Ammonium and nitrate contents were determined by continuous flow colorimetry, using the Griess–Ilosvay and the indophenol methods, respectively. SWC (mm) and SMN (kg ha⁻¹) were calculated by taking account of the bulk density of fine materials and eventually the proportion of stone materials.

Our protocol did not include replicate measurements of SWC and SMN, but considered a large number of measuring sites. This choice was made to have a good assessment of fluxes at the basin scale in accordance with geo-statistical rules (Bruckler et al., 1997). The errors on measurements were tested on single cores taken in August 1993. They allowed to estimate the confidence intervals for SWC at harvest at 10, 37 and 11 mm for DL, SLC and SLS, respectively \( (p < 0.10) \). The relative error on SMN varied between 15 and 25\% \( (p < 0.10) \), in agreement with the results of Vinther (1994).

2.2.3. Plant measurements

Plant samples were taken in six plots of 0.3 m² size in each sampling site. In the case of pea, rapeseed and sugarbeet crops, plant samples were only used to analyse the N content of the whole plant and harvested organs; the dry matter produced was calculated from
the yield recorded by the farmer. In the case of cereals, sunflower and maize, plant samples were taken to measure the yield, dry matter and N content. The confidence interval of the estimate is about 10% of the mean ($p < 0.10$). CC dry matter was measured at the end of November, just before destruction. Total N content was measured using an elemental CN analyser (Dumas method). Crop and soil N measurements were used to calculate the over-fertilisation, as defined in Appendix A.

2.2.4. Model parametrisation

The climatic input data are the daily rainfall, potential evapotranspiration and air temperature. The data inputs are the water and SMN contents measured in different soil layers at different dates, and eventual N uptake by crops in winter. The measurements made in late autumn were used as initial dates of calculations in the majority of situations.

The input soil data of LIXIM are the water contents at field capacity (WFC), at permanent wilting point (WWP) and the apparent bulk density (BD) of each soil layer. WFC is estimated as the median value of water contents measured in mid-February during the studied period (Hénin et al., 1969). WWP is taken as the lowest value of water contents observed at harvest or given by regional references (Baize, 1989). BD was measured in duplicate in all soil types using a gamma density probe. The depth at which drainage and leaching are calculated is constant for all the study period; it was defined as the minimum of the measurement depth and the rooting depth, namely 120 cm on loamy soils. The soil water content (SWC, mm) is the product of water content, layer thickness and bulk density. WFC varied between 196 and 423 mm (Table 1). The ratio of actual to potential evapotranspiration was set at 0.5 in bare soils in autumn or winter and at 1.0 in winter for a complete vegetative cover (Ballif, 1996; Mary et al., 1999). It was fitted by the model in the other cases, particularly in the case of covered soil in autumn. The mineralisation rate was always fitted by the model. The mean nitrate concentration is calculated as the ratio between cumulative leaching and drainage.

2.2.5. LIXIM evaluation

We conducted a sensitivity analysis to test the effect of the: (i) crop uptake impact, (ii) initialisation date and (iii) soil depth on leaching calculations. We have firstly estimated the maximum error on N leaching by comparing LIXIM outputs with or without accounting for N uptake by plants. The sensitivity to the second factor was tested during the 1995/1996 period which is characterised by a dry autumn and a late drainage. The sensitivity to the latter factor is required because uncertainties remain on the maximum rooting depth.

LIXIM was tested for its ability to reproduce the variables SWC and SMN from end of autumn (November or early December) to mid-February for all situations.

The last evaluation of the model has consisted in comparing its prediction of nitrate concentration in drained water below the rooting zone during years 1991–1995 with the nitrate concentration measured in the subsoil on September 1995. The latter concentration was measured on subsoil cores taken by deep coring between 2 and 10 m depth. The subsoil samples were extracted and analysed for water, nitrate and ammonium contents as indicated previously. The mean nitrate concentration in subsoil is calculated over the depth containing the same amount of water than that which had drained during the preceding years. The comparison with the predicted nitrate concentration relies on the assumptions that nitrate is conservative below the rooting depth and that its transfer is mainly convective and vertical.

3. Results

3.1. Crop response to GAP and AEP

3.1.1. Implementing the recommendations

The nitrogen fertiliser rates actually applied by farmers were in good agreement with the recommended rates, during both the GAP and the AEP periods (Table 2). Although recommended, the incorporation of crop residues in soil was not systematic: it was realized in 70% of situations. Catch crops before spring crops were grown in 30% of the cropping area, whereas the maximum was 40%; 4% correspond to sugarbeet before spring peas, where it was impossible to establish a CC, and 6% correspond to the fields left bare due to the need to destroy perennial weeds. Volunteers production was significant in 32% of fields during short fallow.
3.1.2. Crop production

No significant difference in crop yield was found between the GAP (1991–1997) and the AEP (1996–1999) periods (Table 3). This may be due to the large variability in yields among fields, particularly among soils. The cereal yields varied from 3.5 to 11.0 Mg ha\(^{-1}\). The yields actually obtained (\(Y_0\)) were 3% lower on average than the yield objectives (\(Y\)), but the difference (\(Y_0/Y\)) was not correlated to the soil type. The N content of plants at harvest was significantly lower in the second period with a reduced fertilisation. The difference was visible both on exported products and on returned crop residues (Table 3).

