Nutrient Balances in Field Vegetable Production Systems

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Keywords: nitrate leaching, residual soil mineral N, N in crop residues, nutrient management legislation, N surplus, "Farming with a future"

Abstract

In this review paper an overview of the nitrogen (N) and phosphorus (P) cycles in agricultural systems is presented. The information summarized provides general information on the important processes involved as they relate to losses from agricultural systems. Such background information is a prerequisite for designing management strategies to achieve a sustainable balance between reducing the environmental impact of N losses and protecting farmers' profitability. In field vegetable production most N is lost via nitrate leaching because often large amounts of nitrogen remain in the soil after harvest of the crop. This N includes residual soil mineral N and N present in crop residues. Quantitative data are presented on residual soil mineral N, N present in crop residues and nitrate leaching in field vegetable production systems. To combat too high nitrate leaching from agricultural soils the European Commission has issued the Nitrate Directive. Information on this Directive and on how the Dutch government imposed legislation to meet the demands of the Nitrate Directive is given. The project "Farming with a future" is also presented. This new project has been set up in The Netherlands to develop and test environmentally and economically sustainable field crop production systems. As an example of the first results of the project, N balances of two systems of leek production are shown.

INTRODUCTION

The high input of nutrients and pesticides in combination with professional farm management resulted in high agricultural production levels in many parts of Western Europe. However, high inputs may result in large losses of nutrients and pesticides and thus have adverse effects on groundwater, surface water, and the atmosphere. Society demands not only safe, healthy and sufficient food of a high quality, but also clean production methods. It is likely that it will become increasingly difficult to sell agricultural products if consumer demands are not satisfied. Nutrient and pesticide emissions from agriculture to the environment should therefore be minimized.

Many current intensive field vegetable production systems emit large amounts of nutrients. Growers usually apply ample quantities of fertilizer and manure. This may be sound from the economic perspective, but this may not be the case from the environmental perspective.

This review paper first presents an overview of the nitrogen (N) and phosphorus (P) cycles in agricultural systems. This has been extensively reviewed elsewhere (Addiscott et al., 1991; Jarvis and Pain, 1997; Romdstad et al., 1997; Wilson et al., 1999; De Clercq et al., 2001; Neeteson and Carton, 2001) and this paper provides 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 farmers' profitability.

In field vegetable production most N is lost via nitrate leaching because often large amounts of nitrogen remain in the soil after harvest of the crop. This N includes residual soil mineral N and N present in crop residues. In the second part of this paper, quantitative data are presented on residual soil mineral N, N present in crop residues and nitrate leaching in field vegetable production systems.

To combat too high nitrate leaching from agricultural soils the European Commission has issued the Nitrate Directive. Information on this Directive and on how an individual member state of the European Union, The Netherlands, imposed legislation to meet the demands of the Nitrate Directive will be given in the third part of this paper.

The project "Farming with a future" is presented in the final part of this paper. This new project has been set up in The Netherlands to develop and test environmentally and economically sustainable field crop production systems. As an example of the first results of the project, N balances of two systems of leek production will be shown.

PROCESSES IN THE N AND P CYCLE OF AGRICULTURAL SYSTEMS

At the farm level, input of nutrients occurs through purchased feeds, fertilizers and atmospheric deposition. Output of nutrients from the farm takes place through animal and crop products, in some cases manure, and through losses. The degree to which losses occur depends on soil and weather conditions and on farm management. Nutrient losses are unwanted because they may have a harmful effect on the environment. Of course, agricultural activities are part of a larger cycle where nutrients cycle through food, the human population and ultimately back into soil, water and atmosphere. These components of the more “global” cycle also contribute to losses and thus also affect the quality of the environment.

The N Cycle

The N is cycled from the large atmospheric pool of dinitrogen gas into agricultural systems. This occurs naturally through biological fixation by leguminous plants or artificially through chemical fixation to produce inorganic N fertilizer. The N processes that occur in agricultural systems include assimilation, mineralization and immobilization, nitrification, denitrification, volatilization, leaching, runoff, and erosion.

