A multi-scale system approach to nutrient management research in the Netherlands

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Introduction

For a long time, research in the Netherlands on nutrient management has been focussed on the effects of nutrient form, rates, timing and application methods on crop yields (Van Der Pauw, 1966; Prins *et al.*, 1980; Van Burg *et al.*, 1980, 1981; Ris *et al.*, 1981; Dilz *et al.*, 1982; Neeteson & Wadman, 1987; Neeteson & Zwetsloot, 1989). Initially the soil was seen as a black box. Later on the concept of nutrient recovery (De Wit, 1953) became a common component of the analyses (Van Der Meer *et al.*, 1987; Neeteson, 1989; Van Keulen & Stol, 1990; Van Noordwijk, 1999; Vellinga & André, 1999).

Initially nutrient management mainly aimed at attaining maximum financial yields. In the course of time environmental considerations became more important (e.g. Prins *et al.*, 1988). Various yardsticks for the determination of the environmental impact of nutrients were developed among which residual soil mineral nitrogen (N) at harvest (Neeteson, 1994; Vellinga *et al.*, 2001; Ten Berge *et al.*, 2002) and the nutrient surplus per unit area or unit output (Janssen, 1999; Neeteson, 2000; Schröder *et al.*, 2002; 2003). At the same time the concepts of site-specific nutrient management and precision farming became popular (Verhagen *et al.*, 1995). Research on precision farming includes the development of soil- and crop-based indicators to support decision-making by farmers on when, where and how much fertilizers should be applied (e.g. Neeteson, 1995; Schröder *et al.*, 2000; Booij *et al.*, 2001). The spatial scale of this type of research is restricted to the field, the temporal scale to months at most.

However, since agriculture is a chain of activities transferring nutrients in a cyclic way from the soil via the crop, animals and men, manure and by-products from society to the soil again, the spatial and temporal scales of nutrient management have to be extended to farm, regional, national or even global level (Figure 1) and to years or even decades, respectively. For that purpose a more strategic level of nutrient management has to be considered.

This paper reviews the effects of nutrient management at a certain scale on nutrient flows at other scales on the basis of a comprehensive framework applied to four examples derived from current Dutch nutrient management issues.

Mechanistic model for nutrient flows in farming systems

Schröder *et al.* (2002) proposed a simple mechanistic model of a farming system characterized by the nutrient conversion efficiencies $\underline{A}$ to $\underline{D}$ (Figure 1) with the dimension kg kg^{-1}. The efficiency of converting soil nutrients to harvestable crop nutrients ($\underline{A}$) depends on crop choice and crop rotation (e.g. Prins *et al.*, 1988; Greenwood *et al.*, 1989; Schröder *et al.*, 1996b, 1997a; Vos & Van Der Putten, 2000), and on fertilizer management strategies (e.g. Schröder *et al.*, 1996a, 1997b, 2000). The value of $\underline{A}$ is also affected by the nature of the fertilizer used. As mineralization from organic nutrients usually takes more than just one year, residual effects from manure and other organic inputs may accumulate over time (Dilz *et al.*, 1990). So it takes time before $\underline{A}$-values associated with organic fertilizers approach the values attainable with mineral fertilizers. This also implies that there are long-term consequences of reduced N and phosphorus (P) rates, as crops may benefit for many years from soil fertility built up in the past (Wolf *et al.*, 1989; Motavalli *et al.*, 1992; Whitmore & Schröder, 1996). So $\underline{A}$-values and thus nutrient surplus and output per unit input should be interpreted with caution when referring to farms that have recently adopted a low-input strategy.

The efficiency of converting harvested crop nutrients into nutrients in feed and bedding material ($\underline{B}$) predominantly depends on the extent to which preservation and feeding losses can be avoided. The efficiency of converting nutrients in feed and bedding material into nutrients in animal produce ($\underline{C}$) depends on the quality of the ration, on the choice to use bedding material at all, on animal species and breed, and on the replacement rate (Aarts *et al.*, 1999b). Finally, the efficiency of returning nutrients in manure to the soil pool ($\underline{D}$) depends on the magnitude of gaseous N losses from stables and storage facilities, and on losses during manure application and grazing. These losses may vary from less than 5% to 50% of the excreted N (Van Der Molen *et al.*, 1990; Bussink & Oenema, 1998; Monteny & Erisman, 1998; Schils *et al.*, 1998; Huijsmans & De Mol, 1999). Variations in the coefficients $\underline{A}$, $\underline{B}$, $\underline{C}$ and $\underline{D}$ can be attributed to differences in operational management skills of farmers. But they may also originate from deliberate decisions on crop types, feed types, fertilizer types, animal types and grazing regimes, and on the types of housing and manure-handling equipment.