The dry matter production of CC was on average 0.9 and 0.6 Mg ha\(^{-1}\) for GAP and AEP, respectively. The mean N content found in CC at destruction was 31 g kg\(^{-1}\) and was not affected by the fertiliser regime. The mean amount of N taken up in CC aerials was 28 and 19 kg ha\(^{-1}\) for GAP and AEP, respectively. CC growth was favoured by early dates of sowing and high amounts of water and mineral N in soil. Volunteers had a significant growth: their mean dry mass was 0.9 Mg ha\(^{-1}\). Their N content depended on the species: 44, 31 and 22 g N kg\(^{-1}\) for pea, barley and rapeseed volunteers, respectively. Volunteers took up as much N as CC (25 kg ha\(^{-1}\)).

### Table 3

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Advent</td>
<td>Applied</td>
</tr>
<tr>
<td>W</td>
<td>165 (26)</td>
<td>164 (24)</td>
</tr>
<tr>
<td>B</td>
<td>134 (23)</td>
<td>137 (20)</td>
</tr>
<tr>
<td>R</td>
<td>192 (30)</td>
<td>193 (29)</td>
</tr>
<tr>
<td>S</td>
<td>125 (37)</td>
<td>124 (31)</td>
</tr>
</tbody>
</table>

| All crops | 127 | 127 | 99 | 97 |

The advised fertilisation for GAP is given by AZOBIL software and corresponds to the potential yield of the fields. It is reduced by 20% for AEP recommendations. Standard errors are in parenthesis. GAP: Good Agricultural Practices; AEP: Agri-Environmental Practices.

### Table 2

Advised and applied N fertilisation of the main crops (kg N ha\(^{-1}\) year\(^{-1}\)), during the two management periods

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Advised</td>
<td>Applied</td>
</tr>
<tr>
<td>W</td>
<td>165 (26)</td>
<td>164 (24)</td>
</tr>
<tr>
<td>B</td>
<td>134 (23)</td>
<td>137 (20)</td>
</tr>
<tr>
<td>R</td>
<td>192 (30)</td>
<td>193 (29)</td>
</tr>
<tr>
<td>S</td>
<td>125 (37)</td>
<td>124 (31)</td>
</tr>
</tbody>
</table>

| All crops | 127 | 127 | 99 | 97 |

The advised fertilisation for GAP is given by AZOBIL software and corresponds to the potential yield of the fields. It is reduced by 20% for AEP recommendations. Standard errors are in parenthesis. GAP: Good Agricultural Practices; AEP: Agri-Environmental Practices.

### Table 3

Mean values of dry yield and N contents in harvested or returned parts of the crops (catch crops or main crops), during the two management periods (GAP and AEP)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry yield (Mg ha(^{-1}))</td>
<td>Harvested-N (g kg(^{-1}))</td>
</tr>
<tr>
<td>B</td>
<td>6.7</td>
<td>16</td>
</tr>
<tr>
<td>W</td>
<td>7.1</td>
<td>17</td>
</tr>
<tr>
<td>R</td>
<td>3.2</td>
<td>33</td>
</tr>
<tr>
<td>P</td>
<td>5.5</td>
<td>38</td>
</tr>
<tr>
<td>S</td>
<td>17.4</td>
<td>6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Volunteers</td>
<td>1.0</td>
<td>–</td>
</tr>
<tr>
<td>CC1</td>
<td>0.7</td>
<td>–</td>
</tr>
<tr>
<td>CC2</td>
<td>1.6</td>
<td>–</td>
</tr>
</tbody>
</table>

a Main crops: R—winter rapeseed; W—winter wheat; B—winter barley; P—spring pea; S—sugarbeet.
b Catch crops: Volunteers from rapeseed, winter barley or spring pea; CC1—catch crops (mustard or rye) with a poor growth (DM < 1 Mg ha\(^{-1}\)); CC2—catch crops with a good growth (DM > 1 Mg ha\(^{-1}\)).
3.2. Water and nitrogen contents

At all dates of measurements (February, harvest and late autumn), soil mineral nitrogen was mainly present as nitrate. The average amount of ammonium–N was 9 kg ha\(^{-1}\), representing 17% of mineral N. Half of it was present in the upper layer (0–30 cm).

### 3.2.1. Evolution of SWC and SMN

In mid-February, SWC was close to WFC in all fields. The soil water deficit (SWD), WFC–SWC, was nil (Table 4). SMN varied significantly \((p < 0.05)\) according to year or soil type. SMN was lowest in 1994 after the wettest winter, and in sandy soils (SSL and SLS).

Soil water deficit and SMN at harvest were significantly influenced by year and crop \((p < 0.05)\) and soil type to a smaller extent \((p < 0.10)\). The mean water deficit was 89 mm which means that soils were about half water depleted at harvest. The average SMN at harvest was 41 kg N ha\(^{-1}\). The year, crop and soil factors explain 40% of SMN variance. SMN varied among years from 20 to 58 kg N ha\(^{-1}\) (Table 4).

It was lowest after sugarbeet (35 kg ha\(^{-1}\)) and highest after spring pea (51 kg ha\(^{-1}\)). It was slightly smaller in deep (37 kg ha\(^{-1}\)) than in shallow soils (43 kg ha\(^{-1}\)).

