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ORIGINAL ARTICLE

Nitrate leaching from organic and conventional arable crop farms in the Seine Basin (France)

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Abstract In the Seine Basin, characterised by intensive arable crops, most of the surface and groundwater is contaminated by nitrate (NO_3^-). The goal of this study is to investigate nitrogen leaching on commercial arable crop farms in five organic and three conventional systems. In 2012–2013, a total of 37 fields are studied on eight arable crop rotations, for three different soil and climate conditions. Our results show a gradient of soil solution concentrations in function of crops, lower for alfalfa (mean 2.8 mg NO_3-N l^{-1}) and higher for crops fertilised after legumes (15 mg NO_3-N l^{-1}). Catch crops decrease nitrate soil solution concentrations, below 10 mg NO_3-N l^{-1}. For a full rotation, the estimated mean concentrations is lower for organic farming, 12 ± 5 mg NO_3-N l^{-1} than for conventional farming 24 ± 11 mg NO_3-N l^{-1}, with however a large range of variability. Overall, organic farming shows lower leaching rates (14–50 kg NO_3-N ha^{-1}) than conventional farms (32–77 kg NO_3-N ha^{-1}). Taking into account the slightly lower productivity of organic systems, we show that yield-scaled leaching values are also lower for organic (0.2 ± 0.1 kg N kg^{-1} N $year^{-1}$) than for conventional systems (0.3 ± 0.1 kg N kg^{-1} N $year^{-1}$). Overall, we show that organic farming systems have lower impact than conventional farming on N leaching, although there is still room for progress in both systems in commercial farms.

Keywords Nitrate leaching · Ceramic cups · Arable crops · Organic farming · Farmer-centred approach

Introduction

Nitrogen (N) is an essential element for plant growth and its use in agriculture as a mineral fertiliser based on the Haber–Bosch process sharply increased after World War II. The current world fertiliser application mean is presently 133 kg N ha^{-1} $year^{-1}$, with strong heterogeneity in time and space. In France, the use of fertilisers reached a maximum of 200 kg N ha^{-1} $year^{-1}$ in the 2000s and has recently decreased to a mean of 150 kg N ha^{-1} $year^{-1}$ (www.faostat.fao.org), due to both price increase (+60 % between 2000 and 2013; www.bdm.insee.fr) and to National and European regulations aiming at protecting water resources. Nitrate pollution of groundwater from agriculture is an issue of major concern for the European Union (EU) (Addiscott et al. 1991; Sutton et al. 2011), which has identified vulnerable zones and

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promoted good agricultural practices since 1991, in the scope of the Nitrate Directive (no. 91/676/CEE). The whole Seine Basin, with intensive crop production, has been classified as a vulnerable zone, because 68 % of its drinking water intakes are contaminated by pesticides and 30 % by nitrate (NO_3^-) (AESN 2013).

Organic farming (OF) is already recognised as a good alternative to combat pesticide pollution and maintain biodiversity (Henneron et al. 2014; Pelosi et al. 2014), but its impact on NO_3^- contamination is still controversial. Only a few studies (34 to our knowledge and none in France) have compared NO_3^- leaching in OF and conventional farming (CF) from arable crops in the EU. Comparisons in terms of area-scaled leaching values are often in favour of OF, with 30–40 % lower values (Berg et al. 1999; Hansen et al. 2000; Korsaeth and Eltun 2000; Haas et al. 2002; Stopes et al. 2002), but in some studies around 20 % more leaching in OF than in CF has been measured (Kristensen et al. 1994; Torstensson et al. 2006; Sapkota et al. 2012). On the other hand, when expressed in yield-scaled units, the differences in leaching rates either are not significant (Kirchmann and Bergstrom 2001; Mondelaers et al. 2009) or disfavour OF (Tuomisto and Helenius 2008; Korsaeth 2008).

The major question we address here is the capacity of OF systems in the Seine Basin to preserve surface and groundwater from NO_3^- contamination in the watershed, while producing arable crops. Launched to fill the gap of knowledge on NO_3^- leaching in the different cropping systems of the Seine Basin, the ABAC regional project (DIM-Astrea, Ile-de-France Region and AESN) is designed as a farmer-centred approach, referring to the "bottom-up" approach from the agroecology concept (Altieri 2002), also named as "the next wave of innovation" according to MacMillan and Benton (2014). We choose to observe real practices of farmers, typical and representative of the cropping systems in their respective sub-region, since experimental plots and commercial farms can give different results, as shown for carbon sequestration by Aguilera et al. (2013).

Although our approach is based on data from a single year, instead of a number of continuous years, we compared systems of arable crop successions in organic and conventional commercial farms. Such data are essential for water managers seeking to protect groundwater quality, compatible with drinking water production, for the 16 million inhabitants of the Seine Basin. In this context, area-scaled leaching values are pertinent indicators for assessing the impact of agriculture on water quality, while yield-scaled leaching values (i.e. expressed per unit calorie or N harvested) reflect the trade-off of production versus environmental contamination.

Therefore, soil solution concentrations are measured below the root zone, with vertical porous ceramic cups (Stopes et al. 2002). The vertical ceramic cups can be set up quickly without destruction of the soil's horizons and sampled water in the soil solution zone can be directly analysed for NO_3^- concentrations.

Also, determining the diffuse sources associated with different agricultural practices, as an input to models of biogeochemical nutrient fluxes, will be an additional perspective of this study. As an example, the Seneque-Riverstrahler model, developed for calculating water quality of large river basins, such as the Seine watershed, is able to explore possible agricultural scenarios (Thieu et al. 2011) and their impact at the coastal zone in terms of eutrophication (Garnier et al. 2010; Passy et al. 2013).

Materials and methods

Localisation and characteristics of the main areas

The Seine Basin, with a surface of 78,650 km^2, has substantial agricultural activity. The climate is humid and temperate, with a large gradient of temperature and rainfall. Arable crops cover around 60 % of the utilised agricultural land (UAL) with wheat as a dominant crop (29 % UAL). In this area, OF accounts for only 1.5 % UAL, compared with 3.8 % UAL in France in 2012.