The model formulates the ratio of nutrient outputs and inputs (O/I, kg kg^{-1}) and the surplus per unit output (S/O, kg kg^{-1}) at farm level in terms of these four conversion coefficients so that it can be used to evaluate the impact of changes in the four key coefficients on these system characteristics. These coefficients appear particularly sensitive to variations in the conversion efficiency of soil nutrients in crop nutrients ($\underline{A}$). For instance, an increase in $\underline{A}$ from a common 65% to 75% results for dairy farms in a relative increase in O/I and a relative decrease in S/O, each of about 30% (Schröder *et al.*, 2002). The model further allows calculating required inputs per unit

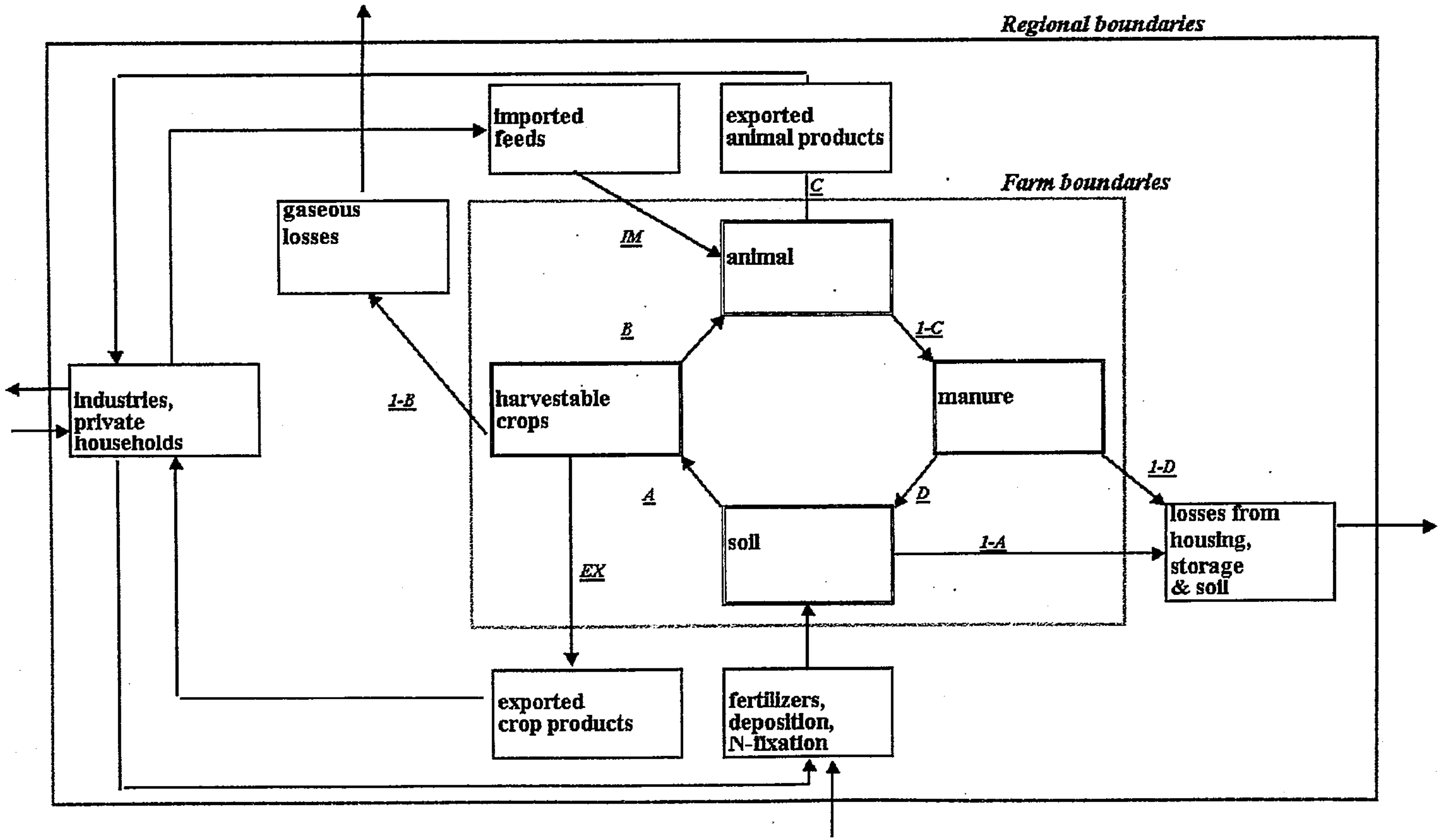

Figure 1. Diagram of a mechanistic model for nutrient flows of farming systems (after Schröder *et al.*, 2002a). See text for explanation of coefficients <u>A</u>, <u>B</u>, <u>C</u>, <u>D</u>, <u>IM</u> and <u>EX</u>.

