

Managing residues and nitrogen in intensive cropping systems. New understanding for efficient recovery by crops.

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Abstract

In intensive agriculture regions the use of large amounts of N fertiliser results in a progressive increase of losses in the N balance and therefore to deleterious effects on the environment. Nowadays, farmers are constrained by EU and national directives, to adopt a more cautious N fertilisation strategy; it might increase the frequency that crops will experience N deficiency. A better understanding of crop-nutrient interactions is necessary for maximising N uptake capacity of crops and for optimising the N use efficiency by crops. The theory developed in this paper supports the hypothesis that crop N uptake is co-regulated by (i) the mineral soil N concentration and (ii) the potential growth rate of the crop. The agronomic nitrogen efficiency can be split into two components (i) the N uptake efficiency, and (ii) the N conversion efficiency. These two efficiencies increase with the rate and duration of crop growth, but with some differences between species when they are compared at same crop mass. A better understanding of the mineralisation-immobilisation turn-over of N in the soil is needed for predicting soil N supply and the N recovery from crop residues. Fertiliser recovery is the result of the balance between crop N uptake and N-immobilisation by microbial processes. Therefore, the concept of "soil N supply" to a crop cannot be longer considered as a function of soil and climate conditions only, but should be considered also take into account the interactions between plant and soil processes.

Improving crop and nutrient management is a prerequisite for optimising crop production and minimizing environmental risks due to N losses. The optimum rate of N application cannot simply be determined by the balance-sheet method. The uncertainties in the prediction of crop N demand require the use of crop N status indicators. Management of crop residues by different soil tillage and the introduction of cover crops within arable crop rotation as a mean to control soil N availability and nitrate leaching are discussed. The need of research on management of N at various scales, from the field to the landscape, in space and time is also emphasised.

Media summary

Crop N uptake capacity and N use efficiency are controlled by crop growth rate itself. Soil N supply and fertiliser recovery depends on the competition between plant and microbial processes

Keywords

Nitrogen demand, mineralisation, immobilisation, residues, leaching

Introduction

In intensive agriculture production systems, high application rates of N-fertilisers, produced at the expense of high fossil energy cost, have enabled the huge expansion of the world population during the last five decades, while at the same time in more extensive areas N deficiency continues to limit agriculture production. The challenges for world agriculture today is (i) to continue to maintain or to increase its productivity to meet the food demand of the increasing global human population, but also (ii) to avoid the degradation of the global environment by preservation of water quality, by reducing emission of greenhouse and trace gases into the atmosphere, and by saving fossil energy. The question is: are the improvement of crop productivity and preservation of environment reconcilable objectives?

For many years in intensive agriculture regions, the low price of N fertilisers compared to harvested products has encouraged farmers to apply more N than required for maximising benefits. The net result has been a progressive increase in the N balance and an elevated risk of NO₃⁻ leaching (Addiscott et al., 1991). This effect, combined with the long residence time of N in the soil water, and within soil organic matter suggest that the pollution of ground water that we observe today in many regions of industrialized countries could well be the delayed consequence of the intensification of cropping systems one or two decades ago (Mariotti, 1997). However, adoption of a more cautious N fertilisation strategy might

increase the frequency of situations where crops experience temporary N deficiency and the risk of a reduced yield and/or produce quality. Therefore, optimising crop production with the goal of reducing environmental hazards requires improved management of nitrogen use by crops (Cassman *et al.* 2003). We need to improve our understanding of the regulatory mechanisms by which nitrogen is absorbed and utilised for growth and grain development. We also need a better understanding of soil microbial processes and the interaction between C and N cycles in order to optimise recycling in residue, soil organic matter management and improve the prediction of soil N supply. This new system-based knowledge should help us to devise practical solutions to improve the recovery of nutrients by crops at the level of individual crops and crop rotations (temporal scale) and at the level of a field or landscape (spatial scale) with emphasis on the scale at which the environmental hazards have to be faced (Neeteson *et al.* 2002). In the first part we develop a general approach to determine crop N demand and the efficiency of recovery of both soil N and fertiliser N. The second part deals with the dynamics of N in soil and the recycling of crop residues and the third part presents and discusses the prospects for improving management for N fertilisation, crop residues, cover crops, at the field level but also at higher scales of space and time.

Dynamics of crop N uptake and N use efficiency by crops

Crop growth and N requirement

Crop N demand can be defined as the result of maximum crop mass and the optimal plant N concentration at harvest. Maximum crop mass at harvest results from the **potential crop growth rate** over the **crop growth duration**. The daily crop N demand is the quantity of N required each day to maintain the growth rate of the crop at its potential over a given period. This dynamic approach has been used extensively on forage grasses and alfalfa (Lemaire and Salette, 1984, Lemaire *et al.*, 1985) and further developed on annual crops (Justes *et al.*, 1994; Plénet and Lemaire, 1999). All these studies bring very convergent results that have been put together within a consistent theory (Greenwood *et al.*, 1990; Lemaire and Gastal, 1997; Gastal and Lemaire, 2002): (i) the **actual plant N-concentration (%N)** in a crop stand declines even under favourable N supply conditions. The decline of N-concentration versus shoot biomass (W) can be described by a negative power function:

$$\%N = a(W)^{-b} \quad (1)$$

Therefore, cumulative N uptake (N_U) is related to crop mass as follows:

$$N_U = a(W)^{1-b} \quad (2)$$

The value of coefficient a represents the quantity of N in crop when $W=1 \text{ t.ha}^{-1}$, the coefficient $1-b$ being the ratio between the relative N uptake rate and the relative crop growth rate. (ii) the **critical plant N concentration (%N_c)**, i.e. the minimum plant N-concentration needed to reach the maximum growth rate, can be calculated using the same type of equation. It defines the **critical N uptake (N_{UC})**, i.e. the **N requirement** allowing maximum crop growth, as follows:

$$N_{UC} = \alpha W^{1-\beta} \quad (3)$$

The daily N requirement of a crop to sustain its maximum growth rate is then:

$$\frac{dN_{UC}}{dt} = \frac{dN_{UC}}{dW} \cdot \frac{dW}{dt} = \alpha(1-\beta)W^{-\beta} \left(\frac{dW}{dt} \right)_{\max} \quad (4)$$

Parameters α and β have been established precisely for different crops. As shown in Table 1, α does not change very much among a wide range of species, while β allows the distinction between C3 and C4 species. (iii) a **Nitrogen Nutrition Index (NNI)** has been proposed on this basis to define the N status of the plant. It is defined as the ratio between the actual plant N concentration (%N) and the critical plant N concentration (%N_c) corresponding to the same biomass of the crop. Any N deficiency experienced by a crop can be expressed by its magnitude through the lower value of NNI reached by the crop, and the duration of the period where $NNI < 1$ (Lemaire and Gastal, 1997). Both parameters are useful since linear relationships have been found between the product $NNI \times$ "duration of crop N

Table 1: Values of parameter of the critical N uptake curve: $Nuc = \alpha(W)^{1-\beta}$ (Equation 3) for different C3 and C4 species (α in kg N.ha⁻¹ for W in t.ha⁻¹): ⁽¹⁾ Lemaire and Salette 1984; ⁽²⁾ Lemaire et al. 1986; ⁽³⁾ Ney et al. 1997; ⁽⁴⁾ Justes et al. 1994; ⁽⁵⁾ Colnenne et al. 1998; ⁽⁶⁾ Tei et al. 2002; ⁽⁷⁾ Plénet and Cruz 1997; ⁽⁸⁾ Plénet and Lemaire 1999.