A total of eight agricultural systems was studied in three sectors of the Seine Basin, with different rainfall patterns, pedology and agriculture practices. The first group is located in the East of the Seine Basin, in Seine & Marne (S&M), with deep loamy soil (luvisol) generally drained due to hydromorphic conditions, over a calcareous substratum. The mean annual rainfall is around 700 mm and the mean annual temperature 9.7 °C (40 years of measurements at the Boissy-le-Châtel weather station). Most of agriculture in S&M is characterised by winter wheat, alternating with maize or faba beans, with only 1.1 % UAL in OF.

Table 1 Main characteristics of the cropping systems studied in the three regions (S&M, Oise, Yonne) in OF and CF with the number of the fields studied, the exogenous fertiliser types used and the tillage presence (X) or absence (No)

Region	Systems	Number of fields studied	Fertiliser types	Tillage
S&M	CF1	2	Mineral or organic	x
S&M	CF2	2	Mineral	No
Oise	CF3	3	Mineral	X
S&M	OF1	5	Vinasse and horse manure	X
S&M	OF2	9	Poultry, horse manure and vinasse	X
Oise	OF3	3	Vinasse	X
Oise	OF4	6	Vinasse	X
Yonne	OF5	6	–	X

The second group, located in the North of the Seine Basin, in Oise, is characterised by a chalky substratum, present in nearly all the periphery of the Seine Basin. The annual averages in rainfall and temperature are similar to those of the S&M, 697 mm and 9.7 °C, respectively (30 years of data measured in the Saint Quentin, Météo France weather station). Oise agriculture is dominated by arable crops like wheat (>50 % UAL), rape seed and sugar root production, with only 1.3 % UAL in OF. The third group is located in the South of the Seine Basin, in Yonne, with average annual rainfall and temperature of 880 mm and 10.7 °C, respectively (30 years of data measured in Cruzy, Météo France weather station) and a chalky substratum. Percentages of oat and oilseed rape are higher in Yonne than in the other sectors, as OF which accounts for 4.1 % UAL.

Agricultural practices studied

Five OF and three CF cropping systems were studied, characterised by different practices and regions. In S&M, four cropping systems were studied, including two CFs and two OFs. The CF rotations last 2 years with tillage (CF1) or without tillage (CF2), whereas one OF rotation lasts 5 years with low exogenous fertilisation (OF1) and the other lasts 9 years with exogenous fertilisation (OF2). In Oise, the three systems studied count two OFs, one with a three crops rotation (OF3) and the second with a 6 years rotation (OF4), both using vinasse on cereals; the CFs, is characterised by a 3 years rotation (CF3). The last OF located in Yonne is autonomous, a 6 years rotation with no exogenous fertilisation (OF5). Except CF2, all the systems use standard tillage (Table 1). The conversion time to organic systems ranges from 3 (OF1, OF3, OF5) to 10 years (OF2, OF4). In this region, because of the very low livestock density, arable crop farms in OF replace mineral fertilisers by the introduction of legume crops and a low proportion of exogenous organic fertiliser application (manure, vinasse, poultry droppings, etc.). In order to compensate herbicide applications, OF requires tillage, harrow, hoe, crops diversification and introduction of forage crops such as alfalfa, which, besides nitrogen symbiotic fixing, considerably reduces self-propagating weeds.

All OF rotations were rather long (mean 7 years) including alfalfa in the beginning. For OF systems, 30 fields were equipped with ceramic cups including nine different crops: alfalfa (eight fields), wheat (nine fields), flax (two fields), faba beans (three fields) and lentils (one field), and rye, oat or triticale and maize (one field each) (Table 2). In CF, with shorter rotation (2–3 years), seven fields were instrumented for five different crops: wheat (four fields), rapeseed, faba beans and maize (one field each). Exogenous fertilisation in OF is between 8 and 200 kg N ha^{-1} and 74–238 kg N ha^{-1} in CF. Organic fertilisers, applied during the study, were sugar beet vinasse (17 kg N t^{-1}), horse manure (7 kg N t^{-1}) or poultry manure (43 kg N t^{-1}). Mineral fertilisation was generally a combination of calcium ammonium nitrate (CAN, 27 % N) and urea (35 % N). During the study, catch crops (CC) as mixed seeds (60 % vetch, 15 % clover, 15 % lacy phacelia, 10 % mustard) were grown from September to December on CF1 and OF1.

Field measurements

Ceramic cups

Ceramic cups have been used, since 1904, to measure NO_3^- in groundwater (Briggs and McCall

Table 2 Data of the fields instrumented in the eight systems in OF and CF including crops, previous crops with straw buried (b.) or exported (e.) and its net BNF inputs, N exogenous inputs (organic or mineral fertilisers) in 2012–2013, SMN before fall tillage (October; November; December), soil solution concentrations (soil solution conc.) and N harvested