area and surpluses per unit area (S, kg ha^{-1}) from either the targeted output per unit area or the attainable harvestable crop yield per unit area, or *vice versa*. The model also illustrates that O/I, S/O and S are not only determined by the operational skills of the farmer, but also by strategic decisions pertaining to the extent to which the farmer leaves the processing of crops to others (as in an arable farm) or to the extent to which he opts for self-sufficiency in feed supply. The fraction of harvested nutrients that are exported ($\underline{EX}$) and the fraction of nutrients in feed and bedding material that are imported ($\underline{IM}$) characterize these aspects (Figure 1). Variation in strategic decisions on $\underline{EX}$ and $\underline{IM}$ has considerable consequences for O/I, S/O and S so that differences in these indices do not necessarily reflect differences in operational management skills. To identify the scope for system improvement, analysis of the underlying conversion coefficients is indispensable (Schiere & Van Keulen, 1999; Van Bruchem *et al.*, 1999a; Aarts *et al.*, 2000a,b; Schröder *et al.*, 2002). Schröder *et al.* (2002) also showed that disintegration of mixed farms into specialized farms might lead to an apparent improvement of nutrient use efficiency at farm level, but this improvement may disappear when the efficiency is evaluated at higher spatial scales. Van Noordwijk (1999) arrived at a similar conclusion.

Minimizing ammonia volatilization in animal production systems

Ammoniacal N is easily lost by volatilization from animal excrements. Ammonia losses inflict costs as they need compensation by external N inputs and are harmful to surrounding ecosystems. Replacement of surface-application of manure by injection is one of the measures that can reduce ammonia losses (Van Der Meer *et al.*, 1987). In terms of Figure 1 this measure increases the value of $\underline{D}$. Most farmers contract out injection, but the heavy equipment used by contractors may negatively affect soil structure, sward quality and soil life so that the higher value of $\underline{D}$ may lead to lower values of $\underline{A}$ (Figure 1).

Ammonia losses from land-spread manure can also be reduced by measures that lower the ammonia content of the manure such as adding materials low in N / high in carbon (C) to the animal ration (Van Bruchem *et al.*, 1999b) or to the excrements. Such measures may indeed increase $\underline{D}$ from land-spread manure or manure excreted during grazing. However, to reduce the ammonia content sufficiently so as to make injection redundant, rations are needed so low in N that a trade-off in terms of $\underline{C}$ cannot be avoided due to increased herd size requirements. If silage maize is used to reduce the relatively high N concentration of grass-dominated rations, there may be a trade-off in terms of $\underline{A}$, as the $\underline{A}$-value of arable crops is generally lower than that of permanent grassland (Ten Berge *et al.*, 2000b).

If materials low in N / high in C are added to the excrements (e.g. if solid manure instead of slurry is produced), the intended increase in $\underline{D}$ in the field can be counteracted by a decrease at the yard due to losses associated with regular turning of manure heaps (Dewes, 1995; Bokhorst & Ter Berg, 2001; Berry *et al.*, 2002). Moreover, when manure is applied in spring, crop demand is generally better matched with the supply from liquid manure than from solid manure, even if the long-term residual effect of the solid manure is taken into account (Schröder, 2003). So even if coefficient D is improved, this may carry a price in terms of A. This example illustrates the strong interactions among farm components. So evaluations of nutrient efficiencies must cover the whole farm.

Minimizing nutrient losses on dairy farms

Because of interactions between measures taken in the compartments soil, crop, animals and manure, further validation of our fractional knowledge is required based on real life cases. For that reason the experimental dairy farm 'De Marke' was started in 1989 (Aarts *et al.*, 1992; 1999a). The farming system was designed to achieve an annual milk production of 11,600 kg ha^{-1}. Management of 'De Marke' is directed at improving the conversion of excreted nutrients in harvestable crop nutrients (D and A in Figure 1) and of crop nutrients in milk (B and C in Figure 1). Annual nutrient outputs and losses are compensated by imported feed rather than by mineral fertilizer inputs (IM = 0.26 kg N per kg N, Figure 1). This incomplete self-sufficiency on feeds makes it easier to increase the nutrient efficiency than complete self-reliance. However, the IM-value of 0.30 kg N per kg N on comparable commercial farms is even slightly higher.

At 'De Marke' cattle take up less N in feed than at comparable commercial farms. This results in a relatively high conversion efficiency of feed in milk and meat (C in Figure 1), implying that the animals excrete less N. Subsequently, this smaller amount of manure-N is efficiently converted into harvestable crop-N through a combination of adapted animal housing, optimal timing of manure spreading, restricted grazing, and specific crop rotation (so, D and A in Figure 1) (Aarts *et al.*, 1999a).

