The Environmental Impact of Nitrogen in Field Vegetable Production

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Abstract

Many intensive systems of field vegetable production are not sustainable because they lose excessive amounts of nitrogen (N) to the environment.

Processes in the N cycle of agricultural systems include assimilation, mineralization/immobilization, nitrification, denitrification, ammonia volatilization, nitrate leaching, runoff and erosion. Emission of N from agriculture may affect the quality of the atmosphere, ground and surface waters. This occurs through leaching, ammonia volatilization, denitrification, nitrification, runoff and erosion. In field vegetable production, nitrate leaching is the dominant process affecting the environment. Often, large amounts of nitrogen, including residual soil mineral nitrogen and the nitrogen present in crop residues remain in the soil after harvest of the crop. Both sources of nitrogen may affect groundwater quality through nitrate leaching.

Residual soil mineral nitrogen levels after application of the recommended rates of nitrogen fertiliser to Brussels sprouts, white cabbage and onions are low to moderate (20-75 kg N ha^{-1}). Application of the recommended rates to other field vegetables, however, may leave large amounts of residual soil mineral nitrogen, especially after crops that are harvested before maturing, e.g., spinach, where residual soil mineral nitrogen may even exceed 200 kg N ha^{-1}. Obviously, large amounts of nitrate will then be at risk of leaching and denitrifying in the period after harvest.

Crop residues of spinach and celeriac contain 25-60 kg N ha^{-1}, cauliflower residues 80-120 kg N ha^{-1}, and white cabbage and Brussels sprout residues as much as 150-250 kg N ha^{-1}. If the residues decompose before winter, nitrogen from the decomposed plant material may leach or denitrify during the subsequent winter period.

Realistic estimates of nitrogen losses through leaching and denitrification after harvest of field vegetables were generated with a simulation model. It was calculated that leaching losses may exceed 200 kg N ha^{-1} after spinach or leeks, but denitrification was low. Leaching and denitrification losses after Brussels sprouts and cabbage were much lower.

INTRODUCTION

One of the definitions of sustainable is “capable of being maintained at a steady level without exhausting natural resources or causing severe ecological damage” (Anonymous, 1992). Many current intensive systems of vegetable production are not sustainable in this way because they do cause ecological damage. Growers usually apply large amounts of nitrogen (N) fertiliser to obtain high yields of good quality. This may be sound from an economic perspective, but not be from the environmental perspective.

In this paper, we first provide an overview of the N cycle in agricultural systems and the factors that control them. This has been extensively reviewed elsewhere (Addiscott et al. (1991), Jarvis and Pain (1997), Romdstad et al. (1997), Wilson et al. (1999)) and the information summarized here will provide general information on the important processes involved as they relate to losses from agricultural systems. Such background information is considered to be a prerequisite for designing management strategies to achieve a sustainable balance between reducing the environmental impact of N losses and protecting farmer's profitability.

Nitrate leaching is the dominant loss process of N in field vegetable production. Often, large amounts of nitrogen remain in the soil after harvest of the vegetable crop. This nitrogen includes residual soil mineral nitrogen and nitrogen present in crop residues. Both sources of nitrogen may have a harmful effect on the environment. They affect groundwater quality through nitrate leaching, and air quality through nitrous oxide emission. In the second part of this paper, we present quantitative data for the residual soil mineral nitrogen and nitrogen present in crop residues when the current nitrogen fertiliser recommendations for field vegetables are followed.

Sustainable nitrogen management should aim at supplying sufficient nitrogen for optimum crop growth, development and quality whilst keeping losses to the environment to a minimum.

PROCESSES IN THE N CYCLE OF AGRICULTURAL SYSTEMS

Nitrogen is cycled from the large atmospheric pool of dinitrogen gas (N_2) into the soil ecosystem. This occurs naturally through biological fixation (by leguminous plants) or artificially by chemical fixation (manufacturing processes to produce inorganic N fertilizer). In Europe, the latter is more important for agricultural systems. The largest pool of N in the soil is in the organic matter. The N processes that occur within the soil ecosystem include assimilation, mineralization/immobilization, nitrification, denitrification, leaching, ammonia volatilization, runoff and erosion.