Despite a large variability, a significant relationship was found between the measured excess of mineral N at harvest (ΔSMN) and the calculated excess of fertiliser (OF) (Appendix A; Fig. 2). The data can be fitted to a plateau plus linear function, as proposed by Makowski et al. (1999). The plateau is obtained for OF values lower than −13 kg ha\(^{-1}\) and corresponds to \(ΔSMN = 2\) kg ha\(^{-1}\), i.e. not different from 0. This

### Table 4

Soil water deficit (SWD) and mineral nitrogen (SMN) measured at crop harvest, in late autumn and in mid-February, according to the year, crop and soil types

<table>
<thead>
<tr>
<th></th>
<th>SWD (mm)</th>
<th></th>
<th></th>
<th>SMN (kg N ha(^{-1}))</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mid-February</td>
<td>Harvest</td>
<td>Late autumn</td>
<td>Mid-February</td>
<td>Harvest</td>
<td>Late autumn</td>
</tr>
<tr>
<td>(a) Per year</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1991</td>
<td>16(^a)</td>
<td>123(^a)</td>
<td>57(^a)</td>
<td>72(^a)</td>
<td>38(^ab)</td>
<td>55(^ab)</td>
</tr>
<tr>
<td>1992</td>
<td>20(^a)</td>
<td>20(^b)</td>
<td>0(^b)</td>
<td>58(^a)</td>
<td>58(^b)</td>
<td>47(^ab)</td>
</tr>
<tr>
<td>1993</td>
<td>4(^ab)</td>
<td>93(^a)</td>
<td>15(^ab)</td>
<td>61(^a)</td>
<td>43(^ab)</td>
<td>45(^a)</td>
</tr>
<tr>
<td>1994</td>
<td>−11(^b)</td>
<td>110(^a)</td>
<td>15(^ab)</td>
<td>28(^b)</td>
<td>50(^ab)</td>
<td>57(^ab)</td>
</tr>
<tr>
<td>1995</td>
<td>−10(^b)</td>
<td>82(^a)</td>
<td>41(^a)</td>
<td>52(^a)</td>
<td>37(^ab)</td>
<td>74(^b)</td>
</tr>
<tr>
<td>1996</td>
<td>7(^ab)</td>
<td>127(^a)</td>
<td>−3(^b)</td>
<td>74(^a)</td>
<td>43(^ab)</td>
<td>64(^ab)</td>
</tr>
<tr>
<td>1997</td>
<td>9(^ab)</td>
<td>55(^b)</td>
<td>6(^b)</td>
<td>63(^a)</td>
<td>49(^ab)</td>
<td>62(^ab)</td>
</tr>
<tr>
<td>1998</td>
<td>3(^ab)</td>
<td>98(^a)</td>
<td>6(^b)</td>
<td>63(^a)</td>
<td>32(^a)</td>
<td>49(^a)</td>
</tr>
<tr>
<td>1999</td>
<td>−12(^b)</td>
<td>90(^a)</td>
<td>46(^a)</td>
<td>50(^a)</td>
<td>20(^a)</td>
<td>40(^a)</td>
</tr>
<tr>
<td>(b) Per crop(^*)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R–W</td>
<td>2(^ab)</td>
<td>62(^b)</td>
<td>8(^b)</td>
<td>50(^a)</td>
<td>50(^a)</td>
<td>61(^ab)</td>
</tr>
<tr>
<td>W–R</td>
<td>8(^a)</td>
<td>118(^a)</td>
<td>7(^b)</td>
<td>66(^a)</td>
<td>36(^b)</td>
<td>45(^b)</td>
</tr>
<tr>
<td>W–B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P–W</td>
<td>−5(^ab)</td>
<td>117(^a)</td>
<td>16(^b)</td>
<td>55(^a)</td>
<td>51(^a)</td>
<td>95(^a)</td>
</tr>
<tr>
<td>S–W</td>
<td>−13(^b)</td>
<td>79(^ab)</td>
<td>38(^a)</td>
<td>47(^ab)</td>
<td>35(^b)</td>
<td>48(^b)</td>
</tr>
<tr>
<td>B–CC</td>
<td>6(^b)</td>
<td>78(^ab)</td>
<td>14(^b)</td>
<td>48(^ab)</td>
<td>38(^b)</td>
<td>40(^b)</td>
</tr>
<tr>
<td>(c) Per soil type(^**)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DL</td>
<td>−1(^ab)</td>
<td>97(^a)</td>
<td>21(^a)</td>
<td>61(^a)</td>
<td>37(^a)</td>
<td>57(^a)</td>
</tr>
<tr>
<td>SLC</td>
<td>−1(^ab)</td>
<td>80(^ab)</td>
<td>25(^a)</td>
<td>59(^a)</td>
<td>45(^a)</td>
<td>64(^a)</td>
</tr>
<tr>
<td>SSL</td>
<td>8(^ab)</td>
<td>87(^ab)</td>
<td>15(^a)</td>
<td>43(^b)</td>
<td>44(^a)</td>
<td>58(^a)</td>
</tr>
<tr>
<td>SLS</td>
<td>5(^ab)</td>
<td>66(^b)</td>
<td>5(^a)</td>
<td>39(^b)</td>
<td>39(^a)</td>
<td>40(^b)</td>
</tr>
<tr>
<td>Average</td>
<td>2</td>
<td>89</td>
<td>17</td>
<td>58</td>
<td>41</td>
<td>55</td>
</tr>
</tbody>
</table>

SWD and SMN are measured up to 120 cm in deep soils and 90 cm in shallow soils. Letters (a and b) indicate groups which differ statistically (test of Kruskal–Wallis, \(p < 0.10\)).