Performance of 'De Marke' shows that compared with commercial farms of similar intensity drastic reductions in N and P surpluses are feasible, especially because of lower inputs of nutrients through fertilizers and feed. Averaged over 1994–1997, the annual N surplus of 154 kg ha^{-1} was 63% lower than on commercial farms in the same period, and the phosphorus surplus of only 3 kg ha^{-1} was even 92% lower (Aarts *et al.*, 1999a; 2000a, b).

Efficiencies of N-conversion at 'De Marke' are 0.68 for A, 0.93 for B, 0.23 for C and 0.91 for D, whereas corresponding figures for commercial farms of similar intensity were 0.63, 0.71, 0.19 and 0.83 (Hilhorst *et al.*, 2001). Taking account of the appropriate IM-values, the O/I's at 'De Marke' and at commercial farms were 0.32 and 0.16 kg N per kg N, respectively. The corresponding S/O's were 2.2 and 5.3 kg N per kg N.

Nutrient management in organic farming systems

Organic agriculture intends to rely on an integral approach to nutrient management (e.g. Schröder & Van Leeuwen-Haagsma, 2002). As organic farming almost completely refrains from mineral fertilizers, maintaining soil fertility is commonly based on the use of animal manure. The N/P ratio in animal manners is usually much lower than the N/P ratio of the produce leaving the farm (Schröder, 2003). In Dutch organic farming this N-deficiency is compensated by either over-applying manure that partly originates from non-organic resources or by depleting soil-fertility that has been built up in the conventional past (Wijnands *et al.*, 2002). Ideally, legumes should supplement N input. However, many specialized organic arable farmers are reluctant to grow less profitable crops like legumes, and resort to less sustainable solutions. The need for legumes is the more pressing when the N/P ratio of the manure is lower. So organic farmers may have to reconsider their traditional preference for solid manure in view of their lower N/P ratio and given the current constraints on permitted levy-free P-surpluses in the Netherlands (Neeteson, 2000). Although solid manure with their inherent low content of water-soluble N, are a rational choice when late summer or autumn provides the only time windows for application, their N/P ratio is lower than that of liquid manure (Schröder, 2003), due to gaseous N-losses (1-<u>D</u> in Figure 1) associated with the production, storage and handling of solid manure (Dewes, 1995; Bokhorst & Ter Berg, 2001; Berry *et al.*, 2002).

On farms of similar intensity, use of solid manure leads to (much) smaller annual applications of directly available ammoniacal N and larger applications of organic N, resulting in a larger (equilibrium) pool of soil organic N and more abundant soil life. Consequently, annual mineralization is larger. Sometimes, these associated phenomena lead to the incorrect perception that the abundance of soil life itself is the cause of enhanced mineralization. But until now there is no convincing evidence that a more abundant soil life associated with the use of solid manure contributes to a better recovery (<u>A</u> in Figure 1) of N by crops (e.g. Langmeijer *et al.*, 2001). Because of the relatively high organic matter/N ratio solid manure is preferred to slurry in intensive crop rotations in which organic matter pools cannot be replenished via crop residues, like with conventional flower bulb growing farms and vegetable-oriented organic farms in the Netherlands. These farms leave the (economically less attractive) production of legumes, grass leys and cereals needed for the production of manure in general and that of solid manure in particular, to other farms in the region or even abroad.

Also specialized organic livestock farmers prefer solid manure to provide proper bedding for the animals, as required by regulations. However, for the production of every 25 tons of solid manure, the straw of about 1 ha of cereals is needed. This mismatch of organic cereal production and organic animal numbers may thus constrain unlimited use of solid manure in the Netherlands. Research directed at the reconciliation of efficient N use and animal welfare is therefore urgently needed.

This example illustrates that nutrient management involves more than the operational management at field level: decisions at the level of the field or the yard interact with processes in the soil or the herd. Moreover, decisions at the level of one specialized farm can have large consequences for other specialized farms. In addition, organic farming intends to re-establish its relationships with society through nutrient recycling. In the Netherlands, approximately 90 kg N and 13 kg P per ha are annually removed via products from organic farms to Dutch society and societies abroad (Hofstad & Schröder, 2002). At present, this leakage is compensated for by inputs from conventional farms and organic farms abroad. Apparently, the globalization of nutrient fluxes applies to organic farming too, which makes it difficult to substantiate the intentions related to sustainability, integrity, recycling and traceability.