Farm system	Crops (2012–2013)	Previous crops (2011–2012)	Net BNF previous crops (kg N ha^{-1})	N exogenous inputs (kg N ha^{-1})	Crop Harvest (2012–2013) (kg N ha^{-1})	SMN after fall tillage (2012) (kg N ha^{-1})	Soil solution conc. (mg N l^{-1})	Fertiliser types
CF1	CC[a]-faba	Wheat (b)	0	74	221	44.5	2.4	Vinasse
CF1	Wheat	Pea	19	165	175	52.1	23.2	Ammonitrate
CF2	Wheat	Faba- maize (b.)	154	212	162	25.4	28.7	N, P, K (2 −2 −1)
CF2	Faba-maize	Wheat (b.)	0	175	125	10.4	6.5	N, P, K (2 −2 −1)
CF3	Wheat	Wheat (e.)	0	238	168	24.7	24.5	N, P, K (2 −2 −1.8)
CF3	Rapeseed	Wheat (e.)	0	130	116	23.5	30.9	N, P, K (2 −2 −1.8)
CF3	Wheat	Peas	39	136	215	41.9	61.1	N, P, K (2 −2 −1.8)
OF1	Alfalfa 2	Alfafa 1 (e.)	137	0	304	14.9	1	
OF1	Alfalfa 2	Alfafa 1 (b.)	173	0	304	16.1	4	
OF1	Wheat	Faba beans	28	80	72	n.d	10.4	Vinasse, horse manure
OF1	CC[a]-flax	Wheat (b.)	0	50	31	n.d	9.2	Vinasse
OF1	CC[a]-beans	Wheat (b.)	0	0	52	n.d	6.2	
OF2	Alfalfa 1	Triticale (e.)	0	0	75	5.4	2.4	
OF2	Alfalfa 2	Alfalfa 1 (e.)	157	0	403	12.8	3	
OF2	Wheat	Alfalfa 2 (e.)	190	0	125	37.5	17	
OF2	Flax	Wheat (e.)	0	0	39	24.1	23	
OF2	Wheat	Flax (b.)	0	200	86	43.1	42	Poultry and horse manure
OF2	Baresoil-lentils	Wheat (e.)	0	0	59	24.1	17	
OF2	Triticale	Lentils	8	50	96	23.5	23	Vinasse
OF2	Wheat	Faba beans	55	200	95	19.5	26	Horse and poultry manure
OF2	Oat	Wheat (e.)	0	140	120	16.8	8.7	Horse manure
OF3	Alfafa 2	Alfalfa 1 (e.)	146	0	310	8.4	18	
OF3	Baresoil-wheat	Triticale (b.)	0	0	98	n.d	31	
OF3	Wheat	Maize (b.)	0	48	80	25.6	25	Vinasse
OF4	Alfafa1	Wheat (b.)	0	0	81	8.4	7	
OF4	Wheat	Alfafa 2 (e.)	102	0	70	6.2	13	

Table 2 continued

Farm system	Crops (2012–2013)	Previous crops (2011–2012)	Net BNF previous crops (kg N ha^{-1})	N exogenous inputs (kg N ha^{-1})	Crop Harvest (2012–2013) (kg N ha^{-1})	SMN after fall tillage (2012) (kg N ha^{-1})	Soil solution conc. (mg N l^{-1})	Fertiliser types
OF4	Wheat	Maize (b.)	0	0	95	12.8	5	
OF4	Maize	Wheat (b.)	0	0	78	11.3	16	
OF4	Baresoil-faba	Spelt (b.)	0	0	66	4.8	2	
OF4	Wheat	Vegetables	0	32	70	4.8	1	Vinasse
OF5	Alfalfa 2	Alfalfa 1 (e.)	170	0	397	0.9	2	
OF5	Alfalfa 3	Alfalfa 2 (e.)	187	0	217	13.1	7	
OF5	Wheat	Wheat (e.)	0	0	30	10.2	9	
OF5	Baresoil-faba	Sunflower	0	0	74	8.3	9	
OF5	Wheat	Faba beans	31	0	38	13.3	18	
OF5	Rye	Wheat spring (b.)	0	0	24	11.9	5	

[a] CC ploughed in December 2012

1904). Their cost, effectiveness and ease of installation have made them the most commonly used devices for collecting soil solution water. Because our experimental study is farmer-centred, all the ceramic cups were installed vertically to avoid soil damage in the fields. Furthermore, this approach is supported by the comparison between results from both horizontal and vertical installations, which did not show significant differences ($P \geq 0.05$) (Bowman et al. 2002). Although the vertical installation is flexible, the porous ceramic cups must be removed before plowing, which can make a long-term monitoring campaign difficult. All the soils of the ABAC farm network were at least 90 cm deep, favourable for installing vertical ceramic cups taking into account 80–90 % of the root density. A total of 37 fields were equipped with ceramic cups measuring 85 cm in length (SDEC, France, *SPS Ø 31* mm), implemented with a manual auger of the same diameter, with the head placed 5 cm below the ground surface, allowing shallow tillage. We assumed that six ceramic cups per field (i.e. 37 × 6 cups) would make it possible to determine the local variability; other studies generally using at least three (Eriksen et al. 1999) and up to ten ceramic cups (Stopes et al. 2002). The ceramic cups were arranged on a line parallel to the soil tillage, a minimum of 14 m from the edge of the field, in order to avoid any side effect. After 48 h of vacuum setting, samples were taken weekly at the beginning of the rainy hydrological season, when the soil is water saturated (first month) and fortnightly for the rest of the drainage period. Many of the farmers were involved in the sampling process. The period of sample collection lasted 6 months, from December 12th, 2012 to May 22nd, 2013, with an average of 10 sampling dates ($\approx$2500 samples for analysis).

Soil samples

For each field, right after tillage (from October to December), the six samples of soils are extracted over 90 cm depth. Soil samples were collected with the auger and pooled for the three layers [0–30], [30–60] and [60–90] cm. The fresh soil samples were stored for a few days at 4 °C, until analysis of humidity and soil mineral nitrogen (SMN) and then frozen at −18 °C for further analysis (texture and C, N content).

Analyses

Soil analysis

Triplicates of soil were weighed (30 g) to determine moisture and soil organic matter (SOM) using the loss-on-ignition method. Soil samples were heated at 105 °C (48 h) for the former, and calcined at 450 °C (4 h) for the latter, and re-weighed after each step. Soil mineral nitrogen concentrations were determined after KCl extraction, with 5 g of soil in 20 ml of KCl (2 M) for 2 h on a shaking table. The suspensions were centrifuged for 10 min at 3,000 rpm and the supernatant is frozen at −18 °C until analysis in the autoanalyzer (Quaatro, Bran & Luebbe). The rest of the sample is freeze-dried to determine the particle size distribution (without decarbonation), soil organic carbon (SOC) (after decarbonation), and loss of ignition at 1,000 °C, and total N (LAS, INRA Arras).