\(^*\) Crops: R—winter rapeseed; W—winter wheat; B—winter barley; P—spring pea; S—sugarbeet. The first symbol corresponds to the harvested crop, the second one to the crop present during the following autumn. All catch crops (CC) precede spring crops.

\(^**\) Soils: DL—deep loam; SLC—loamy clay over marl and rocks; SSL—shallow sandy loam over limestone; SLS—shallow loamy sand over sand.
indicates that AZOBIL recommendation is well calibrated to minimise the residual SMN at harvest. The slope of the linear function is 0.40. The mean over-fertilisation was 22 kg ha$^{-1}$ for GAP and 1 kg ha$^{-1}$ for AEP. According to the fitted curve, AEP should reduce SMN by 9 kg N ha$^{-1}$ in comparison with GAP.

SWC in late autumn varied between years from 304 to 369 mm, so that the water deficit varied from $-3$ to 57 mm. This confirms the fact that drainage was about to start at this date in most situations, and that it had already begun in some years (for example, 1992). The mean SMN measured at the end of autumn was 55 kg ha$^{-1}$, i.e. 14 kg ha$^{-1}$ greater than SMN at harvest. SMN depended on year and land occupation ($p < 0.05$) and soil type ($p < 0.10$). It was lowest after catch crops (B–CC: 40 kg ha$^{-1}$) and highest under winter wheat following spring pea (P–W: 95 kg ha$^{-1}$). SMN varied from 40 kg ha$^{-1}$ in sandy soils to 64 kg ha$^{-1}$ in loamy soils. It was not significantly affected by the GAP/AEP factor.

3.2.2. Variation of soil mineral N in autumn

We can compare SMN in late autumn versus SMN at harvest. The two variables were significantly correlated ($r = 0.46$), but with a large dispersion (Fig. 3). In situations before winter wheat (Fig. 3a), i.e. situations after sugarbeet, rapeseed or spring peas, SMN increased from harvest to late autumn almost in all fields: the mean variation was +25 kg ha$^{-1}$. The mean variation in bare soils (without volunteers) was +17 kg ha$^{-1}$. The effect of volunteers depended on plant species: rapeseed volunteers tended to stabilise SMN, whereas pea volunteers increased it markedly (mean increase = 64 kg ha$^{-1}$). The much higher

Fig. 2. Relationship between the excess of mineral nitrogen at harvest ($\Delta$SMN, kg N ha$^{-1}$) and the over-fertilisation calculated a posteriori (OF, kg N ha$^{-1}$), for the two management periods (GAP and AEP). The definition of these variables is given in Appendix A.
release of N is attributed due to the much higher N content of pea volunteers, as mentioned before, which suggests that young peas had a very active N\(_2\) fixation during this short fallow period.

In situations after wheat harvest (Fig. 3b), i.e. situations with burley, rapeseed or CC, SMN increased or decreased from harvest to late autumn, depending on situations: the mean variation was higher for winter barley (+11 kg N ha\(^{-1}\)), lower for catch crops (+1 kg N ha\(^{-1}\)) and intermediate for rapeseed (+7 kg N ha\(^{-1}\)). It ranks in the same order than sowing dates.

Measurements of SMN at harvest and CC destruction and N uptake by CC allow to assess net N mineralisation since the situations corresponding to high risk of N leaching during autumn have been excluded (Table 5). The average mineralisation during August–November (about 4 months) was 30 kg N ha\(^{-1}\). It was significantly higher in the situations with straw removed (45 kg ha\(^{-1}\)) compared to those with straw return (21 kg ha\(^{-1}\)). The difference, 24 kg ha\(^{-1}\), is attributed to the net immobilisation of straw decomposing in soil.

### 3.3. Water and nitrogen fluxes

#### 3.3.1. Evaluation of LIXIM

LIXIM was able to reproduce the SWC and SMN measured in February (Fig. 4). The small bias (–3 mm) and root mean square error (31 mm) found for SWC is comparable to the error of measurement. The SMN prediction over the whole profile in February is satisfactory: there is little bias (+4 kg N ha\(^{-1}\)), the RMSE is 9 kg N ha\(^{-1}\) and the relative error is 26%, also comparable to the measurement variability. This agreement concerns both bare soils and soils with a slow growing crop. In bare soils, the model had been successfully evaluated for water and nitrate by
comparison with lysimeters (Mary et al., 1999) and porous cups measurements (Vertès et al., 2001). The test of the nitrate concentration calculation, integrated along 3 or 4 years, is presented in Section 3.4.1.

The mineralisation rate calculated by LIXIM in bare soils during the winter period was on average 0.83 ± 0.27 kg N ha⁻¹ day⁻¹ (at 15 °C and optimum water content); this is comparable to the daily mineralisation rates found in similar soils (Mary et al., 1999). The consistency of these estimates suggests that mineralisation and leaching were correctly evaluated by the LIXIM model.

3.3.2. Sensitivity analysis

In our study, bare soils contributed for 57% to the whole drainage (Table 6). In cropped soils, the main part of whole drainage occurred in autumn (9%) and winter (21%). At these periods, N uptake by plants is small (the mean N uptake was 16 and 15 kg N ha⁻¹, respectively). In period 3 (5 February–15 April), plant absorption becomes important: the mean N uptake during this period was 48 kg N ha⁻¹. We have compared LIXIM outputs with or without accounting for N uptake by plants. The maximum error made in cropped soils varies according to the drainage period from 0.5 to 9.6 kg N ha⁻¹ year⁻¹. If we account for the relative contribution of these periods to the whole leaching, the maximum error which may be committed is 2.5 kg N ha⁻¹ year⁻¹, i.e. 9% of the mean leaching value. The uncertainty on leaching calculation due to the presence of crops seems reasonable.