Nutrient management and multifunctional land use

Agriculture is considered a major contributor of N and P losses to the environment, which justifies a call for control (Neeteson, 2000; Schröder *et al.*, 2003). Developing control measures is complicated, if only because action (farm management) and response (environmental effect) generally do not coincide in space and time. For instance, regional water quality, including that in coastal zones, is not only determined by the quality of water directly under and alongside agricultural land but also by the discharge of water and nutrients from land use other than agriculture. In addition, the initial charge from agriculture in its course to downstream water systems and groundwater is at least temporarily muffled by chemical processes (Oenema *et al.*, 1998). Obviously the impact of agriculture on regional water quality becomes more evident if agriculture is the dominant form of land use. The spatial scale at which environmental goals have to be achieved strongly determines to what extent 'dilution' from non-agricultural land use can be taken into account.

Many environmental indicators have the dimension 'units load *per unit area*' (Schröder *et al.*, 2002; 2003). Extensification of farming systems then provides an option to reduce the environmental impact. Such farming systems are attractive because they provide the opportunity to combine production with other functions, such as supplying habitats for wild flora and fauna and improving landscape qualities (e.g. allowing grazing cows instead of keeping them indoors in order to reduce N-leaching risks from too high a urine load). To maintain regional production on the basis of such systems, more land may be required. On the other hand, society may want that land for other purposes than (multifunctional) agriculture. So at higher spatial scales, realization of a set of multiple goals may be better served by intensive, highly productive, specialized farming systems on a limited area, than by extensive, multifunctional systems on a larger area. Multiplication of area and loss per unit area may result in a similar environment load in both situations. It is also relevant therefore to evaluate farming systems in terms of their environmental impact *per unit output* and their utilization of other resources, such as land, water, energy and labour (De Wit, 1992). However, too strong a segregation of functions (e.g. rural *versus* urban, cultural *versus* natural, production *versus* environmental quality) may alienate agriculture from society. This may conflict with the desire for rural vitality, the need for transparent and traceable food chains and the human aspiration for fluid but respectable objectives like proximity, self-sufficiency and 'naturalness'. Too strong a focus on the environmental impact per unit output may also stimulate farmers to specialize in either arable or livestock production. Such a development can have a negative effect on nutrient use efficiency of society as a whole (Schröder *et al.*, 2002) or may incur a high consumption of fossil energy due to the inevitable trans-regional transport of manure, feedstuffs, bedding materials and farm products, including animals. Moreover, highly intensive and specialized farming systems operating at the edge of environmental requirements probably have higher demands for administration and control, for capital and for knowledge transfer, as suggested by cost benefit analyses of precision farming (Lowenberg-DeBoer & Boehlje, 1996; De Haan, 2001). The price of these requirements must be weighed against the benefits of a high efficiency per unit output of such intensive farms.

In conclusion

Many measures can be taken to promote efficient use of nutrients. However, if measures are evaluated at very small spatial and/or temporal scales they may be recommended or rejected wrongly, as antagonistic or synergetic effects at higher levels of integration are ignored. Evaluations at such higher levels should be common practice in research on nutrient management. The complexity of these evaluations may require sophisticated optimization techniques (e.g. Ten Berge *et al.*, 2000a).

References

Aarts, H.F.M., E.E. Biewinga & H. Van Keulen, 1992. Dairy farming systems based on efficient nutrient management. *Netherlands Journal of Agricultural Science* 40: 285–299.

Aarts, H.F.M., B. Habekotté, G.J. Hilhorst, G. Koskamp, F.C. Van Der Schans & C.K. De Vries, 1999a. Efficient resource management in dairy farming on sandy soil. *Netherlands Journal of Agricultural Science* 47: 153–167.

Aarts, H.F.M., B. Habekotté & H. Van Keulen, 1999b. Limits to intensity of milk production in sandy areas in The Netherlands. *Netherlands Journal of Agricultural Science* 47: 263–277.

Aarts, H.F.M., B. Habekotté & H. Van Keulen, 2000a. Phosphorus (P) management in the 'De Marke' dairy farming system. *Nutrient Cycling in Agroecosystems* 56: 219–229.

Aarts, H.F.M., B. Habekotté & H. Van Keulen, 2000b. Nitrogen (N) management in the 'De Marke' dairy farming system. *Nutrient Cycling in Agroecosystems* 56: 231–240.

Berry, P.M., R. Sylvester-Bradley, L. Philipps, D.J. Hatch, S.P. Cuttle, F.W. Rayns & P. Gosling, 2002. Is the productivity of organic farms restricted by the supply of available nitrogen? *Soil Use and Management* 18: 248–255.

Bokhorst, J. & C. Ter Berg, 2001. Handbook Manure and Compost. Louis Bolk Instituut, Driebergen, 292 pp. (In Dutch)

Booij, R., D Uenk, C. Lokhorst & S. Sonneveld, 2001. Monitoring crop nitrogen status in potatoes, using crop light reflection. In: S. Blackmore & G. Grenier (Eds.), Proceedings of the Third European Conference on Precision Agriculture, 23–26 June 1996, Minneapolis, Minnesota. American Society of Agronomy etc., Madison, pp. 893–898.