Assimilation

Crops and the soil microbial biomass can assimilate both NO_3^- and NH_4^+. Therefore, the management of N in agricultural systems attempts to match the supply of these ions and the assimilative requirements of crops (and of the soil microbial biomass), so that farmers achieve their production targets and potential losses are minimised.

Mineralization/Immobilization

Organic matter is an important source of plant available N and indeed of other nutrients as well. Most of the N in the organic matter is present as proteins and other nitrogenous compounds. These arise from the decomposition of plant material, added organic matter (*e.g.* plant residues, manures) or components of dead microorganisms. The macro-faunal community plays an important role in degrading organic residues and the organic N is made plant available through micro-faunal and microbial degradation in a process called mineralization or ammonification. It results in the release of ammonia (NH_3) that stabilizes in most soils as ammonium (NH_4^+) except in highly alkaline soils. This process is reversible with available N being converted into the microbial biomass and is known as immobilization. The net effect of mineralization/immobilization is the release or binding of available N into the soil system. In fertile soils, net mineralization can make a significant contribution to the annual plant available N pool. For example, in established grassland soils the net contribution of the mineralization/immobilization processes has been measured at over 300 kg N ha^{-1} per annum.

The quality of the organic matter, for example as determined by its carbon: nitrogen (C:N) ratio influences the net N release. The higher the C:N ratio the lower the rate of net mineralization. The management of the soil system in terms of crop type, rotation, levels and type of N inputs all impact on the mineralization/immobilization processes. Environmental factors, such as temperature and moisture conditions, influence the process rates in terms of their impact on microbial activity. Rates will be slower when temperatures are low or when moisture is limiting.

Mineralization/immobilization is a complex process and to date is not fully understood and although some models exist, accurate predictions of the temporal trends in net mineralization rates are not yet possible. The vast number of combinations of soils, crops, weather, management practices and time scales that influence it compound the problem. However, as research continues to provide more knowledge on the processes and their interactions, models will be further developed that will facilitate more accurate predictions of rates and timing of net mineralization.

Nitrification

The NH_4^+ produced during the mineralization process is converted to nitrate (NO_3^-) in the next phase of the N cycle. This aerobic, bacterially driven process is called nitrification and involves the oxidation of NH_4^+ to nitrite (NO_2^-) and further to NO_3^-, N_2O and some NO_x can be released by this process. The importance of nitrification is that it provides a mechanism that transforms the relatively immobile NH_4^+ into NO_3^-, which is highly mobile. In arable soils, nitrification is usually considered to be non-limiting, while in grassland soils there can be large differences depending on management with higher rates associated with higher levels of N inputs.

Nitrification is influenced by an interactive and complex set of soil and environmental controls, including soil pH. The rates and dynamics of these processes depend directly, and indirectly, upon N inputs to the system interacting with external factors. There are direct inputs to the soil mineral N pool from fertilizer inputs. Enhanced transfer of N through the organic components, which may be derived from either fertilizer or biological fixation, will also contribute to N inputs.

Denitrification

Under anaerobic soil conditions certain microorganisms are capable of using the oxygen derived from NO_2^- or NO_3^- in place of atmospheric oxygen (O_2). This process is called denitrification. The gaseous end products are nitrous oxide (N_2O), NO_2, N_2 and NO_x. In some soils, chemical denitrification can occur. Denitrification generally takes place in the top 10 cm of soils and the gases produced are released to the atmosphere. The rate of the process depends on soil moisture, temperature and aeration, and the supply of carbon and substrate (NO_2^- or NO_3^-). Denitrification is, therefore, more likely to occur in poorly drained, fine textured soils and in situations with a high water table where anaerobic conditions are more likely to be present.

N_2O is ozone destructive and is considered one of the gases responsible for global warming. Greater quantities of the undesirable N_2O are produced under conditions where anaerobicity is less pronounced, under acidic soil conditions and lower temperatures.