1. Assimilation. Crops and soil microbial biomass can assimilate both nitrate and ammonium. N management in agricultural systems attempts to match the supply of nitrate and ammonium to crop N requirement, so that production targets will be met and potential losses are minimized.

2. Mineralization and Immobilization. Organic matter represents the largest pool of nitrogen in soil. Most of the N in soil organic matter is present in the form of proteins and other nitrogenous compounds. These result from the decomposition of plant material, added organic matter or components of dead microorganisms. Part of the organic N is made available to plants through microfaunal and microbiological degradation in a process called mineralization. It results in the release of ammonium. Immobilization is the reverse process, converting ammonium or nitrate into microbial biomass. The net effect of mineralization and immobilization represents the release or removal of mineral N into or from the soil system. In fertile soils, net mineralization can make a significant contribution to the annual plant-available N pool.

3. Nitrification. The ammonium produced during the mineralization process is converted into nitrate in the next phase of the N cycle. This aerobic, bacteria-driven process is called nitrification and involves the oxidation of ammonium to nitrite and further to nitrate. Nitrous oxide and some nitric oxide can be released by this process. The importance of nitrification is that it provides a mechanism that transforms the relatively immobile ammonium into the highly mobile nitrate.

4. Denitrification. Under anaerobic soil conditions certain microorganisms are capable of using the oxygen from nitrate, nitrite or nitrous oxide instead of elemental oxygen. This process is called denitrification. The gaseous end products are dinitrogen, nitrous oxide, nitrite and nitric oxide. Nitrous oxide is ozone-destructive and is one of the global warming gases. Greater quantities of the undesirable nitrous oxide are produced under acidic soil conditions and lower temperatures. Denitrification is more likely to occur in poorly drained, fine-textured soils and in situations with high water tables where anaerobic conditions are more likely to be present.

5. Volatilization. Volatilization of ammonia occurs from soils, excreta, animal houses, stored and applied manure, and from plants. High soil pH, dry soils and high temperatures increase the potential for the process to take place. Ammonia that is lost from agricultural systems to the atmosphere is generally re-deposited onto soil or aquatic ecosystems. In this way ammonia is part of the so-called acid rain. Ammonia volatilization is a significant loss pathway of N from agricultural systems and it may result in undesirable changes in the N balance of sensitive ecosystems.

6. Leaching. Leaching is the downward movement of N through the soil profile. Water movement in the soil profile can be vertical to groundwater or horizontal to surface drains. Leaching can be a major source of N loss from agricultural systems. Because it is negatively charged, nitrate is not adsorbed onto the soil colloids and remains in the soil solution and will be transported in water moving through the profile. Some ammonium and organic-N compounds do also leach from agricultural soils, but in intensively managed systems their contribution to total loss is relatively small. The potential for leaching losses depends on soil type, weather conditions, and on the presence of nitrate in the soil. Additions of N from inorganic or organic fertilizers over and above crop requirements for optimum crop growth and also the incorporation of crop residues add to the potential for N leaching losses. Mineralization also contributes to the supply of N for leaching. Nitrate leaching is unwanted since it has a negative effect on groundwater quality and it contributes to eutrophication of surface waters.

7. Runoff and Erosion. Runoff is the amount of precipitation in excess of infiltration and evapotranspiration. Runoff can transport materials away from fields into surface water systems. It transports nutrients in dissolved and in particulate form. Some nitrate will be lost via this route, and it may be the major pathway for ammonium transfer as absorbed to soil particles. Erosion is the transport of soil particles by wind or water. Erosion can also remove nutrients bound to soil particles.

The P Cycle

The quantities and forms of P in soils depend on the degree of weathering, the nature of soil parent materials, and the application of phosphate fertilizers and manure. In soils, P is present in inorganic and organic forms. Both these forms are involved in transformations that release water-soluble P from solid forms. The pathways and mechanisms through which P evolves into its different forms are both complex and dynamic.