The sensitivity analysis realized for the 1995/1996 year showed that LIXIM outputs were not significantly affected by the initialisation date chosen: harvest, September or late autumn (Table 7). The mean errors on drainage, leaching and concentration are, respectively, 49 mm, 2.8 kg N ha⁻¹ and 2 mg NO₃ L⁻¹. These values are close to the measurements errors on SWC and SMN.

In contrast, LIXIM calculations were sensitive to the soil depth, i.e. the maximum depth at which crops can recover water and mineral N. Increasing the soil depth from 90 to 120 cm in the shallow soils and from 120 to 150 cm in the deep loamy soils resulted in a small reduction in drained water and a marked reduction in leached nitrate. It decreased the nitrate concentration from 71 to 59 mg L⁻¹ in shallow soils and from 31 to 23 mg L⁻¹ in deep soils, i.e. a 17 and 25% reduction, respectively. This effect, already mentioned by Lilburne et al. (2003), emphasizes the importance of defining the maximum depth influenced by the rooting system in order to predict the absolute N leaching. We determined the maximum rooting depths of winter wheat at anthesis on 12 sites: the measured values were 158, 97, 88 and 53 cm in DL, SLC, SSL and SLS soils, respectively. These values are close to the leaching depth in shallow soils, but lower than that used in deep soils. Then, we may over-estimate N leaching in the deeper soils. However, the prediction of the relative effect of several factors on leaching can be trusted because the leached N (or the concentrations) calculated in the 36 sites at the two depths were very highly correlated.

### Table 6

<table>
<thead>
<tr>
<th>Contribution to whole drainage (%)</th>
<th>Period 1 (20 September–30 November)</th>
<th>Period 2 (30 November–5 February)</th>
<th>Period 3 (5 February–15 Apr)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare soils</td>
<td>11</td>
<td>31</td>
<td>16</td>
<td>57</td>
</tr>
<tr>
<td>Cropped soils</td>
<td>9</td>
<td>21</td>
<td>13</td>
<td>43</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Contribution to whole leaching (%)</th>
<th>Period 1 (20 September–30 November)</th>
<th>Period 2 (30 November–5 February)</th>
<th>Period 3 (5 February–15 Apr)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare soils</td>
<td>11</td>
<td>19</td>
<td>17</td>
<td>48</td>
</tr>
<tr>
<td>Cropped soils</td>
<td>12</td>
<td>21</td>
<td>19</td>
<td>52</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Maximal error on N leaching calculation in cropped soils (kg N ha⁻¹ year⁻¹)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute errorᵃ</td>
<td>13.1</td>
</tr>
<tr>
<td>Weighted errorᵇ</td>
<td>2.5</td>
</tr>
</tbody>
</table>

ᵃ The maximal error is the difference between LIXIM simulations made with or without accounting for plant absorption.
ᵇ The weighted error accounts for the contribution of cropped soils to whole leaching.
3.3.3. Drained water, leached nitrogen and nitrate concentration

If we consider all individual sites, the amounts of drained water varied widely from 17 to 590 mm year$^{-1}$ (Fig. 5). The year, soil and crop rotation factors explain 83% of the variance. Elementary drainage varied primarily from year to year, between 79 and 443 mm (Table 8). Mean drainage varied significantly with crop type: the smallest value (153 mm) was obtained after sugarbeet crops which have an active growth and transpiration until harvest; the crops harvested early produced the larger amount of drained water (278 mm). Concerning soils, the deep loamy soils had less drainage than the other soil types but the difference was not statistically significant.

The quantity of nitrogen leached annually on each individual site varied from 0 to 154 kg N ha$^{-1}$. The year, soil and crop type explain 59% of the variance. The mean amount of N leached was 27 kg N ha$^{-1}$. N leached varied by a five-, four- and three-fold factor according to the year, the crop and soil type, respectively. The year effect (from 8 to 45 kg N ha$^{-1}$) was strongly linked with the amount of drained water. Leaching varied with land occupation from 11 kg N ha$^{-1}$ (S–W) to 42 kg N ha$^{-1}$ (P–W). The mean leaching was 16 kg N ha$^{-1}$ in the loamy soils and 50 kg N ha$^{-1}$ in the sandy soils. Changing the rooting depth does not alter the soil impact on N leaching (Table 7). Leaching did not differ significantly between GAP and AEP situations.

Nitrate concentration in the drained water calculated for each site and each year varied also widely, from 1 to 300 mg L$^{-1}$. At the annual scale, the concentration varied much less than leaching, between 35 and 59 mg L$^{-1}$. Nitrate concentration was primarily affected by soil type: the lowest value is obtained in deep loamy soils (31 mg L$^{-1}$) and the highest in shallow sandy soils (92 mg L$^{-1}$). The sugarbeet–wheat succession gave the lowest concentration (32 mg L$^{-1}$), whereas the pea–wheat succession resulted in the highest one (80 mg L$^{-1}$).