Ammonia volatilization

The volatilization of ammonia (NH_3), i.e. the release of NH_3 from soils, excreta (especially urea), animal houses and manure stores depends on the NH_3/NH_4^+ being present in the aqueous phase. Therefore, the application of liquid animal manure or inorganic fertilizer (urea or NH_3/NH_4^+ based) to soils will increase the potential for volatilization depending on the method of application to the land. Urea is a major nitrogenous constituent of animal urine and some inorganic fertilizers. Its biological decomposition during the ammonification process results in the production of NH_4^+. High soil pH, dry soils and high temperatures increase the potential for NH_3 volatilization. Intensive livestock production systems are the single largest contributors of N loss through volatilization from agriculture because of the quantities of manure produced. Ammonia lost from the soil to the atmosphere is generally re-deposited onto soil or aquatic ecosystems. Volatilization and the subsequent deposition of N results in undesirable changes in the N balance of sensitive ecosystems as well as being a significant pathway for N losses from agricultural systems.

Exchange of NH_3 to and from crop plants also occurs, but this is generally considered to be neutral with inputs of NH_4^+/NO_3^- from the atmosphere balancing the emissions that occur from plant tissues as they senesce.

Leaching

This is the downward movement of N through the soil profile. Water movement in the soil profile can be vertically to groundwater or horizontally to surface drains. Leaching can be a major source of N loss from the soil ecosystem. The negatively charged NO_3^- ion is not adsorbed onto the soil colloids of most soils in temperate zones and remains in the soil solution and will be transported in water moving through the profile. There is evidence that NH_4^+ and organically bound N are also contributors to leaching losses from agricultural soil ecosystems, but in intensively managed systems their contribution to total loss in excess water is generally small. The potential for leaching losses depends on soil type/texture and structure (higher potential in the freer draining soils), rainfall volumes and patterns, agronomic management of the soil and the supply of leachable N.

Runoff and erosion

Providing that there is sufficient gradient, runoff is the amount of precipitation in excess of infiltration and evapo-transpiration which can transport materials away from fields into surface water systems. Surface runoff transports nutrients in dissolved and particulate form. Transport of soil particles (organic as well as inorganic) by wind or water is called erosion. The proportion of dissolved and particulate N losses in runoff water depends on the soil and its management. Some NO_3^- will be lost via this route in dissolved form, and it may be the major pathway for NH_4^+ and organic N transfer when absorbed on soil particles.

ENVIRONMENTAL IMPACTS OF N IN FIELD VEGETABLE PRODUCTION

Emission of nitrogen from field vegetable production systems may affect the quality of the atmosphere, ground water and surface waters (Table 1). This occurs through leaching, ammonia volatilization, denitrification, nitrification, runoff and erosion.

NITRATE LEACHING IN FIELD VEGETABLE PRODUCTION

In Western Europe, nitrate leaching from the root zone to aquifers occurs mainly in the period from late autumn to early spring when precipitation exceeds evapotranspiration. There is extensive evidence that in the past two decades the nitrate content of water in Western European aquifers has increased due to agricultural practices (Goulding *et al*., 1990; Owen and Jürgens-Gschwind, 1986; Vinten et al., 1992). This is undesirable as groundwater is an important source of drinking water. The European Union (EU) has set a maximum permissible concentration of 50 mg NO_3 per litre (= 11.3 mg N per litre) for drinking water (Anonymous, 1980). Assuming that nitrate is not lost from the groundwater through denitrification, that drinking water is extracted from shallow groundwater only, and that the annual precipitation surplus is 300 mm (the average value for The Netherlands), the EU criterion would already be exceeded after leaching of 34 kg N ha^{-1}. Obviously, denitrification does occur, especially in heavy-textured soils with a shallow groundwater table. Therefore, it was suggested that the maximum acceptable amount of nitrate present in soil at the onset of winter should be set at 70 kg N ha^{-1} (Goossensen and Meeuwissen, 1990). This value assumes that 50% of the nitrate is denitrified in soil and groundwater.