1. Inorganic P. The forms of inorganic P in soil are derived primarily from the weathering of primary and secondary minerals, of which apatite is the most dominant form in many soils. Soluble P represents P in the soil solution that is readily available to the plant. It typically accounts for less than 0.1% of total soil P. The labile fraction of inorganic P can replenish the soil solution following uptake of the soluble forms by the crop.

2. Organic P. Much of the P in soils is present in organic forms. These are mainly of plant and microbial origin. Some organic P compounds are easier transformed than others. This means that there are stable and labile pools of organically bound P. The transfer of organic P in soils between labile and inorganic forms occurs largely through the activities of microorganisms and phosphatase enzymes present in soils. Organic P compounds undergo mineralization and immobilization with the aid of soil microorganisms and growing plants. Transformations of inorganic P are related to the ease with which various forms become soluble, soil pH, and the presence and amounts of aluminum, iron and calcium.

3. Leaching and Runoff. A key difference between N and P in soil is that P attaches strongly to the soil matrix and, therefore, does not generally leach in large quantities through the soil profile. But when soils become phosphate-saturated, leaching will be enhanced. The P is also lost from agricultural systems through runoff in amounts that can have environmental impact. These losses tend to be higher from heavy soils than from light soils because heavy soils have lower infiltration capacities. Both leaching and runoff of phosphate have a negative effect on water quality.

NITRATE LEACHING IN FIELD VEGETABLE PRODUCTION

In vegetable production systems nitrate leaching generally constitutes the major process of nutrient emission to the environment. Under European conditions nitrate leaching usually takes place during the winter period when precipitation exceeds evapotranspiration and when there is no crop to absorb nitrate and water. In field vegetable production, N present in crop residues remaining on the field and mineral N present in the soil at harvest, i.e. residual soil mineral N, are the main sources of nitrate leaching. Whether N in crop residues or residual soil mineral N is the major source, depends on the type of crop.

The amount of N in crop residues of radish, onion for seed production, lettuce, asparagus and spinach is low (< 35 kg N ha^{-1}), so these residues will not contribute much to nitrate leaching. The residues of crops such as white and savoy cabbage, cauliflower, green peas and Brussels sprouts, however, contain large amounts of N (150-220 kg N ha^{-1}) when the recommended rates of N fertilizer are applied (Neeteson, 1995). It is likely that after decomposition the residues of these crops -when left on the field- may strongly contribute to nitrate leaching. Obviously, when more N is applied than is recommended, the N content of crop residues will be even higher.

Crops such as Brussels sprouts and white cabbage, when fertilized according to the recommendations, generally leave little soil mineral nitrogen (< 50 kg N ha^{-1}) at harvest. Residual soil mineral N levels after cauliflower, celeriac, leeks and spinach, however, may exceed 200 kg N ha^{-1} in the 0-90 cm layer (Neeteson, 1994; 1999; Van Enckevort et al., 2002). Obviously a large amount of this mineral N will leach during the subsequent winter. Similar to N in crop residues, residual soil mineral-N levels rise when more than the recommended amount of fertilizer N is applied.

The literature yields no results of direct measurements of nitrate leaching from fields where vegetables are grown. Currently available computer simulation models make it possible to generate realistic estimates of nitrogen losses. Based on actual data on N fertilizer application rates De Paz and Ramos (2001) estimated nitrate leaching in a vegetable production area close to Valencia (Spain). The N fertilizer application rates were extremely high (more than 1000 kg N ha^{-1} yr^{-1}) resulting in average nitrate leaching rates of 375 kg N ha^{-1}. Model calculations by Whitmore (1996) confirmed that on sandy soils in The Netherlands, even when the recommended rates of N fertilizer are not exceeded, large amounts of nitrate (80-250 kg N ha^{-1}) may leach after crops such as Brussels sprouts, cabbage, leeks, and spinach.

EUROPEAN LEGISLATION ON NUTRIENT MANAGEMENT

Ultimately, legislation on nutrient management aims at reaching environmental goals. A major aim of this legislation is meeting the standard of the Nitrate Directive of the European Commission: the nitrate concentration in groundwater that is intended to be used for drinking water may not exceed 50 mg nitrate L^{-1} (European Commission, 1991), but minimizing ammonia volatilization is also an important objective of the legislation.