Soil solution analysis

The soil solution taken from each ceramic cup is frozen until analysis of the N concentrations using an autoanalyzer Quaatro (Bran & Luebbe). The method used to measure ammonium (NH_4^+) is based on the reaction of the blue indophenol (Slawyk and MacIsaac 1972). Nitrite (NO_2^-) and NO_3^- were measured using the sulphanilamide method (Jones 1984) and NO_3^- concentrations were determined after reduction to nitrite.

Calculations

Percolating water flow

The daily percolating water flow (W_i, mm day^{-1}) was calculated using climate data from the nearest weather station (Irstea or Meteo France) in each sector (S&M, Oise, Yonne) located in Boissy-le-Châtel (48°49′15″N3°08′19″E), Mesnil-sur-Bull (48°04′42″N3°35′00″E) and Arces (48°04′42″N3°35′00″E), respectively. We used daily rainfall (R_i, mm) and daily potential evapotranspiration (ETP_i, mm) to calculate W_i during the sampling period.

The daily water storage (WS_i, mm day^{-1}) was incremented by the daily previous water storage (WS_{i-1}, mm day^{-1}), R_i, ETP_i multiplied by a crop coefficient (k) fixed at 0.5 during the winter period (Perrier et al. 1980; Katerji and Perrier 1985; Allen 2000) and the previous water inflow (W_{i-1}, mm day^{-1}) (Eq. 1). Then W_i was determined by the difference between the WS_i and the water holding capacity up to its field capacity (WHC_{FC}, mm) (Eq. 2), which was determined from soil characteristics (depth, texture and structure) (Bruand et al. 2004).

$$WS_i = \max\left(WS_{i-1} + R_i - k.ETP_i - W_{i-1};\, 0\right) \quad (1)$$

$$W_i = \max\left(WS_i - WHC_{FC};\, 0\right) \quad (2)$$

The N leached flow was calculated between each collecting date, by multiplying the average concentration by the amount of infiltrated water. Leaching was measured for a 6 months sampling period, from December to May and is assumed to represent the total leaching of the year, as vegetation uptake and evaporation prevent leaching during the rest of the year.

N inputs: fertilisers and biological nitrogen fixation

The calculation of total N inputs takes into account exogenous inputs, via the application of organic and mineral fertilisers and biological N fixation (BNF) by previous legume crops.

The amount and N content of fertilisers (organic and mineral) and the straw management (buried or exported) were documented by farmers. The BNF is estimated from yields, using the relations established in Anglade et al. (submitted) for six legume species commonly grown in Northern Europe namely alfalfa, faba bean, field pea, lentil and white/red clover. Highly significant linear relationships were found between total N accumulation in shoot (Ny) and the amount of fixed N_2 derived from atmosphere (BNF), with different regression coefficients depending on species (α_{cult}; β_{cult}). In order to take into account below-ground contributions (BGN), comprising N associated with roots, nodules and rhizodeposition via exudates and decaying root cells and hyphae, multiplicative factors (BG) derived from a literature review were attributed, amounting 1.3 and 1.7 for grain and forage legumes, respectively (Eq. 3).

$$BNF\left(kg\ N\ ha^{-1}\right) = BG * \left[\alpha_{cult} * Ny_{cult} + \beta_{cult}\right] \quad (3)$$

Then, net input by BNF (net BNF) from the preceding crop is obtained by subtracting N harvested, in grain or in herbage, from the estimated total N input (including BGN) derived from N_2 fixation. We assumed an above-ground N harvest index (NHI) value of 0.75 for grain legumes. For alfalfa, different values were used depending on cutting regimes, e.g., 3 cuts at a height of 10 cm (3-inches), with one left in the field as green manure, is common.

Statistical analysis

All the statistical analyses were performed using R software. Differences within data sets were analysed using the Kolmogorov–Smirnov test to verify normality ($P > 0.05$). Analysis of variance tests (ANOVA) were determined for the data sets from the different areas, cropping systems and depths. Significance is accepted at $P < 0.05$.

Results

Soil properties in OF and CF

Textures

Composition in silt, sand (coarse and fine) and clay were determined for each field for the three layers. In all the fields, the clay percentages increased significantly with depth (p value = 5.5e-07***), whereas the silt percentages significantly decreased (p value = 0.0002***). Average clay was around 25 % and maximum in CF3 (31 %) and OF4 (29 %), and minimum in OF5 (21 %). The mean percentage of sand was around 10 %, maximum in OF5 (24 %) and minimum in OF2 (4.5 %). The mean WHC_{FC} was 200 mm in Oise, 180 mm in S&M and 160 mm in Yonne.

Nutrients

Nutrients as SOM, SOC and total N decreased with depth (p value = $6.5.e^{-14}$***), with no significant differences between the OF and CF systems in this network. The SOM values were significantly different within depths and between systems (p value = 0.003**), but not between systems (OF, CF) (p value = 0.2). Soil mineral N before the period of drainage was measured in the eight systems. Ammonium concentrations were stable in relation to depth, with a mean of 10 ± 0.6 kg NH_4-N ha^{-1} for all systems. Nitrate concentrations were significantly higher in the first layer (0–30 cm) (p value = $6.5e^{-14}$***), with high variations between fields, e.g., within a range from 1 to 17 kg NO_3-N ha^{-1}. Soil mineral N were not significantly different between the OF and CF systems, due to the high variability between fields in terms of crops, and the preceding crop, and hence agricultural practices (Table 2). Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Soil solution concentrations for the typical OF and CF crop successions

Soil solution concentrations showed variations along the drainage period in all fields. The percentage variation from the six ceramic cups at one date averaged 47 %, mainly because of the high micro-heterogeneity of the soils in terms of their composition, texture and therefore physical and biogeochemical processes. In the following, for each field, we will use the mean soil solution concentration, measured during the drainage period (~6 cups × 10 sampling dates). In all the equipped fields, soil solution concentrations increased as a function of SMN integrated over the soil profile (Fig. 1a). Soil mineral N can therefore be used in a first approach, as an indicator of soil solution concentrations. No relation was found between soil solution concentrations and SOM (Fig. 1b).