Species	α	β
⁽¹⁾ Grasses C3	48	0.32
⁽²⁾ Lucerne C3	48	0.33
⁽³⁾ Pea C3	51	0.32
⁽⁴⁾ Wheat C3	53	0.44
⁽⁵⁾ Rape C3	45	0.25
⁽⁶⁾ Tomato C3	45	0.33
⁽⁷⁾ Maize C4	34	0.37
⁽⁸⁾ Sorghum C4	39	0.39

deficiency” and the ratio between actual and potential biomass or yield (Plénet and Cruz, 1997; Jeuffroy and Recous, 1999). Lemaire and Meynard (1997) have shown that such a diagnostic tool is relevant for estimating the actual N status in different conditions and especially when availability of N is affected by drought. Different other N indices has been proposed by various authors (Angus and Moncur 1985; Porter, 1993; Hunt and Pararajasingham, 1995; Williams et al. 1989) and introduced in crop models for estimating crop N deficiency. Most of these N indices are based on empirical relationships between “critical N concentration” (or a range between minimum and maximum plant N concentrations) and time or “cumulative degree-days” or phenological stages along the crop cycle. The NNI method appears to have a more general application; it could allow the calibration of more operating diagnostic tools in field such as chlorophyll-meter (Peng et al. 1996).

Control and regulation of crop N uptake

The theory presented above supposes a feed-back control of crop N uptake by the crop growth rate as suggested by equation (2). As reviewed by Lemaire and Millard (1999), plant N uptake, whatever the source of N supply, nitrate or ammonium absorption or N₂ fixation, is down-regulated by shoot N and C signaling. A positive signal comes from C supply, and a negative one comes from organic N re-circulated from shoot to root through the phloem, the latter acting as a N satiety signal (Lejay et al., 1999; Forde, 2002). Nevertheless it has been reported in hydroponic-studies that absorption of NO₃⁻ depends on its concentration in root medium and is well described as a process with multiphase kinetics. That implies at least two groups of transport systems, with a low and high affinity for nitrate (Glass et al., 2002). These two systems seem to apply also in the field as shown by Devienne-Baret et al. (2000). These authors have proposed a formula accounting for co-regulation of crop N uptake by soil NO₃⁻ concentration and plant growth rate. They derived the following equation for the daily N uptake rate of a crop:

$$\frac{dN_U}{dt} = (1-b)N_C \left(\frac{dW}{dt} \right)_{\max} \left[V_H \frac{C}{K_H + C} + V_L \frac{C}{K_L + C} \right] \quad (5)$$

where (V_H, K_H) and (V_L, K_L) are the parameters of Michaelis-Menten formula describing the high and low affinity transport systems for nitrate, respectively; C is the actual NO₃⁻ concentration in the soil solution; N_C is the critical N concentration for the biomass W .

We propose to analyse the crop response to N supply through a series of “N uptake – Biomass” trajectories, as shown in Figure 1 Each of these trajectories is deduced from equation (5) for a constant value of C . Among these trajectories, we have represented (c) the **critical N uptake** as defined above, (m) the **maximum N uptake** which should correspond to the saturation of the root absorption capacity of the crop, (s) a **non-fertilised N uptake** which represents a highly limiting soil N supply condition, and (f) a **sub-optimal fertilised N uptake** trajectory. Each trajectory represents a virtually constant N supply situation, whereas a real crop in a changing environment can move from one trajectory to another particularly due to changes in soil nitrate concentration (C). The crop response to fertiliser additions is illustrated by the two dotted lines $A_s A_f A_c A_m$ or $B_s B_f B_c B_m$. A and B can represent either (i) a time interval, (ii) two different genotypes at the same time having different growth potential, or (iii) two different environments (i.e. temperature) allowing different potential growth rate. So whatever the cause of the variation in crop mass, growth duration, environment or genotype, provided that N supply remains constant, any increase in crop mass (dW) is accompanied by a corresponding increase in crop N uptake (dN_U) according to equation (5).

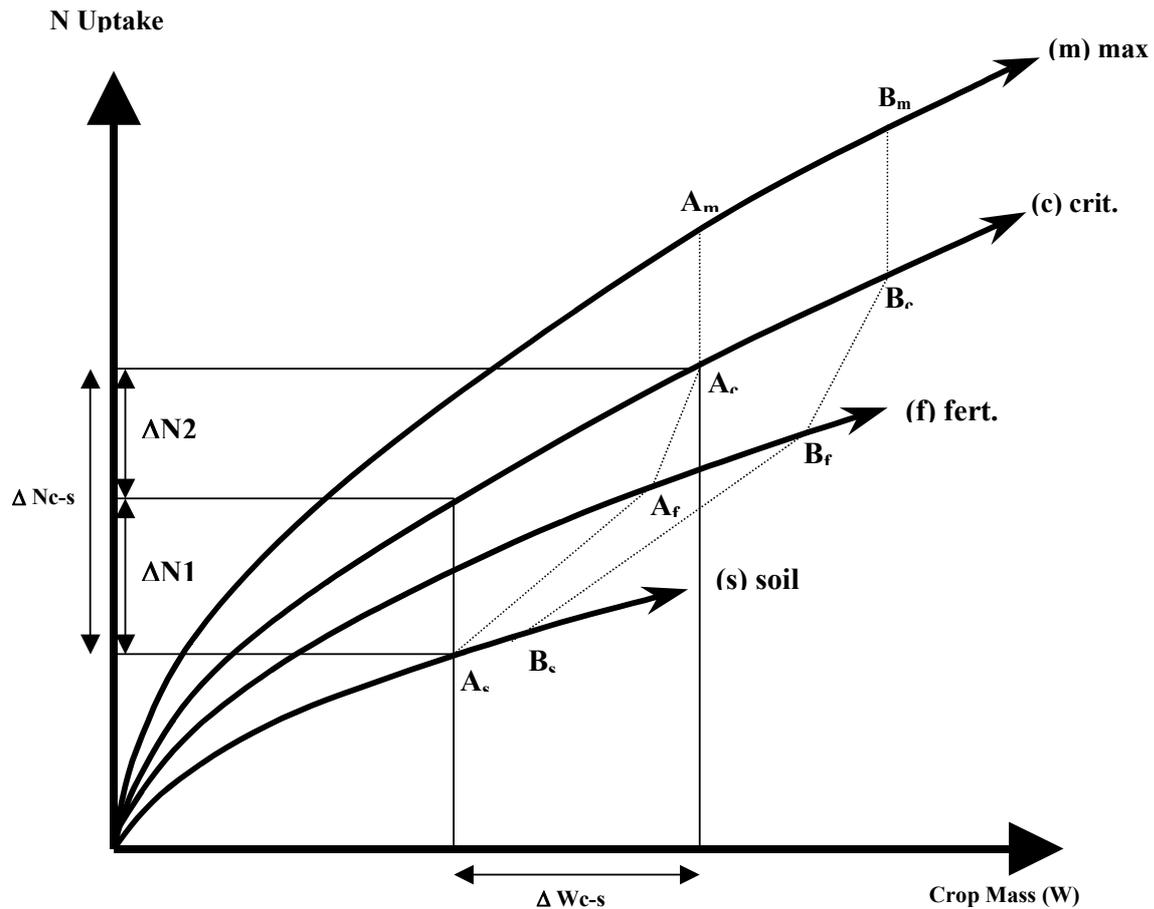


Figure 1: N uptake - Crop mass trajectories for different steady states N supply: (c) critical N uptake, (m) maximum N uptake, (s) non-fertilized and, (f) sub-ptimal N application. (A) and (B) represent either (i) two growth stages of the same crop, or (ii) two crops having different growth rate, or (iii) an environmental effect. The dotted lines represent the responses curves to increased N supply at a given time.