![Fig. 5. Nitrate concentration in drained water (mg NO$_3$ L$^{-1}$) vs. drained water (mm year$^{-1}$) for several crop successions. The hyperbola correspond to fixed amounts of leached N (L in kg ha$^{-1}$ year$^{-1}$). Symbols are similar to Table 4.](image-url)
As expected, leached N was significantly correlated with drained water (\(r^2 = 0.31, n = 256\)). In contrast, nitrate concentration was not correlated with drained water, even when considering only the highest drainage values (Fig. 5). This indicates that there was no significant effect of nitrate 'dilution' even in shallow soils and wet years. On other hand, low nitrate concentration associated with low drainage has a low impact on leaching. Both water and N fluxes are required to predict the GAP impact on a long term.

3.4. Cumulative fluxes

3.4.1. Comparison with nitrate concentration in subsoil

In each of the nine sites which were cored deeply, we added the water and nitrogen fluxes calculated by LIXIM from 1991, 1992 or 1993 to 1995 and calculated the mean concentration in drained water during this period. This concentration was then compared to that measured in 1995 in the corresponding subsoils (Table 9). The time period for calculation in each site was adjusted so that the amount of drained water equalled the amount of water contained in the subsoil core (average = 1042 mm). The mean observed nitrate concentration was 39 mg L\(^{-1}\). This value is close to that calculated with LIXIM: 41 mg L\(^{-1}\). The regression equation between simulated and observed values is \(y = 0.99x\) (intercept not significantly different from 0), \(r^2 = 0.84\). The concentration is particularly high in one site, corresponding to the sandy soil with a shallow rooting potential: 122 mg L\(^{-1}\). In the two situations with the lowest concentrations (sites no. 1 and 3), LIXIM calculations were greater than the measured concentrations: this might be due to the under-estimation of the rooting depth, as mentioned previously. However, if we consider the spatial variability of SMN and the possibility of dispersive transport, we conclude that the calculations with LIXIM were in reasonable agreement with the observations.

3.4.2. Cumulative fluxes over 8 years

The cumulative drainage and leaching over the 8 years varied between sites from 161 to 369 mm year\(^{-1}\) and from 10 and 83 kg N ha\(^{-1}\) year\(^{-1}\), respectively. The nitrate concentration varied about as much, from 20 to 123 mg L\(^{-1}\) (Fig. 6). The amount of drained water is negatively correlated with soil water content at field capacity, but the determination coefficient is small (\(r^2 = 0.23\)). Leached N and nitrate concentration are highly and negatively correlated with WFC (\(r^2 = 0.60\) and 0.58, respectively). These variables can be fitted to a linear or an exponential curve, the latter being more relevant than the former. The fitted curves are \(L = 157 \exp(-0.0053\text{WFC})\) and \(C = 220 \exp(-0.0044\text{WFC})\) for the leached N and the concentration, respectively. The nitrate concentration varies from 36 mg L\(^{-1}\) in deep soils (mean WFC = 416 mm) to 60 mg L\(^{-1}\) in shallow soils (mean WFC = 299 mm).

3.4.3. Fluxes per rotation

The effect of crop nature on water and nitrogen fluxes cannot be studied alone, at least because fluxes are influenced by the preceding and the next crops. It must be analysed as a crop rotation effect. On the basis
of the observed crop successions, we could define six main rotations: 2 year (S–W and P–W) and 3 year rotations (S–W–B, R–W–B, P–W–B and S–P–W). They represent, respectively, 13, 14, 8, 13, 7 and 5% of the land occupation. Most crop successions can be obtained as a mixture of these rotations.

The effect of crop rotation on nitrate concentration was almost independent on soil effect (Fig. 7). We first discuss the situations with CC which are the observed ones. The higher was the proportion of spring peas in the crop succession, the greater was the nitrate concentration. Conversely, the higher the sugarbeet proportion, the lower the concentration. Cereals and rapeseed crops had an intermediate effect. The variation due to crop rotation was lowest in deep loamy soils (18 mg L$^{-1}$) and highest (47 mg L$^{-1}$) in shallow loamy sand soils. The relative effect of crop rotation (ratio of the concentration to the mean concentration per group of soil) was the same for the three groups of soils (52%). The soil type exerted an important effect: the concentration was lowest in deep loamy soils and greatest in shallow loamy sand soils.

The effect of absence of CC was then simulated using the observed situations and assuming that CC reduced drainage by 30 mm (Justes et al., 1999). At the plot–year scale, the mean nitrate concentration calculated before spring crops without CC is 85 mg L$^{-1}$. Therefore, the absence of CC would have increased the nitrate concentration in all rotations, on average by 44 mg NO$_3$ L$^{-1}$, i.e. 50% of the concentration without CC. The benefit of CC would vary between 11 and 46 mg L$^{-1}$. The relative benefit (ratio of the reduction in nitrate concentration due to CC to the nitrate concentration of the situation without CC) depends on its frequency within the rotation: it varies from 0% in the R–W–B rotation to 42% in the S–W rotation. The mean benefit was 23% and did not depend on soil type.
4. Discussion

The mean SMN content found at wheat harvest (36 kg ha\(^{-1}\) over a mean depth of 105 cm) is moderate. It is equal to the mean value of the experimental dataset compiled by Makowski et al. (1999) for unfertilised wheat, and lower than that reported by Webster et al. (2003): 43 kg ha\(^{-1}\) over 0–60 cm. We found that SMN at harvest was significantly greater after pea and rapeseed than after cereals or sugarbeet, whereas Webster et al. (2003) did not. No correlation was observed between SMN measured in February and at the following harvest. This suggests that residual N present in soil in February, which varied from 14 to 164 kg ha\(^{-1}\), was well accounted for in the N fertilisation.