Variations in organic rotations

Regarding OF, the lowest soil solution concentration was found for fields cultivated with legumes (5 ± 4 mg NO_3-N l^{-1}). The first year after alfalfa was ploughed, the mean soil solution concentration was 15 ± 2 mg NO_3-N l^{-1}, due to mineralisation and 12 ± 9 mg NO_3-N l^{-1} for the second year (Fig. 2a). Grain legumes without fertilisation (faba beans, lentils in the fourth position in the rotation) had a mean soil solution concentration of 9 ± 6 mg NO_3-N l^{-1}. Crops after the legumes, with a mean 68 kg NO_3-N ha^{-1} net BNF, had a mean soil solution concentration of 21 ± 6 mg NO_3-N l^{-1}. At the end of the rotation, cereals with low N input showed a mean soil solution concentration of 12 ± 8 mg NO_3-N l^{-1}. The use of mixed-seeds as CCs led to low concentrations, 5 mg NO_3-N l^{-1} in OF1. Overall, the mean N soil

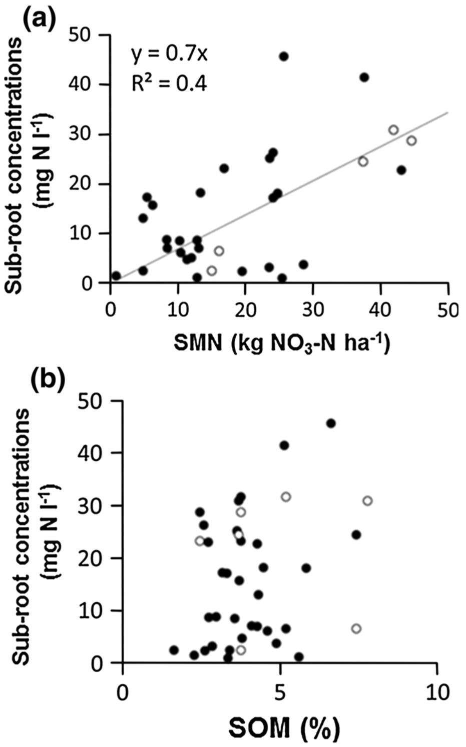

Fig. 1 Relations between **a** sub-root concentrations and SMN before the drainage period and **b** sub-root concentrations and SOM, over the profile in all the fields instrumented in ceramic cups: *black circles* (organic) and *open circles* (conventional) fields

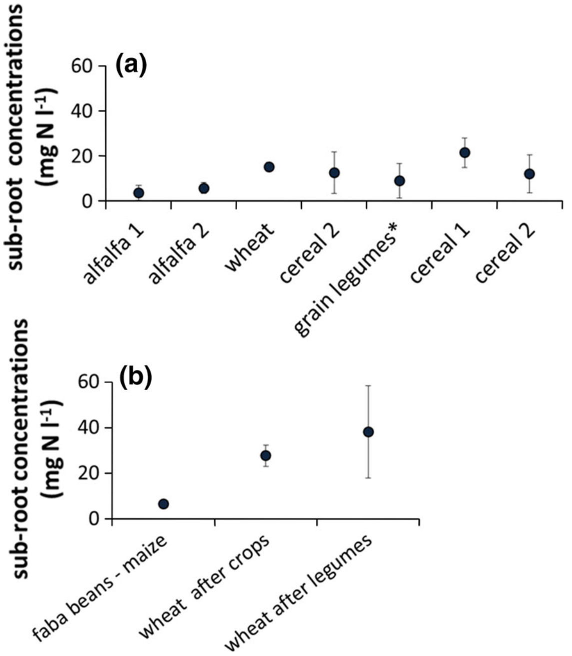

Fig. 2 Means (±SD) sub-root concentrations. **a** From organic rotation with succeeding crops: alfalfa 1 (n = 3), alfalfa 2 (n = 5), wheat post-alfalfa 2 (n = 3), cereals 2 (n = 3), grain legumes (n = 3), cereal 1 (n = 5), cereal 2 (n = 5); **b** from conventional rotation with maize (n = 1), wheat after crops (n = 2) and wheat after legume (n = 3). *sampling following CC ploughing in December 2012 or bare soil

solution concentration for the 7-years theoretical OF rotation was 12 ± 5 mg NO_3-N l^{-1}.

Variations in conventional rotations

For conventional rotations, N soil solution concentrations were measured in S&M and Oise (Fig. 2b). Maize succeeding faba-beans led to the lowest concentrations (6 mg NO_3-N l^{-1}); fertilised crops resulted in a mean concentration of 28 ± 4 mg NO_3-N l^{-1}, whereas the concentration for wheat after legumes reached 38 ± 20 mg NO_3-N l^{-1}. Green manure used as a biannual CC resulted in considerable soil solution concentration, as for wheat on CF2 (30 mg NO_3-N l^{-1}), higher than crops after legumes when exported, and as for wheat post-peas on CF1 (23 mg NO_3-N l^{-1}). Mean soil solution concentration, for the 3-years theoretical CF rotation (wheat, legumes with CC, wheat) was 24 ± 11 mg NO_3-N l^{-1}.

At total, considering the typical crop successions for OF (seven crops) and CF (three crops) in the studied region, soil solution concentrations were on average lower for OF than for CF (12 mg NO_3-N l^{-1} against 24 mg NO_3-N l^{-1}), although this difference is not statistically significant given the high variability within each system.