This graph of Figure 1 and equations (5) provide a framework for analysing the genotypic variability of crop N uptake capacity across a wide range of N supply. As shown in Table 1, the **critical trajectory** seems to be similar among species of the same metabolic group, so the intra-specific variability in N uptake capacity must be very restricted for near-optimum N supply conditions, when genotypes are compared at similar growth potential. Nevertheless, the variability in **maximum uptake trajectory** among species or genotypes has never been analysed. Such variability could confer to some species or genotypes the ability to store greater quantity of N during periods of large N supply. The **non-fertilized trajectory** is determined by both the capacity of the soil to provide N for plant under an available form (value of C) and also the ability of plant root system to capture this endogenous N as rapidly as possible (value of V_H and K_H).

Figure 2 shows N_U-W trajectories in the case of two perennial grass species growing under the same conditions. At high rates of N application, the two species followed a similar trajectory, close to the critical one. At low N application, cocksfoot had a higher trajectory than tall fescue, indicating that its N uptake capacity was higher despite a similar crop growth rate. Similar data for maize and sorghum crops are presented in Figure 3. At high N application rates, maize followed the critical trajectory, while sorghum accumulated N far above the critical curve. The overall N uptake of the two crops at the end of the growing period was approximately the same. Despite its lower potential growth than maize, sorghum can accumulate similar quantities of N when soil supply is high. At low N application, sorghum was able to take up more N than maize. These examples demonstrate that large differences can exist between species in their capacity to capture N at low concentration in soil. The difference for N uptake at high N supply should depend on both the growth potential of crop species and its ability to

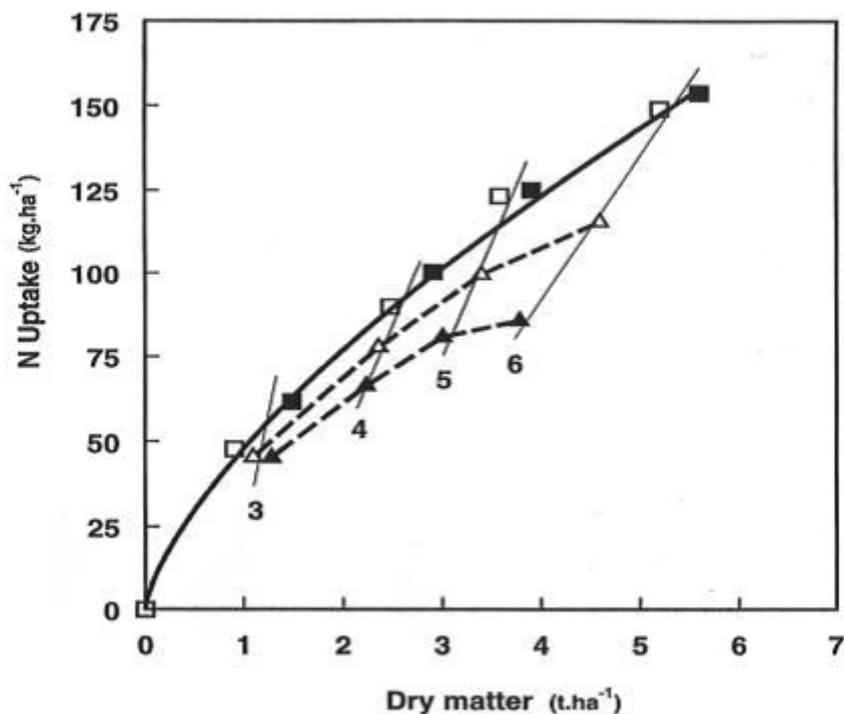


Figure 2: Dynamics of N uptake in relation to dry matter accumulation for tall fescue (*dark symbols*) and cocksfoot (*open symbols*) during summer regrowth with irrigation and after an application of 60 (*triangles*) or 120 (*squares*) kg N ha⁻¹. The line represent the critical N uptake curve: $N = 48 (W)^{0.68}$ for grasses (Table 1). The numerals refer to weeks of regrowth after cutting.

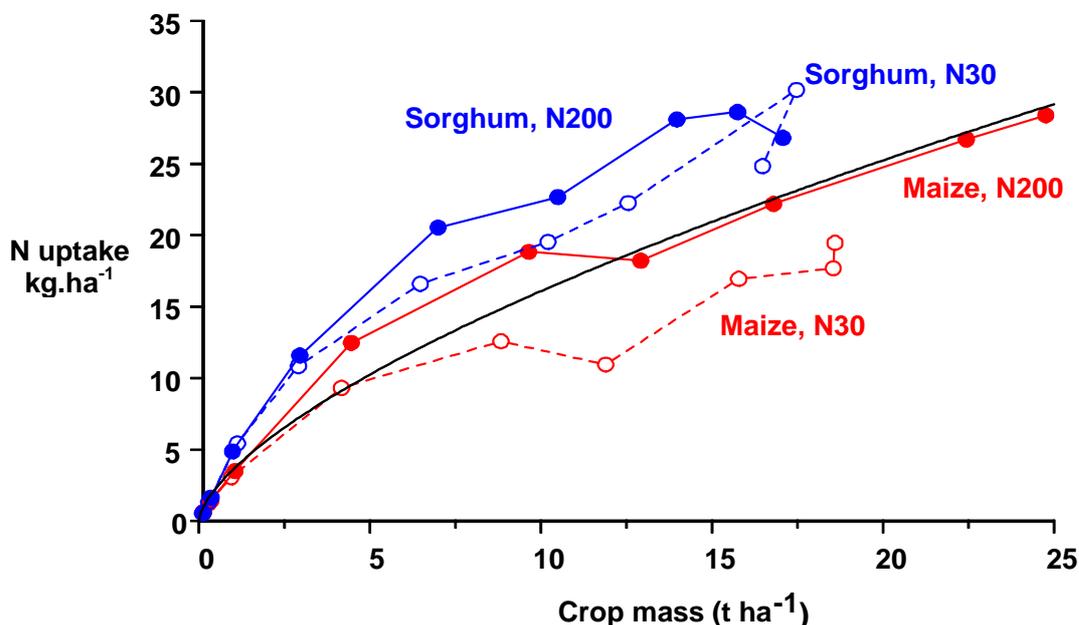


Figure 3: Comparison of N uptake-Crop mass trajectories between maize and sorghum cultivated at two contrasting N application rates (after Lemaire *et al.* 1996) and critical N uptake curve for both species: $N = 36(W)^{0.62}$ (see Table 1).

store 'luxury' N (extra N above the critical level). Genotypic variability in N uptake capacity at different levels of N supply has been investigated on species such as rice (Borell *et al.*, 1998), wheat (Le Gouis *et al.*, 2000) and maize (Bertin and Gallais, 2001). Moreover, there have been studies on varieties showing more N uptake with modern cultivars than with the older ones (Brancourt-Hulmel, *et al.* 2003, Ortiz Monasterios *et al.* (1997). So, modern cultivars have a higher N uptake capacity because their productivity has been improved, what corresponds to a shift from A to B on the graph of Figure 1. It would be also interesting to get an improvement of the **intrinsic N uptake capacity** of the cultivars, i.e.

the N uptake capacity at similar crop mass. Figure 2 and 3 show that such variability exists at inter-specific level: so, it would be possible to investigate the intra-specific variability of the intrinsic N uptake capacity. Five hypotheses can be formulated to explain such a possible variability:

(i) a preferential allocation of N to shoots. Recent studies indicate that plant below-ground N may represent 30-60% of the total N for legumes at pod filling stage and around 35% for cereals at grain filling stage (McNeil et al. 1997; Peoples and Baldock 2001, Kahn et al. 2002). So some variation in shoot vs root allocation of N could explain differences in shoot N recovery between species. As pointed out by these authors, methods for estimating shoot N allocation without bias have to be implemented more intensively in order to compare properly N balances between different crop species and different cropping systems; (ii) a denser root system which would allow a more complete and rapid exhaustion of soil mineral N; (iii) a high morphological plasticity in root growth would allow the plant to more efficiently exploit local high concentrations of mineral N in soils (Zhang and Forde, 2000). Nevertheless this effect seems to be relevant only for plant-to-plant competition, not for the whole crop (Hodge *et al.*, 1999); (iv) a more efficient root system (e.g. with a high affinity absorption and/or higher density) would favour the plant in the competition with soil microbes for taking up mineral N released by gross mineralisation; (v) a variation in quality or quantity of C exudates which could change the gross N fluxes in the rhizosphere (Paterson, 2003). These hypotheses are not exclusive and could act together within the soil-plant-microbes system as discussed below. They provide keys for interpreting the genotype-environment interactions, and relevant objectives for functional genomic research programmes.

N efficiency in crops

To agronomists, Nitrogen Efficiency (*NE*) of a crop represents its capacity to produce a supplement of yield (*dY*) for each added unit of fertiliser N (*dN_F*), i.e. the derivative of the yield response curve versus N application rate. As this response curve is asymptotic, *NE* declines with *N_F*. *NE* can be calculated not only for yield but also for crop mass, harvest index or protein content (Borell *et al.*, 1998). In this paper, we will analyse *NE* only for crop mass (*W*). In fact most agronomists use the average efficiency that corresponds to the integration of *NE* from the application rate 0 to the application rate *N_F*. This average efficiency also decreases with the level of application rate.

From an ecophysiological or plant breeding point of view, such a general criterion does not permit a mechanistic analysis of the physiological traits controlling *NE* because plant responds to the total N supply (*N_T*) that includes fertiliser application and endogenous N supply. A more powerful method of analysis of *NE* implies a distinction between the response of the crop to N application (*S*) in term of N uptake and the response of the crop in term of biomass to the increased N uptake as proposed by van Keulen and Stol (1991):

$$NE = \frac{dN_U}{dS} \cdot \frac{dW}{dN_U} \quad (6)$$

The first term of this equation is the efficiency of N accumulation (*NAE*) and the second one is the efficiency of conversion of plant N into crop mass or yield (*NCE*). The response curve of N uptake to N supply is asymptotic, and then *NAE* declines with any increase in either soil N supply or N application rate, making comparison of crops at similar N application rate dependent on soil N supply. Moreover, because N uptake for a given N supply condition depends on crop growth rate, as shown in Equation (7), then differences in *NAE* should appear between species having different potential growth rate even if they are compared at same N application rate and under the same soil N supply. So when comparing *NE* and *NAE* between species or genotypes the increase in *NAE* with crop growth potential is trivial. Therefore it is interesting to consider the variability of intrinsic *NAE*, i.e. at similar crop mass.

The *NCE* can be analysed by two different approaches. The first one corresponds to the N productivity concept (*NP*) as defined in plant ecology (Ågren, 1985). It represents the efficiency at which each additional N is associated with each additional dry mass (or carbon) during plant growth at steady state N supply condition. So *NP* can be analysed along each trajectory of Figure 1, according to the reciprocal of the derivative of equation (2):

$$NP = \frac{dW}{dN_U} = \frac{W^b}{a(1-b)} \quad (7)$$

NP increases with crop biomass and decreases with *a*, i.e. the level of N supply. The comparison of *NP* between plants differing in growth rates is trivial because big plants should have higher *NP* than small

ones. Plants having a higher *NAE* in a given N supply condition should have a greater *a* value and then a lower *NP* than plants with lower *NAE* leading to a negative relationships between *NCE* and *NAE* when comparing genotypes without any clear identification of the variation in *NP* and *NAE* due to variation in *W* as shown in Figures 2 and 3.

The second approach for studying *NCE* is agronomic. *NCE* is defined as the increase in crop mass (ΔW) or crop yield (ΔY) per unit of extra N uptake (ΔN_U), when the differences in N uptake are measured at the same time and are obtained through different N supply conditions. *NCE* and *NP* are in fact two ways of expressing the efficiency at which the plant uses N to accumulate biomass: the first one (*NCE*) considers plant response to variations in N supply, while the second (*NP*) deals with plant growth under constant N supply condition. These two approaches are related to each other, as shown on Figure 1. The decrease in *NCE* along the response curve $A_s, A_f, A_c...$ (dotted line) is the result of two opposite effects: (i) a decrease in *NP* associated with the increased plant N status (effect of *a*), and (ii) an increase in *NP* due to the increased crop mass as shown by equation 7. In consequence, genotypes having a higher potential growth rate should have a higher Nitrogen Conversion Efficiency than slow growing ones.

The main conclusion is that the efficiency of apparent N recovery (*NAE*) and N conversion (*NCE*) by crops both increase with the potential of dry matter accumulation of the species and genotype. Both efficiencies decrease with increasing N supply. From a breeding point of view, the general objective of increasing crop mass accumulation should be also beneficial in terms of N efficiency. It would be interesting to investigate the genotypic variability at the intra-specific level and breed for high “intrinsic” *NAE*. Such a crop could be grown with less fertiliser-N, thus reducing the risk for N losses. The capacity of genotypes to have high *NAE* at high N supply should be also investigated either for their capacity to store higher quantity of N within leaves and stems for further efficient use for grain filling, or either for a higher post-anthesis N-uptake capacity. These crops could absorb excess mineral N in soil more rapidly preventing potential N losses. Explicit breeding for high *NCE* does not seem necessary because high *NCE* is directly associated with high potential dry matter accumulation, and as a consequence breeding progress in a number of crops has unwittingly raised *NCE*. Nevertheless, studies on grain filling processes in relation to leaf senescence and N relocation are also necessary (Borell *et al.*, 1997; Borrell *et al.* 2000), but such an analysis is beyond the scope of the current paper and would require a specific review.

N dynamics in soil and recycling in crop residue

Mineralisation-immobilisation turnover in soil and soil N supply

The availability of ammonium and nitrate in soils results from the competition between several opposing soil processes: (i) the gross immobilisation that corresponds to the assimilation of inorganic nitrogen by soil heterotrophic micro-organisms, the growth and activity of which depend on the availability of organic C; (ii) the gross mineralisation that corresponds to the release of NH_4^+ into the soil solution during the decomposition of soil organic matter (SOM); (iii) the nitrification of NH_4^+ to NO_3^- by the nitrifying micro-flora. Mineralisation and immobilisation of N occur simultaneously, therefore N is continually transferred within the soil from organic to inorganic forms and *vice versa* through the Mineralisation-Immobilisation Turnover (MIT). The ^{15}N isotope dilution/enrichment techniques are the only tools for quantifying separately the two opposite gross processes, and also nitrification (Murphy *et al.*, 2003).

Gross mineralisation which corresponds to the oxidation of SOM by endocellular and exocellular enzymes from a wide range of non-specific micro-organisms is determined by soil properties such as clay and CaCO_3 content, pH and SOM content. Gross immobilisation is mainly driven by the availability of easily decomposable organic C. Nitrification is highly dependent on soil pH. Therefore the three processes do not respond to the same soil factors. They also have different sensitivity to temperature and soil water content.