SMN increased with the excess of fertiliser-N measured a posteriori. The slope of the regression line is 0.40. It is close to the values (0.40–0.50) reported by Machet et al. (1997) and that (0.47) given by Makowski et al. (1999). The mean over-fertilisation for GAP was 22 kg N ha\(^{-1}\), indicating an implicit insurance policy related to the fact that the response curve is only known retrospectively (Addiscott et al., 1991). It was nil for AEP. According to the fitted curve, AEP should reduce SMN at harvest by 9 kg N ha\(^{-1}\) in comparison with GAP. This reduction should result in smaller leaching losses, which have not been detected. The reason is likely to be the compensatory effect of CC on leaching: indeed, CC took up less N during the AEP than the GAP period.

The SMN contents measured in late autumn also varied with crop type. The high values (average 95 kg ha\(^{-1}\)) found for wheat after pea (P–W) are confirmed by regional data (not shown). The mean of the four other rotations without legume and CC is 52 kg ha\(^{-1}\), so that the increase in N release due to pea is 43 kg ha\(^{-1}\). This is consistent with the results of Beckie et al. (1997) who estimated that the mean contribution of pea to the nutrition of the next crop was 25 kg N ha\(^{-1}\). Our results suggest that the growth of pea volunteers and their subsequent decomposition favour this N release.

Straw incorporation can help reducing nitrate losses since it decreased net mineralisation during the autumn. The net immobilisation due to cereal straw decomposition has been estimated at 24 kg ha\(^{-1}\) from harvest to December; this is consistent with the values (17–24 kg ha\(^{-1}\)) found by Mary et al. (1996) for our farming practices and those (10–25 kg N ha\(^{-1}\)) reported by Nicholson et al. (1997), even after repeated incorporation of straw.

We found that nitrate leaching was greatly affected by soil type. This confirms earlier work by Nieder et al. (1995), Boniface (1996), Simmelsgaard (1998) and Hoffmann and Johnsson (1999). The first authors
analysed 205 plots in Germany from 1986 to 1988 and calculated losses from 16 kg N ha$^{-1}$ year$^{-1}$ in clayey or loamy soils to 63 kg N ha$^{-1}$ year$^{-1}$ in sandy soils. Their results are comparable to ours: 16 kg N ha$^{-1}$ year$^{-1}$ in deep loamy soils and 50 kg N ha$^{-1}$ year$^{-1}$ in shallow rooted sandy soils. Studies conducted by Hall et al. (2001) and Lilburne et al. (2003) have simulated nitrate leaching in North-eastern Colorado and in New Zealand, respectively. They indicate that leached N can vary by a five- to nine-fold factor due to soil type. Richter et al. (1998) and Webster et al. (2003) have also shown that WFC is an important explicative variable.

Shallow soils with a lower yield potential may then contribute greatly to leaching even when fertilisation is carefully planned, as shown by Pang et al. (1998). However, the relative differences between soils are smaller for concentration than for leaching. This may result from water dilution in shallow soils. Gorres and Gold (1996) simulated no difference between soils when drainage was very high (700 mm). Johnson et al. (2002) did not find any dilution in porous cups for a drainage less than 300 mm. Webster et al. (2003) in shallow soils found that nitrate concentration in ceramic cups decreased when drainage exceeded 300 mm. Our calculations did not show significant dilution for the cumulative results, but did show a dilution with time during the wet winter 1993/1994 which produced an average drainage of 443 mm.

We found that nitrate leaching was greatly affected by crop type and farmer practices, in agreement with Hall et al. (2001). The impact of crop nature has been assessed at the rotation scale, in order to integrate the effect of preceding and following crops. The mean effect of catch crops has been estimated at 22 mg L$^{-1}$, i.e. a reduction of 11 kg ha$^{-1}$ of leached N, at the rotation scale. The mean relative benefit of CC also decreased from 51%, at the yearly scale, to 23% at rotation scale. The value obtained at yearly scale is significant but lower than that observed on experimental sites in Northern France (Chapot, 1995; Justes et al., 1999). This is attributed to the moderate growth of CC in our ‘on farm’ conditions. Volunteers, particularly from barley or rape, can also have a large impact, as shown by Justes et al. (1999). The relative range of variation due to crop nature was halved from the annual scale (98%) to the rotation scale (52%). Because of this large temporal scale effect, the scale of the rotation is the relevant one to assess the impact of cropping systems improvements on nitrate concentration.

The efficiency of improved agricultural practices with regard to the EU drinking water guideline depends on situations. These practices are clearly more ‘environment friendly’ than the conventional practices which were simulated at 88 mg L$^{-1}$ (Beaudoin et al., 2004). We could not find a significant difference in the mean nitrate concentration in drainage between the GAP and the AEP periods (51 and 56 mg L$^{-1}$, respectively). Maize crops grown with carefully planned fertilisation in Canada gave a similar concentration: 55 mg L$^{-1}$ (Milburn and Richards, 1993), whereas conventional practices could provide higher concentrations: 67–80 mg L$^{-1}$ (Tan et al., 2002). Johnson et al. (2002) in UK found that nitrate concentration in shallow soil could greatly exceed the guideline, even for the ‘protective system’: they measured 96 mg L$^{-1}$ for ‘full N rate’ (about equivalent to GAP) and 80 mg L$^{-1}$ for the ‘protective’ with an additional 25% reduction in N fertilisation (equivalent to AEP), during a 10 year study. Webster et al. (2003) found 69 mg L$^{-1}$ in a 6 year study with the ‘LIFE’ system, which included a 30% fertiliser reduction, straw incorporation and reduced tillage. A more drastic scenario to reduce nitrate pollution in shallow soils may consist in introducing set aside on these soils. Richter et al. (1998) found that a 5 year permanent covered fallow decreased the nitrate concentration by 64% at the field scale but 13% over a catchment in Germany: the impact at the catchment scale depends on the involved area and the conditions of fallow destruction.