Impact of N inputs on organic crops

Crops on the fourth or fifth position in the OF rotation were generally fertilised with vinasse, poultry droppings or compost, leading to various N soil solution concentrations. For organic fertilisers as poultry manure or vinasse, the soil solution concentrations were directly impacted by the total N amount applied (Fig. 3). For example, the addition of poultry manure to horse manure or crops after legume (200 kg N ha^{-1}) led to soil solution concentrations over 26 mg NO_3-N l^{-1}. However in presence of CC or horse manure alone, soil solution concentrations were lower than 11 mg NO_3-N l^{-1} despite high amounts of organic N applied. For a vinasse application (50 kg N ha^{-1}) without CC, the soil solution concentration was 25 mg NO_3-N l^{-1}, whereas in presence of CC, the soil solution concentrations decreased to 6 ± 5 mg NO_3-N l^{-1}. Also, for crops after grain legumes, the application of compost before vinasse decreased the soil solution concentrations from 22.8 to 10.4 mg NO_3-N l^{-1}. Concerning legumes, although net BNF was five times higher for crops after 2 years of alfalfa (150 kg N ha^{-1}) than for crops after grain legumes (30 kg N ha^{-1}), their corresponding soil solution concentrations means were 15 ± 3 mg NO_3-N l^{-1} and 20 ± 3 mg NO_3-N l^{-1} respectively (Table 2).

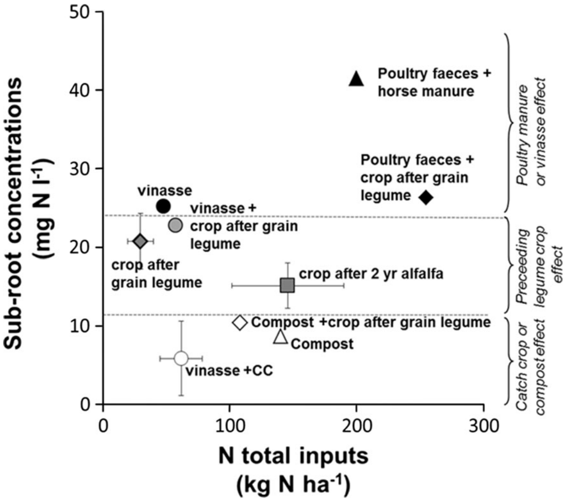

Fig. 3 Effect of N inputs (amounts and types: organic fertilisers, legumes) and CC on sub-root concentrations in OF fields

Influence of crop management, soil and climate on nitrate losses

Differently from the previous section where we have analysed soil solution concentrations for typical crop successions for OF and CF, here we analysed soil solution concentrations and N leaching by cropping systems.

Relation between N inputs and soil solution concentrations

Mean soil solution concentrations and N inputs have been calculated for each systems (Fig. 4a). In S&M, OF1 had the lowest mean soil solution concentration with 6 ± 5 mg NO_3-N l^{-1}, covering three legumes on a five crops rotation which account two-thirds of the N inputs. The lowest mean soil solution concentration observed in conventional was 13 ± 7 mg NO_3-N l^{-1} in CF1, in relation to low N inputs (129 kg N ha^{-1} year^{-1}). For the full OF2 rotation, soil solution concentrations mean was 18 ± 9 mg NO_3-N l^{-1}, using both exogenous inputs (66 kg N ha^{-1} year^{-1}) and net BNF (45 kg N ha^{-1} year^{-1}), a figure close to that found on the no-till system, CF2, amounting 19 ± 10 mg NO_3-N l^{-1}, also coming from fertilisers and net BNF (348 kg N ha^{-1} year^{-1}). In Oise, the soil solution concentrations showed considerable variations between cropping systems. The highest soil solution concentrations means have been measured in CF3 (39 ± 15 mg NO_3-N l^{-1}) for 181 kg N ha^{-1} year^{-1} total inputs, coming at 87 % N inputs from synthetic fertilisers, which is typical of conventional practices in this area and in OF3 (25 ± 8 mg NO_3-N l^{-1}) for 89 kg N ha^{-1} year^{-1} N total inputs (83 % N inputs from net BNF). In contrary, in OF4 the mean soil solution concentration on the rotation was 7 ± 6 mg N l^{-1}, in relation to low total inputs (22 kg N ha^{-1} year^{-1}) with nearly no exogenous inputs (5 kg N ha^{-1} year^{-1}). In Yonne, the mean soil solution concentration was 8 ± 3 mg N l^{-1} for OF5 (no CF investigation in this area), in reference to no exogenous input and three legumes on 6 years rotation providing 65 kg N ha^{-1} year^{-1} net BNF (Table 2).

Hydrological conditions and leaching

Water holding capacity at field capacity equalled 180 mm in S&M, 190 mm in Oise and 160 mm in Yonne. Finally, the Wi cumulated during the drainage period was 235 mm in S&M, 209 mm in Oise and 239 mm in Yonne.

In most cases, the conversions from concentration to leaching (concentration x infiltrated water) did not change the final ranking of the cropping systems in terms of NO_3^- leaching, except in Yonne (Fig. 4b). Indeed, OF5 contributed to a higher leaching (37 kg NO_3-N ha^{-1} year^{-1}) than OF4 in Oise (13 kg NO_3-N ha^{-1} year^{-1}), despite their similar soil solution concentrations, due to its higher Wi in 2012–2013, e.g. in Yonne (239 m) than in Oise (209 mm). In S&M or Oise,