Some current regulations in The Netherlands will be presented as an example. These include the obligation to cover storage facilities for animal manure, compulsory low-emission application methods for animal manure to land, a ban on spreading animal manure on agricultural land during the winter period, and levies on exceeding the maximum permissible annual nitrogen and phosphorus surplus for farms (Ministry of Agriculture, Nature Management, and Fisheries 1995; 1999; Neeteson, 2000; Henkens and Van Keulen, 2001). The first two measures aim at reducing ammonia volatilization, the third at reducing nitrate leaching to groundwater, and the fourth at reducing all emissions of N and P.

Obligation to Cover Storage Facilities for Animal Manure

Since application of manure during fall and winter is prohibited, livestock farmers are forced to increase their capacity for storing livestock wastes. The total storage capacity should be up to nine months' supply. To prevent ammonia emission from livestock wastes during storage, all storage facilities that have been built after June 1 1987 should be covered. Subsidies are available for the construction of new and the improvement of existing storage facilities.

Compulsory Low-emission Application Methods for Animal Manure

In 1980, when animal manure was still surface-applied, about half of the ammonia emission from agriculture took place after spreading of manure. Since volatilization of ammonia can be largely reduced by manure incorporation into the soil immediately after spreading (Heck, 1931; Van der Molen et al., 1990), Dutch farmers are now obliged to incorporate manure during or immediately after application. On grassland the manure has to be injected into the soil or into the sward, while on arable land the manure has to be directly injected or incorporated into soil within one hour after application.

Ban on Spreading Animal Manure on Agricultural Land during the Winter Period

In The Netherlands, nitrate leaching from the root zone to aquifers occurs mainly in the period from late fall to early spring when precipitation exceeds evapotranspiration and crops are absent or unable to take up nutrients. To reduce leaching of nitrate the Dutch government therefore does not allow the application of animal manure to grassland and most arable land during the winter period. The regulations apply also to inorganic fertilizers. Regional authorities may impose longer periods in which it is not allowed to apply nutrients, but only in nature protection areas. It is never allowed to apply manure on frozen or snow-covered soils. This regulation has been implemented to prevent runoff of nitrogen and phosphorus to surface waters after thaw setting in.

Limits to the Annual Nitrogen and Phosphorus Surplus on Farms

Nutrient budgeting facilitates the understanding of the effects of farm management on nutrient use efficiency (Van der Meer, 1982; Aarts et al., 1992). The nutrient surplus, i.e. annual nutrient input to the farm minus annual nutrient output from the farm, is thereby used as a performance indicator. A study on nutrient budgets of Dutch farms showed that differences in nutrient surplus are predominantly related to differences in farm management (Van der Meer and Van der Putten, 1995). Moreover, it has been observed that farmers can easily understand and draw up the budgets themselves. These positive experiences made farmers' organizations request the Dutch government to introduce a mineral accounting system as a policy instrument for the regulation of N and P emissions from agriculture.

In 1998 the MINerals Accounting System (MINAS) was introduced in The Netherlands. The system follows a farm gate approach: only N and P entering and leaving the farm through the gate have to be accounted for (Table 1). The maximum permissible levels of N and P_2O_5 surpluses are presented in Table 2. Since 1998 the levels have become increasingly stringent. In case the annual permissible levels are exceeded, a levy is charged to the farmer. The levy is € 2.3 for each kg N exceeding the permissible level and € 9 for each kg P_2O_5 exceeding the permissible level.