Nitrate that leaches during the winter period originates from residual soil nitrate, from nitrogen present in crop residues remaining on the field and from soil organic nitrogen mineralised during the autumn and winter period. The major sources of nitrate leaching in field production of vegetables are residual soil nitrate and nitrogen present in crop residues.

Residual Soil Mineral Nitrogen

The extent to which mineral nitrogen accumulates in soil when nitrogen fertiliser recommendations for field vegetables are followed is summarised in Table 2. Most data refer to current recommendations. The data presented for leeks and spinach, however, originate from the early eighties (Neeteson, 1995).

Residual soil mineral nitrogen levels after application of the recommended nitrogen fertiliser rates to Brussels sprouts, white cabbage and onions (grown from seed) are low to moderate: 20-75 kg N ha^{-1} (Table 2). Application of the recommended rates to other field vegetables, however, may leave large amounts of residual soil mineral nitrogen. This is especially the case after crops that are harvested before maturing, e.g., spinach, where residual soil mineral nitrogen may even exceed a value of 200 kg N ha^{-1}. Obviously, large amounts of nitrate will then be at risk of leaching during the subsequent winter.

Everaarts et al. (1996) produced a relationship between the amount of nitrogen applied as fertiliser, the nitrogen remaining in the soil, and cauliflower yield. The key factor is the optimum application rate of nitrogen fertiliser. With only a little extra nitrogen applied, yield ceases to increase or can even fall while the amount of residual nitrogen in the soil begins to increase steeply. Although Chaney (1990) observed a flat response of residual nitrogen to applied nitrogen in winter wheat, Neeteson and Wadman (1991; potatoes and onions), Neeteson (1994; potatoes), and Shepherd and Sylvester-Bradley (1996; oilseed rape) showed that residual nitrogen increases with applied nitrogen.

Nitrogen Present in Crop Residues

Not all nitrogen taken up by crops ends up in harvestable produce. Of the total amount of nitrogen taken up by, e.g., cauliflower, only about 50% is removed from the field with the harvested part (Everaarts et al., 1996). The other 50% remains on the field in the crop residues. Crop residues of spinach and celeriac contain 25 to 60 kg N ha^{-1} (Wehrmann and Scharpf, 1989), cauliflower residues 80 to 120 kg N ha^{-1} (Wehrmann and Scharpf, 1989; Everaarts et al., 1996) and white cabbage and Brussels sprout residues as much as 150 to 250 kg N ha^{-1} (Rahn et al., 1992; Neeteson, 1994). If the residues are (partly) decomposed before winter, nitrogen from the decomposed plant material may leach during the subsequent winter period.

Decomposition of the residues is dependent, amongst other factors on the C:N ratio of the material. Whitmore and Groot (1994) followed residue composition in experiments where leaves of spinach (C:N = 6), leaves of cabbage (C:N = 18), and a mixture of sugar beet leaves and crowns (C:N = 42) were mixed with soil. Spinach released most nitrogen and most quickly, cabbage leaves released nitrogen more slowly, and the sugar beet residues even immobilised nitrogen at the start of the experiment. However, when the whole winter period is considered sugar beet residues normally result in an important net N mineralisation which is important in predicting the risk of leaching.

Model calculations of nitrate leaching in field vegetable production

The literature contains no results of direct measurements of nitrate leaching from fields where vegetables are grown. Measurements on arable fields are found to be scarce. They almost exclusively pertain to cereals and sugar beet (Neeteson, 1995). On these fields the amount of nitrate leached during winter ranged from 10 to 55 kg N ha^{-1} (Goss et al., 1988; Maag et al., 1990; Nielsen et al., 1990). These relatively low values are probably the result of the generally low values of residual soil mineral nitrogen observed after cereals and sugar beet (Neeteson, 1995).

Currently available computer simulation models make it possible to generate realistic estimates of nitrogen losses. Whitmore (1996) developed a simulation model for the release and loss of nitrogen after vegetable crops. The model discriminates between the effect of residual soil mineral nitrogen on nitrate leaching (and denitrification) and the effect of nitrogen present in crop residues.