Like the N produced by mineralisation of native soil organic matter, N added as mineral fertilizer is involved in this mineralisation-immobilisation turnover. The immobilisation rate of added N is determined by the immobilisation capacity of soil which depends on its C availability. The main sources of C in cropped soils are root systems through root litter, rhizodeposition and exudation, plus other crop residues that may be returned to the soil. Due to the high demand of the decomposing microflora for N, the rate of decomposition of the residues is often limited by the availability of mineral N even in situation with frequent addition of mineral N (Mary *et al.*, 1996). In turn, this may result in the accumulation of

undecomposed debris, creating a potential for N immobilisation when N will become available (e.g. after fertiliser application). The amount of immobilised N per unit of decomposed C decreases when N becomes limiting. Jensen and Ambus (2000) reported that 13 kg N were immobilised per ton of C under low N availability *versus* 32 kg N per ton of C under high N availability, in similar conditions. The amount of N (either from soil or from fertilizer) which is immobilised due to heterotrophic microbial activity is therefore determined both by the availability of C and N in soil. Any extra N (added by fertilizer) can contribute to the decomposition of residues in soil. C and N dynamics are closely linked in soil and this interaction is the key for understanding both the short and the long-term evolution of N in soils.

How is MIT influenced by crop type and management? The first way may be through the crop root system. There have been many attempts to quantify the possible direct effects (e.g. C exudation) and indirect effects (e.g. depletion of mineral N by absorption) of plant growth on soil heterotrophic microflora and to understand how their opposite and concomitant effects drives actually the gross immobilisation and mineralisation and determine the resulting net mineralisation. The difficulties of using the isotope ^{15}N method at the mm-scale in the root rhizosphere of a living plant have made the challenge quite impossible until now. Mary and Recous (1994) simulated the order of magnitude of gross mineralisation and immobilisation fluxes in a continuous wheat rotation with the usual amount of organic restitution in Northern Europe. Using data from the literature, obtained under laboratory conditions, they estimated the potential N immobilisation associated to the decomposition of wheat straw, root litter and root exudates (mucilage) to be 120, 20 and 150 kg N ha⁻¹ on an annual basis, respectively. In this situation net mineralisation, gross immobilisation and gross mineralisation were in the ratio 1:2:3. Tlustos et al. (1998) found that permanent grassland soil exhibited MIT turnover rates 30 times higher than those in arable soil, although net N mineralisation rates were similar between systems. Studies using ^{15}N tracing of fertilizer on grasslands also showed that the fertilizer -N disappeared very quickly from soil due to the intensity of microbial immobilisation, and was recovered later by the plant, in significant proportion, thanks to the fast microbial turnover (i.e. high rate of gross mineralisation). Therefore the type of crop and the conditions of growth of a crop - that affect the nature and amount of rhizodeposits and the associated rhizosphere microflora- can alter significantly the soil N supply, either by modifying the gross mineralisation or the gross immobilisation or both.

The second way by which a crop interacts with the soil N cycle is through the above-ground residues that return to soil by senescence or after harvesting. The rate of decomposition of crop residues and the net effect on soil N dynamics are strongly related to the amount, the biochemical composition and the N content of the residues. Soluble C content of the residue determines the initial rate of residue decomposition whereas the lignin content controls the medium to long-term fate of added C (Heal et al., 1997). The N content of the residues is a source of organic N that is also subject to mineralisation, microbial assimilation and humification. The addition of plant residues in soil most often results in a net N immobilisation phase followed by a net mineralisation phase (these processes being evaluated by calculating the difference between a soil amended with crop residues and an unamended soil). In the case of residues rich in N (with a low C:N ratio) the net immobilisation phase decreases in magnitude and duration or even disappears, leading to a net mineralisation of N immediately after the start of decomposition (Mary and Recous, 1994). Using the ^{15}N dilution technique associated with the monitoring of C decomposition in field and laboratory conditions Watkins and Barragrough (1996) found that incorporation of oilseed rape stems or wheat straw with a high C:N ratio was immediately followed by increased gross mineralisation, even greater gross immobilisation and therefore low net mineralisation. Using field values and a model to simulate N fluxes over one-year long study, Garnier *et al.* (2003) found that the cumulative gross N fluxes associated to the decomposition of 8 tons of wheat straw was 743 kg N ha⁻¹ for gross mineralisation, 580 kg N ha⁻¹ for gross immobilisation, leading to a net mineralisation of 163 kg N ha⁻¹. The changes in gross N fluxes associated to the decomposition of straw were completed after one year in the field.

These studies reveal that the magnitude of gross N fluxes in soil is very much larger than the net N mineralisation that determines theoretically the availability of mineral nitrogen in a soil (Murphy et al., 2003). Most of the potential interactions between release of C and N, uptake of N, microbial and micro-fauna growth and death, and the associated gross mineralisation and gross immobilisation processes concern a small volume of soil, due to the mm scale of the rhizospheric processes. Nevertheless the high

intensity of these processes can lead to an overall effect at integrated soil layer scale. So, as illustrated in Figure 2 and 3, different crops growing on the same soil could have different N uptake capacity only because they can affect the equilibrium between gross mineralisation and gross immobilisation, therefore changing the net mineralisation of N. The different hypotheses presented in paragraph II for explaining the differences in soil N uptake capacity between crop species are therefore supported by the possibility of plants to alter the MIT. A higher specific N uptake capacity of its roots (high affinity system) could enable a crop species to reduce the residence time of mineral N in soil and then to decrease its probability to be assimilated by the rhizosphere microflora (see hypothesis iv); a specific C root exudate compound could stimulate either gross mineralisation or gross immobilisation (see hypothesis v). In that context, the concept of "soil N supply" to a crop can no longer be considered by itself e.g. as a function of soil characteristics and climatic conditions only, but should be considered also as dependent on the interactions between crop and soil processes.

Fertiliser recovery in crop: magnitude and role of competing processes

Much research has been done in the past twenty years to understand the fate of fertiliser N in the soil-crop systems, not only to improve the N fertiliser recovery by crops but also to identify and quantify the "unused" N. This unused N can have several deleterious effects on the environment, depending on the process involved. It was shown that in most situations the fate of fertiliser N in the soil-plant system was determined in the very first days to weeks after application, the main other sinks for fertiliser N being microbial immobilisation and gaseous losses (Recous, 2001). The fertilizer N recovery in crop is generally higher with the nitrate form than with the ammonium or urea forms resulting from a larger microbial immobilisation of the ammonium form that leaves less N available for crop N uptake. In some situations the ^{15}N balance realised in the soil+plant pools also suggested higher gas losses with from the ammonium form. In agrosystems of Northern Europe, the recovery of fertilizer N by the crop is usually low for early applications on annual crops, and then it increases with later dates of application until it reaches a maximum value (Recous and Machet, 1999, Strong, 1995, Fischer 1993). In fact, it was shown that fertiliser N applied to annual crops if not rapidly taken up by the crop was not available for crop uptake later on (at least in situations where the soil is not bone dry between crops). Therefore at any date of fertilizer N application there is a strong and rapid competition between crop N demand and other processes, the outcome of which largely determines fertiliser recovery by the plant at harvest. ^{15}N fertilisers studies have been widely used to assess the magnitude of the various processes and to understand how the competition is working.