"FARMING WITH A FUTURE"

The Dutch society demands that agriculture produces in a clean and safe manner and that agriculture not only takes account of food production, but also of other functions in the rural area. As far as the production process is concerned, minimizing nutrient emissions and emission of crop protection agents are the major issues in the eyes of Dutch citizens. The research project "Farming with a future" was set up to design, test and implement sustainable farming systems for arable crops, field vegetables, flower bulbs and tree nursery crops. The project is executed in close cooperation between scientists, farmers, extension service and policy makers. Dissemination of the results to the farming community, consultants and pressure groups is a major aim of “Farming with a Future”. The project is funded by the Dutch Ministry of Agriculture, Nature Management, and Fisheries and the Ministry of Housing, Spatial Planning, and Environment.

“Farming with a Future” combines research on four experimental farms and 33 commercial farms (Table 3). Most of the farms are located on sandy soils, i.e. on soils that are sensitive to nitrate leaching. On the experimental farms production systems are developed that meet the most stringent environmental goals. The research on the experimental farms includes measurement of all relevant processes. On the commercial farms, farmer, extension service and scientists jointly each year develop a farming plan that aims at meeting environmental goals. Promising measures as derived from results obtained at the experimental farms are tested on the commercial farms. The goals set for maximum nutrient emissions are presented in Table 4. The project started in 2000; the first phase will end in 2005. Details on the reasoning behind the project and its set-up are described by Neeteson et al. (2001) and Langeveld et al. (2003). Preliminary results obtained in leek growing systems at the experimental farm for field vegetables (“Meterik”) will be presented in the following paragraphs. The paper of Booij et al. (2003) deals with results of the commercial field vegetable farms.

Experimental Farm “Meterik”

The experimental farm for field vegetables “Meterik” is located on a sandy soil in the south-eastern part of The Netherlands. The main crops are leeks, Chinese cabbage, lettuce, carrots and strawberries. Previous research at “Meterik” showed that high levels of pesticides were applied to strawberries, leeks and lettuce, and also that after these crops high levels of residual soil mineral N were present (Table 5). Since the highest amount of pesticides was used in leeks and since very high levels of soil mineral N remained in the soil at harvest after this crop, in “Meterik” the emphasis was put on the development of sustainable leek growing systems.

Two systems of leek production were included in the research: an Economically Feasible system in which it is attempted to meet the environmental goals but not at the expense of economic profitability, and an Environmentally Desirable system in which the environmental goals must be met.

To be able to meet the goals set for maximum N emissions in the Economically Feasible system N fertilizer was applied according to a refined Dutch NBS system. In a NBS system, which is similar to the German KNS system (Lorentz et al., 1989), N application is split into four or five doses depending on the presence of soil mineral N and crop N demand during the growth period. In the Environmentally Desirable system N fertilizer was applied by means of fertigation, which is an even more refined system than the NBS system. In both the Economically Feasible and the Environmentally Desirable system the target for total N uptake by leeks was set at 230 kg N ha^{-1}, be it that in the Economically Feasible system it was also aimed that a buffer stock of 50 kg mineral N ha^{-1} was present in the soil (Langeveld, 2002). The N-fertilizer application rates in the two leek systems are presented in Table 6.

N-balance Sheets of Leek Production Systems at “Meterik”

The N-balance sheets of the two production systems are shown in Table 7. The N surplus of the Economically Feasible system was 115 kg N ha^{-1}, whereas it was –66 kg N ha^{-1} in the Environmentally Desirable system, suggesting that emissions to the environment were distinctly lower in the latter system. This is confirmed by the much lower level of residual soil mineral N in the Environmental Desirable system (Table 8). It should be noted that the surpluses presented in Table 7 only refer to the fields where leeks were grown and not to the entire farm on which current legislation is based (Table 2). Since there were no differences in leek yield and leek quality between the two systems (Table 8), it can be concluded that it is possible to drastically reduce N emissions to the environment in leek production systems without compromising on leek yields. It should be noted that the costs of the fertigation system are about € 1,000 ha^{-1} higher than the costs of the NBS system. To compensate for the additional costs leek yields in the fertigation system should be about 3 t ha^{-1} higher. It is to be expected that a further reduction in N emissions can be obtained when actual net N mineralization is explicitly taken into account in the determination of N-fertilizer application rates.

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Tables

Table 1. N and P inputs and outputs to be considered in MINAS, the nutrient budgeting system in the Netherlands.