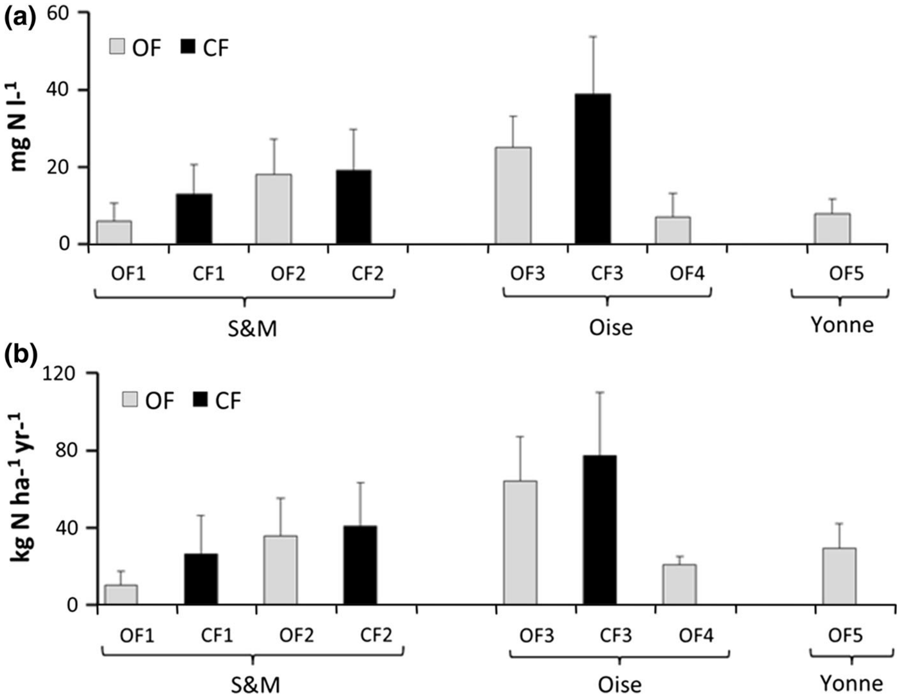

Fig. 4 Sub-root concentrations (**a**) and leaching (**b**) from the different cropping systems in each area (S&M, Oise, Yonne) with OF in *grey* and CF systems in *black*. Standard deviations represent the range of variations within each rotation

leaching for full rotations, were lower, for OF (13–37 kg NO_3-N ha^{-1} year^{-1}) than for CF (32–77 kg NO_3-N ha^{-1} year^{-1}) but the difference is not significant.

Relation between N total inputs, harvest and N leaching

Considering the entire span of the rotations studied, the yearly average total N input, including total BNF over the rotation, was 20 % higher in CF (211 kg N ha^{-1} year^{-1}) than in OF (167 kg N ha^{-1} year^{-1}). Moreover, the total input was distributed differently between total BNF and exogenous fertilisation for OF and CF. Mean total BNF integrated over the whole rotations in OF and CF systems was 132 and 38 kg N ha^{-1} year^{-1}, respectively, whereas the exogenous fertilisation in OF and CF was conversely 23 kg N ha^{-1} year^{-1} and 160 kg N ha^{-1} year^{-1}, respectively. As a result, the soil solution concentrations tended to be lower for the OFs (13 ± 6 mg N l^{-1}) than for the CFs (24 ± 10 mg N l^{-1}). However, a gradient of soil solution concentrations exists in both systems.

The mean harvest was 24 % higher in CF (169 kg N ha^{-1}) than in OF (129 kg N ha^{-1}), with 20 % more total inputs. Thus the means N use efficiency (i.e. the ratio of harvested N on total N inputs) is similar in OF and CF, 78 and 81 % respectively. Looking at leaching per unit kg N harvested (yield-scaled leaching), OF systems still show slightly lower values than CF, ranging from 0.1 to 0.3 kg N kg^{-1} N and 0.2–0.5 kg N kg^{-1} N respectively (Table 3).

Discussion

Experimental design and advantages of studying commercial farms

Herein we compared alternative systems, each with its own logic but having enough features in common for a useful comparison. Our sample of cropping systems is predominated by organic systems because of the lack of available references for OF, comparing with CF. We found a broad diversity of practices existing in both OF and CF, with a wide range of leaching values.

Classical agronomical research is often conducted in factorial experiments deconstructing a complex system in order to isolate specific components and identify cause-and-effect relationships. Factorial experiments are particularly relevant in agronomical studies when they are conducted in the absence of an

Table 3 Yearly means of N inputs: N exogenous (fertilisers), total BNF and atmospheric deposition, harvest and N losses: sub-root concentrations, leaching per ha or per protein for OF and CF rotations studied in S&M, Oise and Yonne

Farms	N exogenous input (kg N ha^{-1} year^{-1})	BNF input previous crop (kg N ha^{-1} year^{-1})	Atmospheric deposition kg N ha^{-1} year^{-1}	Mean N harvest (% N from legumes) (kg N ha^{-1} year^{-1})	Soil solution concentration (mg N l^{-1})	Leaching per ha (kg N ha^{-1} year^{-1})	Leaching per N harvested (kg N kg^{-1} N year^{-1})
CF1	119	10	12	198 (56 %)	13	32	0.2
CF2	194	154	12	143 (0 %)	19	51	0.3
CF3	168	13	12	166 (0 %)	39	77	0.5
OF1	26	293	12	153 (77 %)	6	14	0.1
OF2	66	152	12	122 (42 %)	18	37	0.3
OF3	16	127	12	162 (64 %)	25	50	0.3
OF4	5	63	12	77 (32 %)	7	13	0.2
OF5	0	207	12	130 (79 %)	8	37	0.3

ecosystem context. However, studies of intact agro-ecosystems have established the importance of both long-term and landscape-scale effects, especially in assessing alternative and innovative practices used by farmers on watersheds (Sharpley et al. 1994; Nguyen et al. 1995).

Effect of climate and soil on leaching variability

The three pedo-climatic regions covered in our study (Yonne, S&M and Oise) are representative of the substantial variability in water infiltration in the Seine Basin (Ledoux et al. 2007). It is well known that the amount of infiltrated water is a major determining factor of leaching, and depends on rainfall and soil texture. In this study, Yonne is the most affected by leaching, due to high Wi and the highest sand percentage. In our study, as in many others, the highest leaching is related to the highest sand percentage (Nieder et al. 1995; Beaudoin et al. 2005), for both conventional and organic systems (Hansen et al. 2000).

Key management practices controlling N leaching

Variations in soil solution N concentrations over the rotations are associated with crop type. We conclude here that leaching values have the same ranking in relation to crops (legumes < crops with CC < winter crops < crops after legumes) as those measured in organic systems in Norway, with legumes (6 kg N ha^{-1}), undersown grain (13 kg N ha^{-1}), vegetables (17 kg N ha^{-1}), grain without undersown legumes (30 kg N ha^{-1}) and potatoes (33 kg N ha^{-1}) (Solberg 1995). The soil cover during winter, which ensures incorporation of SMN, as well as the period of implantation and the root depth of the crop explain this ranking.