Bussink, D.W. & O. Oenema, 1998. Ammonia volatilization from dairy farming systems in temperate areas: a review. *Nutrient Cycling in Agroecosystems* 51: 19–33.

De Haan, M.H.A., 2001. Economics of environmental measures on experimental farm 'De Marke'. *Netherlands Journal of Agricultural Science* 49: 179–194.

De Wit, C.T., 1953. A physical theory on placement of fertilizers. Verslagen van Landbouwkundige Onderzoekingen No. 59. Government Printer, The Hague, 71 pp.

De Wit, C.T., 1992. Resource use efficiency. *Agricultural Systems* 40: 125–151.

Dewes, T., 1995. Nitrogen losses from manure heaps. *Biological Agriculture and Horticulture* 11: 309–317.

Dilz K., A. Darwinkel, R. Boon & L.M.J. Verstraeten, 1982. Intensive wheat production as related to nitrogen fertilisation, crop production and soil nitrogen: experience in the Benelux. Proceedings of the Fertiliser Society 211, London, pp. 93–124.

Dilz, K., J. Postmus & W.H. Prins, 1990. Residual effect of long-term application of farmyard manure to silage maize. *Fertilizer Research* 26: 249–252.

Greenwood, D.J., K. Kubo, I.G. Burns & A. Draycott, 1989. Apparent recovery of fertilizer-N by vegetable crops. *Soil Science and Plant Nutrition* 35: 367–381.

Hilhorst, G.J., J. Oenema & H. Van Keulen, 2001. Nitrogen management on experimental dariy farm 'De Marke'; farming system, objectives and results. *Netherlands Journal of Agricultural Science* 49: 135–151.

Hofstad, E. & J.J. Schröder, 2002. Nitrogen and Phosphate Fluxes in Organic Farming in the Netherlands; an Incomplete Cycle. Rapport 48, Plant Research International, Wageningen, 26 pp. (In Dutch)

Huijsmans, J.F.M. & R.M. De Mol, 1999. A model for ammonia volatilization after surface application and subsequent incorporation of manure on arable land. *Journal of Agricultural Enginering Research* 74: 73–82.

Janssen, B.H., 1999. Basics of budgets, buffers and balances of nutrients in relation to sustainability of agroecosystems. In: E.M.A. Smaling, O. Oenema & L.O. Fresco (Eds.), Nutrient Disequilibria in Agroecosystems; Concepts and Case Studies. CAB International, Wallingford etc., pp. 27–56.

Langmeijer, M., A. Oberson, M. Kreuzer, P. Mäder, D. Dubois & E. Frossard, 2001. Does the farming system affect the nitrogen fertiliser value of animal manure? 11th Nitrogen Workshop, Book of Abstracts. Institut National de Recherches Agronomiques (INRA), Reims, pp. 257–258.

Lowenberg-De Boer, J. & M. Boehlje, 1996. Revolution, evolution or dead-end: economic perspectives on precision agriculture. In: P.C. Robert, R.H. Rust & W.E. Larson (Eds.), Precision Agriculture. Proceedings of the Third International Conference on Precision Agriculture, 23–26 June 1996, Minneapolis, Minnesota. American Society of Agronomy etc., Madison, pp. 923–944.

Monteny, G.J. & J.W. Erisman, 1998. Ammonia emission from dairy cow buildings: a review of measurement techniques, influencing factors, and possibilities for reduction. *Netherlands Journal of Agricultural Science* 46: 225–247.

Motavalli, P.P., L.G. Bundy, T.W. Andraski & A.E. Peterson, 1992. Residual effects of long-term fertilization on nitrogen availability to corn. *Journal of Production Agriculture* 5: 363–368.

Neeteson, J.J., 1989. Effect of reduced fertilizer nitrogen application rates on yield and nitrogen recovery of sugar beet and potatoes. *Netherlands Journal of Agricultural Science* 37: 227–236.

Neeteson, J.J., 1994. Residual soil nitrate after application of nitrogen fertilizers to crops. In: D.C. Adriano, A.K. Iskandar & I.P. Murarka (Eds.), Contamination of Groundwaters. Advances in Environmental Science. Science Reviews, Northwood, pp. 347–365.

Neeteson, J.J., 1995. Nitrogen management for intensively grown arable crops and field vegetables. In: P.E. Bacon (Ed.), Nitrogen Fertilization in the Environment. Marcel Dekker, New York, pp. 295–325.

Neeteson, J.J., 2000. Nitrogen and phosphorus management on Dutch dairy farms: legislation and strategies employed to meet the regulations. *Biology and Fertility of Soils* 30: 566–572.

Neeteson, J.J. & W.P. Wadman, 1987. Assessment of economically optimum application rates of fertilizer N on the basis of response curves. *Fertilizer Research* 12: 37–52.