The improvement in crop fertiliser N recovery with later dates of application in the growth cycle might be due to (i) the increased in crop N uptake capacity with increasing crop growth rate as discussed above (equation 5), or/and (ii) the decrease competition by soil N immobilisation due to the exhaustion of residue C from the preceding crop. Recous and Machet (1999) observed that microbial immobilisation of fertilizer N did not vary significantly with application made on winter wheat from tillering stage (early March) to grain filling stage (mid June), therefore the hypothesis (ii) seemed not valid. They concluded that crop N demand at the date of fertilizer N application was the main factor determining the N fertilizer recovery by crop, and this hypothesis was later confirmed by the work of Limaux et al (1999). Therefore field experiments confirmed the assumption that crop N demand determines N recovery in plant at least in conditions where water is not limiting of absorption. Some other pedo-climatic conditions can also affect the competition for N with the crop demand. For example, Powlson *et al.* (1992) showed a relationship between rainfall after application and fraction fertilizer losses, suggesting that environmental conditions such as soil water content may first act mainly on soil processes (here transport of nitrate and denitrification), and significantly reduce the availability of the fertilizer to the crop. Pilbeam (1996) examining ^{15}N data from the literature, obtained with wheat crops over a wide range of climates, observed that in humid environments more ^{15}N fertilizer was recovered in the crop than in the soil, while in the dry environments it was the reverse. He hypothesised that wheat grown under dry environments has a higher root:shoot ratio than wheat grown in humid environments and that residues of dryland crops that are returned to soil have a higher C to N ratio – due to sub-optimal N nutrition of the crop - increasing the immobilisation capacity of the soil. Corbeels *et al.* (1999) and Nannipieri *et al.* (1999) showed that under a Mediterranean climate the recoveries of ^{15}N labeled fertilizer by wheat were lower when N was applied late in the season when drought begins to occur. They proposed the hypothesis of a dominant influence of soil moisture on the fertilizer N uptake by crops. Limaux et al. (1999) observed a linear relationship between N use efficiency of the crop and the unrecovered fertilizer N in the soil+plant N pools. Because

there was no leaching in the situations investigated, the unrecovered N was supposed to have been lost as gas. These results suggested a negative relationship between fraction N volatilised and crop canopy development. An increase in crop height with later dates of N application may significantly modify physical conditions at the soil surface and increasing leaf absorption of volatilised NH₃ (Sommer *et al.*, 1997).

Improving N management at various scales of time and space.

Management of N fertilisation.

Rational N-fertilisation methods are generally based on a predictive mineral N balance, which compares both the soil supply capacity and the plant requirement corresponding to a given yield objective. Soil supply capacity includes the residual mineral N in soil which is measured in mid winter for autumn crops or before sowing for spring crops. These methods can apply to all crops. They are being continuously improved and updated: the improvement consists in calculating the balance terms more accurately (e.g. net mineralisation of SOM, crop N uptake, gaseous losses, nitrate leaching) and adapting them for a wide range of soils and crops; the updating occurs through computer codes which are mainly used by analytical laboratories. Such methods are now widely used by extension services in Northwestern Europe, particularly in France, Belgium and Germany (Denuit *et al.*, 2002; Machet *et al.*, 2003). They provide farmers with fertilisation advice either on particular fields or within small agricultural zones. A recent farmers' survey indicated that about 50% of farmers used this type of method in France (Massé, 2003).

These methods may be improved by associating them with indicators of crop N status, which can be measured during the crop growth. The method consists in four steps: (i) calculating the fertiliser rate (X) required according to the balance method, (ii) applying a reduced rate, e.g. X-40 kg N ha⁻¹, (iii) monitoring the crop N status during the period of important N absorption, and (iv) applying or skipping a last application of N fertiliser. This technique has been developed during the last 10 years in Europe. It allows for better adjustment of the rate and timing of N application and therefore improvement of the fertiliser N recovery by the crop (see above) and a reduced amount of nitrate leached into the aquifers. The first indicator investigated has been the **nitrate concentration in the base of the plant stem** ('sap test'). Nitrate concentration in the stem base is linked to the recent (2-3 days) uptake rate of nitrate by the root system and therefore is an early indicator of the N uptake rate in most cultivated plants. Its use, combined with the balance-sheet method has been patented as Jubil® method (Justes *et al.*, 1997). The method has proved able both to save nitrogen fertiliser and to reduce the residual N at harvest (Mary, 1997).

A similar method has been proposed with another indicator: the **chlorophyll concentration** in the upper leaves of the canopy. This indicator is easier to measure using transmittance devices (N-tester, chlorophyll-meter) or reflectance measurements (Raun *et al.*, 2002). Chlorophyll content (i.e. the product of concentration and leaf area) only represents 2-3% of the leaf N but is highly correlated with total leaf N content. This method has been proved also successful for wheat and potato crops (e.g. Denuit *et al.*, 2002). Although chlorophyll concentration is easier to measure than nitrate concentration, both methods are time-consuming and cannot be currently routinely applied by farmers. Consequently, the use of these methods is no longer increasing (Massé, 2003).

Manual measurements made within a field could be replaced in the next future by reflectance measurements obtained by aerial or satellite sensors, which give integrated values of the whole field, instead of isolated values. All these indicators are indirect estimates of the plant N status and are empirically correlated with the Nitrogen Nutrition Index presented above. But the regression coefficient with NNI is often sensitive to other factors such as leaf shape, canopy structure, leaf age, genotype, etc: it implies that calibration procedures have to be established and updated.

The next step in improving N fertilisation may consist in making site-specific N recommendations and applications, which becomes possible through 'precision agriculture' techniques (Pierce and Nowak, 1997). These techniques can provide exhaustive maps of grain yield through yield sensors on combine harvesters, leaf area index and chlorophyll content through remote sensing data and soil properties through geophysical measurements. They could be particularly interesting in heterogeneous fields, the yield potential of which being highly variable. However, whatever the technique used for decision in fertilizer N application, optimal fertilisation N will never be reached everywhere due to errors on model

predictions and uncertainties on the weather after the time of N fertilisation. Consequently, over-fertilisation may still occur, even if reduced, increasing year after year the risk of nitrate loss to the aquifers or gaseous loss to the atmosphere. Furthermore, on the long-term, intensive agriculture produces unavoidably too much N leaching (Addiscott *et al.*, 1991). Additional management techniques at cropping system level are necessary to control the other sources of nitrogen in soil.

Management of crop residues

The most common practice in intensive arable agriculture of Europe is returning crop residues to the soil. Most crop residues, except young cover crop residues, have a rather high C:N ratio, i.e. greater than 30. Therefore, as discussed in the previous paragraph, incorporation of crop residues vs. removal or burning favours on the short term a net N immobilisation and may then reduce N leaching. Conversely, repeated addition of crop residues has the opposite effect in the long-term: it increases the soil organic matter content and the potential N mineralisation rate (Kumar and Goh, 2000). Nevertheless, the balance of the two processes is likely to be positive. Addiscott *et al.* (1991) suggest that the intensification of agriculture during the past 50 years could have increased the potential net mineralisation of soils. This could be due to a greater return of crop residues and a change in their quality (e.g. residues with a lower C:N ratio), even though the concentration of organic matter in arable soils of western Europe has been stable or decreasing during the last 50 years (part of this effect could be due to deeper ploughing made some years ago).

Table 2. Net N mineralisation (kg N ha⁻¹) due to decomposition of crop residues in soil in field experiments in Northern France: from July to December in year *n*, and from January to July in year *n+1*. Crop residues were returned to the soil at the end of July (*n*). Net mineralisation is the difference between N mineralised in the soil with residues and in the soil without residues. Negative values correspond to net N immobilisation.