Concerning the impact of reduced tillage, no clear recommendation is available at the moment (Di and Cameron, 2002). Under conservative farming, volunteers impact is great and can be confused with the no tillage impact (Stenberg et al., 1999; Johnson et al., 2002).

5. Conclusion

Three combined rules of decision have been applied by the farmers over the catchment in order
to limit the nitrate pollution of the aquifer: N fertiliser optimisation, CC establishment and straw incorporation. The results indicate that applying these ‘Good Agricultural Practices’ should result in a significant reduction in nitrate concentration below the rooting zone, even under actual (non-optimal) farming conditions. The reduction of fertiliser N rate by 20% (‘Agri-Environmental Practices’) does not improve further the situation, probably because the effect of CC is smaller than with GAP. The impact of GAP is highly dependent on soil type: the absolute effect is greater in soils sensitive to leaching. But nitrate concentration in sandy or rocky soils in drained water remains higher than the EU guideline for nitrate in drinkable water. The effects of crop nature or of CC establishment on the range of variation of the mean nitrate concentration are both halved from the annual scale to the rotation scale. Due to this scale effect, the rotation scale is the relevant one to assess the impacts of changes in cropping systems.

GAP should be adapted to soil type: precision agriculture techniques could help to manage spatial variability, and the duration and frequency of catch crops could be increased in shallow soils. CC have other beneficial effects on soil, such as increasing infiltration and reducing erosion risk. A better integration of catch crops within the cropping systems needs more investigations concerning the constraints of the farmers and the means to limit weeds and pests. The crop rotation is another key of choice influencing nitrate pollution but it is necessary to agree with the economic concern. More generally, a systemic approach including tillage, N management and crop protection should be planned in order to aim at sustainable agro-ecosystems.

Acknowledgements

We thank the farmers for their sincere cooperation: R. Chédeville, P. Mory, R. Mory, B. Pillois and M. Pillois. The authors are very grateful to E. Venet, J.P. Quizy, L. Thouant, J.P. Sebbe, P. Devaux and M. Bouchet for their technical assistance, M. Sarrazin and A. Lindor for the pedological map, G. Alavoine and O. Delfosse for the analyses. The Région Picardie and Agence de l’Eau Seine-Normandie are acknowledged for their financial support.

Appendix A. Calculation of over-fertilisation

The predictive nitrogen balance can be written (Meynard et al., 1997):

\[ X = (U_2 + N_2 + L + G) - (M + N_1 + U_1 + A) \]  

(A.1)

where, \( X \): optimal amount of N fertiliser; \( N_2 \): SMN at harvest; \( N_1 \): SMN in February; \( M \): net mineralisation by the soil; \( U_2 \): nitrogen uptake by the crop at harvest; \( U_1 \): nitrogen uptake by the crop in February; \( A \): meteoritic input of nitrogen; \( L \): leaching losses during cropping; \( G \): gaseous losses (denitrification and volatilisation); all values are in kg N ha\(^{-1}\).

The N uptake at harvest can be written, in the case of cereals and rapeseed:

\[ U_2 = b \cdot Y \]  

(A.2)

where \( Y \): objective yield (Mg ha\(^{-1}\)); \( b \): amount of nitrogen absorbed per unit of yield (kg Mg\(^{-1}\)).

The actual nitrogen balance (a posteriori) can be written similarly:

\[ X' = (U_2' + N_2' + L' + G') - (M' + N_1 + U_1 + A) \]  

(A.3)

\[ U_2' = b' \cdot Y' \]  

(A.4)

where \( Y' \) is the actual yield obtained.

Comparing the predictive and the actual N balances allows to define an a posteriori over-fertilisation (OF). We assume that, in a system without organic effluents, the main discrepancy in the prediction concerns the yield and possibly the application of a fertiliser rate different from the recommended one (especially when rule 4 is applied). Then, OF is defined as:

\[ OF = (X' - X) + b(Y - Y') \]  

(A.5)

which can be written:

\[ OF = (X' - X) - (U_2' - U_2) + (b' - b)Y' \]

Using Eqs. (A.1) and (A.3), it comes:

\[ OF = (N_2' - N_2) + (b' - b)Y' + \varepsilon \]  

(A.6)

with:

\[ \varepsilon = (L' - L) + (G' - G) - (M' - M) \]  

(A.7)
Eq. (A.6) indicates that over-fertilisation has two main effects: it increases the amount of mineral nitrogen at harvest (term $\Delta SMN = N_2 - N_1$) and increases the uptake of nitrogen by the crop term $Y(\hat{b} - b)$. A negative $OF$ should lead to minimise $\Delta SMN$. We assume that the $\varepsilon$ term is nil on average with a random distribution.

References