Neeteson, J.J. & H.J.C. Zwetsloot, 1989. An analysis of the response of sugar beet and pototoes to fertilizer nitrogen and soil mineral nitrogen. *Netherlands Journal of Agricultural Science* 37: 129–141.

Oenema, O., P.C.M. Boers, M.M. Van Eerdt, B. Fraters, H.G. Van Der Meer, C.W.J. Roest, J.J. Schröder & W.J. Willems, 1998. Leaching of nitrate from agriculture to groundwater: the effect of policies and measures in the Netherlands. *Environmental Pollution* 102, S1: 471–478.

Prins, W.H., P.F.J. Van Burg & H. Wieling, 1980. The seasonal response of grassland to nitrogen at different intensities of nitrogen fertilization with special reference to methods of response measurements. In: W.H. Prins & G.H. Arnold (Eds.), The Role of Nitrogen in Intensive Grassland Production. Proceedings of an International Symposium of the European Grassland Federation, PUDOC, Wageningen, pp. 35–49.

Prins, W.H., K. Dilz & J.J. Neeteson, 1988. Current Recommendations for Nitrogen Fertilisation within the E.E.C. in Relation to Nitrate Leaching. Proceedings of the Fertiliser Society 276, London, 27 pp.

Ris, J., K.W. Smilde & G. Wijnen, 1981. Nitrogen fertilizer recommendations for arable crops as based on soil analysis. *Fertilizer Research* 2: 21–32.

Schiere J.B. & H. Van Keulen, 1999. Rethinking high input systems of livestock production: a case study of nitrogen emissions in Dutch dairy farming. *Tropical Grasslands* 33: 1–10.

Schils R.L.M., H.G. Van Der Meer, A.P. Wouters, J.H. Geurink & K. Sikkema, 1998. Nitrogen utilization from diluted and undiluted nitric acid treated cattle slurry following surface application to grassland. *Nutrient Cycling in Agroecosystems* 53: 269–280.

Schröder, J.J., 2003. Restoring farmer's confidence in manure benefits the environment. In: J. Martinez & J. Venglovsky (Eds.), Recycling of Agricultural, Municipal and Industrial Residues in Agriculture, Proceedings of the 10th Conference Ramiran FAO Network, 14–18 May 2002, Kosice, pp. 401–416.

Schröder, J.J. & W. Van Leeuwen-Haagsma, 2002. Mineral fluxes between and within organic farms. In: F.G. Wijnands, J.J. Schröder, W. Sukkel & R. Booij (Eds.), Scrutinizing the biological farm; organic arable farming in perspective. Rapport No 303, PPO, Lelystad, pp. 141–153. (In Dutch)

Schröder, J.J., W. Van Dijk & W.J.M. De Groot, 1996a. Nitrogen fluxes in maize cropping systems as affected by cover crops. *Netherlands Journal of Agricultural Science* 44: 293–315.

Schröder, J.J., P. Van Asperen, G.J.M. Van Dongen & F.G. Wijnands, 1996b. Nutrient surpluses on integrated arable farms. *European Journal of Agronomy* 5: 181–191.

Schröder, J.J, L. Ten Holte & B.H. Janssen, 1997a. Non-overwintering cover crops: a significant source of N. *Netherlands Journal of Agricultural Science* 45: 231–248.

Schröder, J.J., L. Ten Holte & G. Brouwer, 1997b. Effects of slurry placement on silage maize yields. *Netherlands Journal of Agricultural Science* 45: 249–261.

Schröder, J.J., J.J. Neeteson, O. Oenema & P.C. Struik, 2000. Does the crop or the soil indicate how to save nitrogen in maize production? *Field Crops Research* 62: 151–164.

Schröder, J.J, H.F.M. Aarts, H.F.M. Ten Berge, H. Van Keulen & J.J. Neeteson, 2002. An evaluation of whole-farm nitrogen balances and related indices for efficient nitrogen use. *European Journal of Agronomy*. (In press)

Schröder, J.J., D. Scholefield, F. Cabral & G. Hofmans, 2003. Sound science and feasible legislation: friends or foes? Submitted to *Nutrient Cycling in Agro-ecosystems.*

Ten Berge, H.F.M., H.G. Van Der Meer, L. Carlier, T. Baan Hofman & J.J. Neeteson, 2002. Limits to nitrogen use on grassland. *Environmental Pollution* 118: 225–238.

Ten Berge, H.F.M., M.K. Van Ittersum, W.A.H. Rossing, G.W.J. Van De Ven & J. Schans, 2000a. Farming options for the Netherlands explored by multi-objective modelling. *European Journal of Agronomy* 13: 263–277.