Year	Crop residue	Disk plough	Soil tillage		Reference
			Rotavator	No tillage ⁵	
July-December (<i>n</i>)					
1990	Wheat straw ¹	-24	-46	-2	Mary <i>et al.</i> (1996, 1999)
1991	Wheat straw ¹	-17	-22	-6	Mary <i>et al.</i> (1996, 1999)
1993	Wheat straw ^{1,4}		-66		Garnier <i>et al.</i> (2003)
1995	Rapeseed straw ²	-20			Justes <i>et al.</i> (1999)
1995	Rapeseed straw ³	-6			Justes <i>et al.</i> (1999)
January-June (<i>n+1</i>)					
1990	Wheat straw ¹	-19	-13	-31	Id.
1991	Wheat straw ¹	-14	+4	-25	
1993	Wheat straw ^{1,4}		+20		
1995	Rapeseed straw ²	+17			
1995	Rapeseed straw ³	+14			

¹ Wheat residues with a high C:N ratio (100), addition of 8.0 t DM ha⁻¹.

² Rapeseed residues with a high C:N ratio (102), addition of 6.4 t DM ha⁻¹.

³ Rapeseed residues with a low C:N ratio (54), addition of 11.8 t DM ha⁻¹.

⁴ This soil (only) initially contained a high amount of mineral N

⁵ The soil was no tilled until January (*n+1*): it was then moldboard ploughed.

Soil tillage has an important effect. Incorporation vs. surface application has two opposite effects: it favours decomposition and N immobilisation whereas tillage favours N mineralisation of native soil N. The net effect depends on the immobilisation potential of crop residues: it is net immobilisation for straw residues and increased mineralisation for rich-N residues. The immobilisation induced by straw decomposition is much lower than the immobilisation potential (see below). In field conditions, it often lies between 20-40 kg N ha⁻¹ (Table 2). It may reduce N leaching by 10-25 kg N ha⁻¹, even after repeated incorporation of straw (Nicholson *et al.*, 1997). Immobilisation can be markedly enhanced if the crop residue is incorporated in soil layers which contain much inorganic N. In that case, an intimate contact between soil and residue clearly increases the decomposition rate and the microbial N immobilisation. Net immobilisation can reach 46-66 kg N ha⁻¹ (Table 2). The subsequent release of nitrogen ('re-mineralisation') is also stimulated and occurs sooner; it occurs during the following year and must be accounted for in the fertiliser recommendation of the next crop. Management practices must therefore aim at favouring crop residues decomposition, which both reduce N leaching in autumn and winter and favour N release for the following crop.

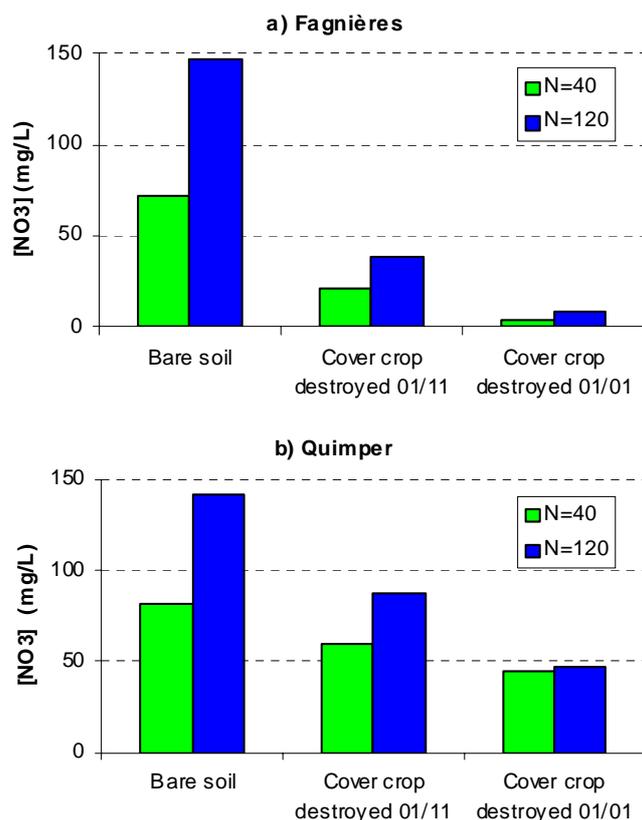


Figure 4. Nitrate concentration in drained water simulated during a long intercropping period in two sites in France: a) Fagnières = continental climate with low rainfall in winter (annual rainfall = 630 mm); b) Quimper = oceanic climate with a high rainfall (annual rainfall = 1230 mm). The simulations compare two initial amounts of mineral N in the profile (90 cm): N = 40 kg ha⁻¹ and N = 120 kg ha⁻¹. They compare the effect of a conventional practice (bare soil), a cover crop ploughed in on 1st of November or 1st of January (next year). The cover crop (mustard) was sown on August 15. Values are the median of concentrations obtained for the last 30 climatic years.

Management of cover crops

Replacement of fallow with cover crops during autumn-winter is an essential agricultural practice to recommend in temperate climates in order to control nitrogen losses to the groundwater (Meisinger *et al.*, 1991). Besides their effect on N leaching, cover crops exert beneficial effects on soil erosion and biological activity. The important issues for cover-crop management include choice of plant species, soil tillage, and sowing and incorporation dates in relation to preceding and following crops within the crop rotation system. Optimisation of these techniques must be made in order to (i) maximise root N uptake by the cover crop, particularly in the deeper soil layers; (ii) minimise extra water consumption, particularly in dry climates, and (iii) favour the release of the N immobilised by the cover crop during its decomposition in soil and its use by the following crop. The optimum techniques satisfying these criteria are not standard but depend on the pedoclimatic conditions of each agricultural zone.

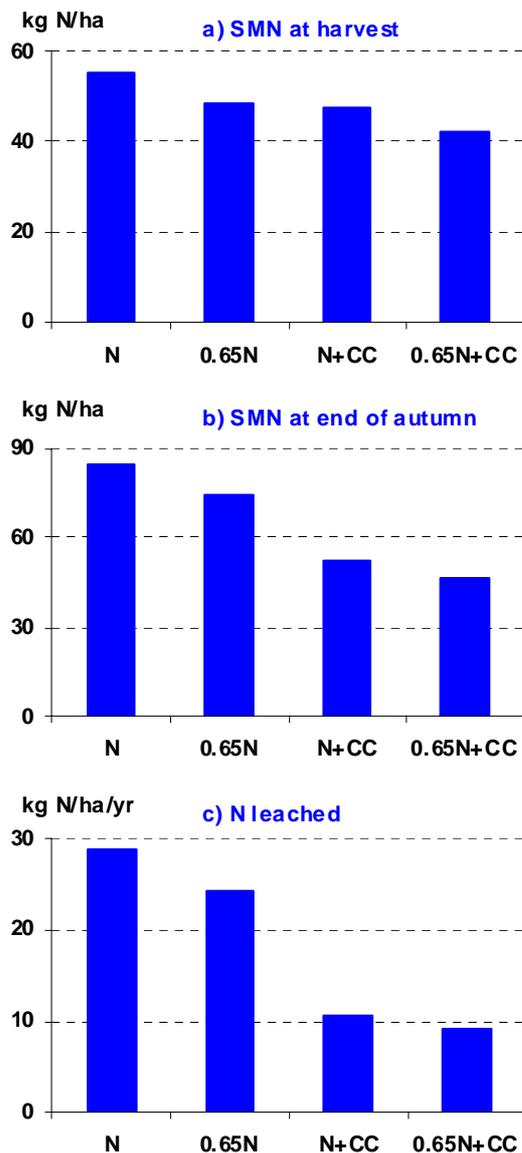


Figure 5. Measured effects of reducing N fertilisation or establishing cover crops on a) soil mineral nitrogen at harvest, b) soil mineral N at the beginning of drainage (end of autumn) and c) N leached during winter. N = conventional fertilisation; 0.65N = fertilisation reduced by 35%, CC = establishment of cover crop each year. Values are the mean of a 12 year continuous experiment at Thibie, France. The crop rotation is sugarbeet – spring peas – winter wheat. N leached is calculated from measurements in porous cups and lysimeters. Data from Mary *et al.* (2002).