Inputs	Outputs
Concentrates	Animal products (milk, meat, eggs, wool)
Fodder from other farms	Fodder to other farms
By-products	Arable products, vegetables
Organic fertilizers from other farms (e.g. animal manure, compost)	Organic fertilizers to other farms (e.g. animal manure, compost)
Animals bought	Animals sold
Inorganic fertilizers	Ammonia loss from housing (correction factor for livestock farms with more than 2 LU ha^{-1})

Table 2. Permissible levels of N and P_2O_5 surpluses in The Netherlands.

Agricultural use	Period	Permissible surplus (kg ha^{-1} yr^{-1})	
		N	P_2O_5
Grassland	1998-1999	300	40
	2000	275	35
	2001	250	35
	2002	220[1]	25
	As from 2003	180[2]	20
Arable land	1998-1999	175	40
	2000	150	35
	2001	150	35
	2002	150[3]	30
	As from 2003	100[4]	20

[1]Grassland soils with a high risk of nitrate leaching: 190 kg N ha^{-1} yr^{-1}
[2]Grassland soils with a high risk of nitrate leaching: 140 kg N ha^{-1} yr^{-1}
[3]Arable soils with a high risk of nitrate leaching: 100 kg N ha^{-1} yr^{-1}
[4]Arable soils with a high risk of nitrate leaching: 60 kg N ha^{-1} yr^{-1}

Table 3. Experimental farms and commercial farms in “Farming with a Future”.

Crops	Number of farms	
	Experimental farms	Commercial farms
Arable crops	1	14
Field vegetables	1	9
Flower bulbs	1	5
Tree nursery crops	1	5
Total	4	33

Table 4. Goals related to nutrient emissions on the farms participating in “Farming with a Future”.

	Commercial farms	Experimental farms
Nitrate in groundwater (mg N L^{-1})	< 11.3	< 5.6
Total N in surface waters (mg N L^{-1})	< 2.2	< 1.0
Ammonia volatilization (kg N ha^{-1} yr^{-1})	< 15	< 5
Total P in fresh surface waters (mg P L^{-1})	< 0.15	< 0.05

Table 5. Residual soil mineral N and the use of pesticides at experimental farm “Meterik” during the period 1997-1999.

Crop	Residual soil mineral N (kg N ha^{-1})	Use of active ingredient (kg ha^{-1} yr^{-1})
Chinese cabbage	46	0.6[1]
Carrots	52	1.8[1]
Strawberries	84	4.8
Leeks	149	6.4
Lettuce	168	4.4[2]

[1] On average 1,5 crop per year
[2] On average 2 crops per year

Table 6. N-fertilizer application rates in two systems of leek production at the experimental farm “Meterik” in 2001. In the Economically Feasible system and the Environmentally Desirable system N fertilizer was applied according to NBS and fertigation, respectively.

Time of application	Fertilizer application rate (kg N ha^{-1})	
	Economically Feasible	Environmentally Desirable
July	50	21
Mid August	165[1]	43
End of September	50	47
October	50	22
November		5
Total	315	138

[1] According to the fertilizer plan 115 kg N ha^{-1} should have been applied; an additional 50 kg N ha^{-1} was erroneously applied

Table 7. N-balance sheets of two systems of leek production at experimental farm “Meterik” in 2001.

	Economically Feasible	Environmentally Desirable
Inputs (kg N ha^{-1})		
N fertilizer	315	138
Atmospheric deposition	42	42
N in irrigation water	11	31
Total	368	211
Output (kg N ha^{-1})		
Produce	253	277
Total	253	277
Surplus (kg N ha^{-1})	115	-66

Table 8. Residual soil mineral N, leek yields and leek quality in two systems of leek production at experimental farm “Meterik” in 2001.

	Target value	Economically Feasible	Environmentally Desirable
Residual soil mineral N (kg N ha^{-1})	45	94	35
Net leek yield (t ha^{-1})	40	43	41
Yield quality (% first grade)	80	64	67