Ten Berge, H.F.M., J.C.M. Withagen, F.J. De Ruijter, M.J.W. Jansen & H.G. Van Der Meer, 2000b. Nitrogen responses in grass and selected field crops; QUADMOD parametrisation and extensions for STONE-application. Report No 24, Plant Research International, Wageningen, 44 pp.

Van Bruchem, J., H. Schiere & H. Van Keulen, 1999a. Dairy farming in the Netherlands in transition towards more efficient nutrient use. *Livestock Production Science* 61: 145–153.

Van Bruchem, J., F.P.M. Verhoeven, L. Brussaard & S. Tamminga, 1999b. Diet and manure characteristics in relation to nitrogen flows in dairy farming systems. In: D. Van Der Heide, E. Kanis, J.W.M. Osse & M.W.A. Verstegen (Eds.), Regulation of Feed Intake. CAB International, Wallingford etc., pp. 219–225.

Van Burg, P.F.J., M.L 'T Hart & H. Thomas, 1980. Nitrogen and grassland: past and present situation in The Netherlands. In: W.H. Prins & G.H. Arnold (Eds.), The Role of Nitrogen in Intensive Grassland Production. Proceedings of an International Symposium of the European Grassland Federation, PUDOC, Wageningen, pp. 15–33.

Van Burg, P.F.J., W.H. Prins, D.J. Den Boer & W.J. Sluiman, 1981. Nitrogen and Intensification of Livestock Farming in EEC Countries. Proceedings of the Fertiliser Society 199, London, 78 pp.

Van Der Meer, H.G., R.B. Thompson, P.J.M. Snijders & J.H. Geuring, 1987. Utilization of nitrogen from injected and surface-spread cattle slurry applied to grassland. In: H.G. Van Der Meer, R.J. Unwin, T.A. Van Dijk & G.C. Ennik (Eds.), Animal Manure on Grassland and Fodder Crops: Fertilizer or Waste? Developments in Plant and Soil Science 30, Martinus Nijhoff, Dordrecht, pp. 47–71.

Van Der Molen J., H.G. Van Faassen, M.Y. Leclerc, R. Vriesema & W.J. Chardon, 1990. Ammonia volatilization from arable land after application of cattle slurry. 1. Field estimates. *Netherlands Journal of Agricultural Science* 38: 145–158

Van Der Paauw, F., 1966. Voraussage des Düngerbedarfs und Ertrags auf Grund von Witterung und Bodenfruchtbarkeit. *Landwirtschaftliche Forschung* 20: 97–105.

Van Keulen, H. & W. Stol, 1991. Quantitative aspects of nitrogen nutrition in crops. *Fertilizer Research* 27: 151–160.

Van Noordwijk, M., 1999. Nutrient cycling in ecosystems versus nutrient budgets of agricultural systems. In: E.M.A. Smaling, O. Oenema & L.O. Fresco (Eds.), Nutrient Disequilibria in Agroecosystems; Concepts and Case Studies. CAB International, Wallingford etc., pp. 1–26.

Vellinga, Th. V. & G. André, 1999. Sixty years of Dutch nitrogen fertiliser experiments, an overview of the effects of soil type, fertiliser input, management and developments in time. *Netherlands Journal of Agricultural Science* 47: 215–241.

Vellinga, Th. V., A.H.J. Van Der Putten & M. Mooij, 2001. Grassland management and nitrate leaching, a model approach. *Netherlands Journal of Agricultural Science* 49: 229–253.

Verhagen, A., H.W.G. Booltink & J. Bouma, 1995. Site-specific management: balancing production and environmental requirements at farm level. *Agricultural Systems* 49: 369–384.

Vos, J. & P.E.L. Van Der Putten, 2000. Nutrient cycling in a cropping system with potato, spring wheat, sugar beet, oats and nitrogen catch crops. I. Input and offtake of nitrogen, phosphorus and potassium. *Nutrient Cycling in Agroecosystems* 56: 87–97.

Whitmore, A.P. & J.J. Schröder, 1996. Modelling the change in soil organic C and N in response to applications of slurry manure. *Plant and Soil* 184: 185–194.

Wolf, J., C.T. De Wit & H. Van Keulen, 1989. Modeling long-term crop response to fertilizer and soil nitrogen. I. The model. *Plant and Soil* 120: 11–22.

Wijnands, F.G., W. Van Leeuwen-Haagsma & F. Van Koesveld, 2002. Towards Good Biological Practice; Results and Experiences from the BIOM Project. In: F.G. Wijnands, J.J. Schröder, W. Sukkel & R. Booij (Eds.), Biologisch Bedrijf onder de Loep; Biologische Akkerbouw en Vollegrondsgroenteteelt in Perspectief. Rapport No 303, PPO, Lelystad, pp. 17–41. (In Dutch)