A large range of dynamic crop models is now available to simulate water, carbon and nitrogen balance in the soil-plant system. Once tuned, these models can be very useful to simulate the impact of various techniques on the growth and N uptake of cover crops and their subsequent decomposition in soil. An example of this approach has consisted of calibrating and using the crop model STICS to search for the best management practices for cover crops (Dorsainvil, 2002). The results illustrated at Figure 4 show that the efficiency of cover crops for reducing the nitrate concentration in drainage water during the winter following their destruction may vary widely. Better efficiency was obtained in the continental climate than in the oceanic one, and for a late date of incorporation than for an early one. The relative efficiency of *cruciferae* (mustard, radish) vs. *graminae* (ryegrass) depends on the growth conditions in autumn (temperature). In intensive agriculture, the leguminous species such *Trifolium* or *Vicia* are not recommended as cover crops because they do not seem efficient in trapping soil nitrate. The efficiency of mixed stands of legumes and non-legumes deserves to be studied.

If cover crops are now recognized to be efficient for short-term reduction of N leaching, their long-term impact is still under debate. The mid-term effects are being studied in one field experiment at Thibie

(Northern France), which compares the reduction of fertiliser N and the introduction of cover crops (Mary *et al.*, 2002). Results indicate that after 12 years, the effect of cover crops on nitrate leaching is as important as it was at the beginning of the experiment. Cover crops reduced leaching by 63% on average over the 12 years (Figure 5). In contrast, reducing fertilisation by 35% compared to the conventional rate decreased leaching by only 16%. A long-term effect of both treatments starts to appear on the amounts of soil mineral N at harvest. But the main effect of cover crops remains the annual effect which appears at the end of autumn, soon after the incorporation of cover crops (Justes *et al.* 1999). After 12 years, the repeated establishment of cover crops has slightly increased soil organic N, soil mineralisation and the yield of the main crops (for a given fertiliser N rate), whereas it continues to markedly reduce the nitrate concentration in the drained water. This confirms the great interest of this technique, although the cover crops used (radish) had a rather small growth and took up moderate amounts of nitrogen (30 kg N ha⁻¹ year⁻¹ in average).

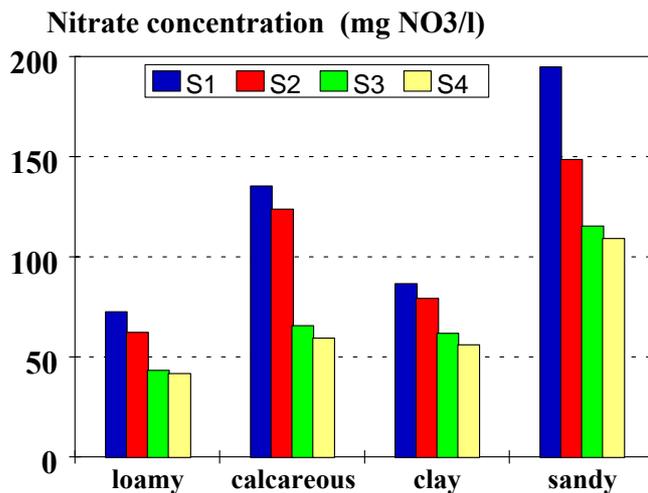


Figure 6. Simulated nitrate concentration in percolating water against soil type and for various agronomic scenarios, at the scale of an agricultural catchment during six years (1991-1997). The main crops were wheat (38%), sugarbeet (18%), peas (15%), barley (13%) and oilseed rape (9%). The simulated scenarios were: S1 = conventional farming (N fertilisation without environmental constraints, no cover crop); S2 = optimized fertilisation using a predictive balance sheet model (no cover crops); S3 = optimised fertilisation and establishment of cover crops before spring crops; S4 = reduced fertilisation (20% less than the optimized rate) and establishment of cover crops before spring crops. The mean annual drainage varied from 230 to 280 mm between the four soil types. From Ter Steege *et al.* (2001).

Management of N at large scales of space and time

Nitrogen management must be considered not only at field scale but also at the regional or at the hydrological unit scale, since these are the relevant scales for water agencies and political decisions. At this scale, the classical experimental approach is no longer possible. Simulation models, associated to GIS, are then essential to simulate the impact of present and past practices, and the effect of alternative future practices including the effects of climatic change.

An example of scenario analysis at the scale of a small agricultural catchment was made by Beaudoin and colleagues in Northern France (cited by Ter Steege *et al.*, 2001). The study concerns intensive arable agriculture (wheat, barley, sugarbeet, rapeseed, peas) in a temperate zone (mean rainfall 700 mm) with varied soils (from sand to clay). It compares the impact of conventional practices (scenario S1) with modified ones: optimisation of fertiliser with a balance-sheet method (S2), establishment of cover crops before spring crops (S3) and a combination of fertiliser reduction and cover crops (S4). Results obtained over six years indicated that soil type was the main determinant of water quality (Figure 6). The simulated nitrate concentration in drainage water was lowest in the deep loamy soils and greatest in the compacted sandy soils. The concentrations were in the following order S1 > S2 > S3 > S4, as expected. The simulated effect of cover crops was, as observed previously, higher than that of reducing fertilisation. Simulations also indicated the importance of a better distribution of crops over the catchment: the establishment of the 6% set-aside land on the more risky zones should allow the reduction of the nitrate concentration of the water percolating towards the aquifer by 18%. This kind of approach, which may be coupled to hydrological models provides understanding of the effects of previous agricultural practices,

particularly the effect of increasing N inputs during the last 50 years, on changes in water quality in surface and groundwater. It can be of great help for decision making in water-resource policies.

Conclusion

A better prediction of the dynamics of the crop N demand, using dynamic crop growth models associated with the use of crop N status diagnostic tools during crop development should allow a better adjustment of N application rate and timing for optimising, N recovery by crops, crop production and produce quality, and minimising environmental risks by avoiding excess mineral N in soil after harvest, when it is susceptible to be leached in autumn and winter. Nevertheless, even with well adjusted N fertilisation management, intensive cropping systems accumulates year after year positive N balances that lead to a constant increase of soil N mineralisation capacities with unavoidable losses of N during winter. The conjunction of the increases in soil N mineralisation capacities with the increase in winter temperature in temperate regions due to climate changes may increase the risks for N leaching. Facing this risk, two actions have to be taken. The first one, in the short term, is to extend the use of cover crops during autumn and winter. Nevertheless, in the long term, this management system could contribute also to increase the soil N mineralisation capacity. The second, in the long term, should be a breeding programme for improving the N-uptake efficiency of species in situations of low N availability. Such improvement for a crop should lead to a reduction of the N-application rate needed for optimising yield and produce quality, and then to a reduction of the soil N balance. So, a breeding programme for high N-uptake efficiency in conditions of low N availability is a relevant objective for extensive cropping systems where the use of N fertilizer is too expensive, but it appears also relevant for intensive cropping systems which face environmental risks. The role of legume crops within intensive cropping systems has also to be evaluated as an alternative source of N supply (Crews and Peoples, 2004) either for an ecological or a human needs point of view. Reconciliation of production and environment objectives is possible only if we are able to give an economic value to the protection of environmental and ecological goods, that is the condition to accept a limitation to intensification.

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