The absolute amounts of soil nitrogen leached were large after all crops but denitrification of soil nitrogen was low (Table 3). Crop residues increased leaching by a relatively small amount, or even reduced it. After spinach or leeks, total leaching losses exceeded 200 kg N ha^{-1}; both these crops use applied nitrogen inefficiently and leave large amounts of soil mineral N after harvest. Losses after Brussels sprouts and cabbage were much lower because both crops extract mineral nitrogen quite efficiently and leave little residual soil mineral nitrogen. Both Brussels sprouts and cabbage do, however, leave larger amounts of crop residues in the soil compared to spinach and leeks, but the differences in C:N ratio led to different effects on the amount of nitrate leached. From the cabbage residues, with a C:N ratio of 15, 30 to 40 kg N ha^{-1} was leached, whereas the sprout residues, with a C:N ratio of 25, did not contribute to leaching; conversely, some nitrogen was immobilised (Table 3).

Crops such as spinach and leeks that use nitrogen inefficiently do so, at least in part, because their roots do not penetrate the subsoil. Leaching from these two crops may be even worse than predicted in Table 3, if the model calculations have assumed wrongly that the residual mineral nitrogen in the soil profile was nearer to the surface than it actually was. In practice, more nitrogen in the subsoil would lead to earlier and more intensive leaching. Furthermore, a good deal of nitrogen may leach during the subsequent growing season from crops with shallow roots or those that receive much irrigation.

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Tables

Table 1. Environmental impact of N in field vegetable production

N compound	Environmental impact	Scale of impact	N processes responsible	Contribution
Nitrate (NO_3^-)	Water quality - Eutrophication - Health	Local: on-farm surface waters. Regional: surface waters, catchment, aquifers. National/international: maritime waters.	Leaching Runoff Erosion	High Low Low
Nitrite (NO_2^-)	Water quality - Fish stocks	Local: on-farm surface waters. Regional: surface waters.	Nitrification Denitrification	Low Low
Ammonia (NH_3)	Acid rain - Acidification of soils - Eutrophication of natural systems	Local: "on farm" deposition. Regional: deposition into natural ecosystems. National/international: cross boundary transfer of NH_3 and deposition.	Ammonia volatilization Emission from plants	Low Low
Nitrous oxide (N_2O)	Greenhouse gas - Global warming Ozone interactions	Global	Nitrification Denitrification	Low Moderate

Table 2. Residual soil mineral nitrogen after field vegetable fertilisation with the recommended rates of nitrogen fertiliser (Neeteson, 1999)

Crop	Recommended rate of nitrogen fertiliser (kg N ha^{-1})	Residual soil mineral nitrogen (kg N ha^{-1})
Brussels sprouts	120-240	20-45
White cabbage	300	50
Onions (grown from seed)	120	75
Cauliflower	180-300	60-210
Celeriac	50-150	50-225
Leeks	100-150	125-200
Spinach	215-290	160-220

Table 3. Nitrogen losses during winter after field vegetables (after Whitmore, 1996). L = leaching losses (defined as losses below 90 cm), D = denitrification losses. Losses from soil

originate from residual soil mineral nitrogen and from mineralisation of native soil organic matter

	Nitrogen losses (kg N ha^{-1})					
	Sandy soil			Clay soil		
	L	D	Total	L	D	Total
Brussels sprouts						
from soil	84	5	89	66	8	74
from crop residues	-3	26	23	-8	25	17
Total	81	31	112	58	33	91
Cabbage						
from soil	90	5	95	77	8	85
from crop residues	41	11	52	30	10	40
Total	131	16	147	107	18	125
Leeks						
from soil	160	5	165	177	8	185
from crop residues	24	5	29	19	4	23
Total	184	10	194	196	12	208
Spinach						
from soil	223	5	228	215	8	223
from crop residues	28	0	28	27	0	27
Total	251	5	256	242	8	250