In this study, we observe similar and very low soil solution concentrations (5.5 mg NO_3-N l^{-1}) during the second year of alfalfa although net BNF from the previous year of alfalfa is high (between 137 and 170 kg N ha^{-1}). This can be explained by the fact that alfalfa is very effective at accessing deep-leached NO_3^- (1 m below the soil surface) and rhizodeposition very low during the crop development in winter. After alfalfa ploughing, the amount of net BNF has an effect on soil solution concentrations, with mean concentrations 15 ± 2 mg N l^{-1} for N inputs

102–190 kg N ha^{-1}. Differences of around 30 % of the soil solution concentrations (from 13 to 17 mg N 1^{-1}) can be explained by differences in net BNF, depending on biomass yields (9 t ha^{-1} with 2 cuts vs. 13 t ha^{-1} with 3 cuts). Such an increased input leads to a 66 % increase in wheat yields (from 3 to 5 t ha^{-1}). As a whole, the incorporation of alfalfa into the soil did not lead to a massive loss of NO_3^-, probably due to its low rate of mineralisation. However we would recommend alfalfa exportation and its date of destruction should be as late as possible (e.g., spring or late winter), in order to reduce NO_3^- leaching (Francis et al. 1992). Moreover, for the two following years after alfalfa ploughing, soil should remain covered during fall-winter season with CC or winter cereal.

The importance of catch crops

Imposed by the Nitrate Directive (91/676/EEC), in 2012, the use of CCs should have reached 100 % of the bare soil surface, however some organic fields are exempted due to late spiked chain harrows in order to reduce weeds propagation. In this study, the mixed-seed CCs reduce N contamination of 60 %, in accordance with most studies which conclude in a positive effect of CCs on NO_3^- leaching, e.g., reductions from 38 to 70 % for mustard (Hooker et al. 2008), from 50 to 79 % for radish (Justes et al. 1999), of 71 % for chicory and of 67 % for ryegrass (Sapkota et al. 2012). However, very few studies have discussed the effect of mixed-seed CCs, which has become more frequent, especially in organic agriculture, showing greater benefits on crop biomass and NO_3^- leaching reduction, than with a single seed (Rinnofner et al. 2008). Moreover some farmers may wish to substitute CCs with green manure (CF2), which is a matter of particular concern. Indeed the long-term effect of green manures would increase the risk of leaching (Möller et al. 2008) and even for CCs such as mustard, an increase from 9 to 26 kg N ha^{-1} - year^{-1} is shown by Constantin et al. (2011) based on 13 years of model simulations. As for legumes, in order to minimise the risk of N leaching, several studies suggest incorporating green manure in spring rather than in autumn (Känkänen et al. 2008), but with a possible negative effect on the yield that needs to be examined, as for ryegrass incorporation (Aronsson et al. 2007). Results are still lacking for irrevocable recommendations and further studies on NO_3^- leaching are needed in order to optimise N management in organic rotations.

Room for improvement in conventional and organic systems

In conventional systems, a variety of N management methods are also possible, such as no-tillage, low N input and CCs… Studies on no-tillage systems have shown a decrease of NO_3^- leaching by a factor of two to four (Angle et al. 1993; Drury et al. 1993). However, as observe on CF2, the association of exogenous N inputs and BNF in a no-tillage system can still lead to substantial NO_3^- leaching. Moreover, the values obtain on CF3 (18–46 mg NO_3-N l^{-1}), are close to the measurements obtain for experimental trials in North of France in the 1990s (between 18 and 33.5 mg NO_3-N l^{-1}: Arlot and Zimmer 1990; Machet and Mary 1990; Chapot 1990; Denys 1990). In contrast, to protect a drinking water spring, the association of low N input and CCs has reduced the N contamination from 16 to 9 mg NO_3-N l^{-1} (Beaudoin et al. 2005).

In the organic cropping systems studied, most organic fertilisers are applied in fall, due to rainy conditions in spring (especially in S&M), preventing field work with farm machines. Together with the period of application, the types of organic fertilisers used can control soil solution concentrations and leaching during the drainage period. For example, poultry manure (OF2) and vinasse (OF1, OF3, OF4) are highly mineralised in contrast to manure, which can, however, lead to a long-term impact (Bergström and Kirchmann 1999). On the other hand, we have shown that alfalfa N management can be improved, especially by exporting part of the harvest or by ploughing it as late as possible within the drainage period.

This study shows that there is room for progress in both systems regarding N management to reconcile good water quality and sustainable agriculture in a single area.

Conclusion

For CF and OF, substantial variations in soil solution N concentrations and N leaching stem from management practices, in terms of fertiliser application timing, quantity and quality, e.g., the combination of different sources of N such as legumes in green manure, as well as mineral and organic fertiliser. The soil solution concentrations were proportional to the amount of organic fertilisers applied, however the relationship is no longer valid in presence of catch crops, horse manure or for crops after legumes. Appropriate N management is an objective to ensure crop growth and to limit nitrogen leaching. In literature, most studies on NO_3^- leaching from organic systems do not include alfalfa (2 or 3 years), as we experiment here in the Parisian basin. Furthermore, reported results generally concern short rotations (4 years), whereas they are rather long in the Seine Basin (7 years). We have shown that in addition to agricultural practices and N management, various other factors such as soil properties and climate contribute to NO_3^- leaching, so that no significant difference between organic and conventional systems in terms of flux of N leaching has been evidenced to date, but a gradient of leaching between the terms of the rotations clearly appears (alfalfa < crops with CC < legumes < crops without fertilisation < crops fertilised in fall or after legumes). In terms of soil solution concentrations of infiltrating water, however, organic cropping systems in a given pedo-climatic context show better performance than their conventional counterparts. When yield-scaled, leaching appear to be in a similar range for both OF and CF. At last, more studies are needed at the system scale, to improve N management in order to reduce NO_3^- concentration in infiltrating water and thus protect the quality of the water resource.

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