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Integrated Nitrogen Input Systems in Denmark

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Cycling of N in agriculture through the use of mineral fertilizers, manures, and N-fixing crops gives rise to many forms of N emissions to the environment, including nitrate (NO_3) leaching, ammonia (NH_3) volatilization, and nitrous oxide (N_2O) emissions, resulting in groundwater pollution, eutrophication of surface waters, soil acidification, and contributions to global warming.

The high rates of N input in intensive North European agricultural systems have given rise to high loss rates, and the focus in Danish agriculture during the past two decades has been on increasing the N use efficiency (NUE) with the aim of reducing losses. The NUE at the system level can be increased by improved handling of manure, targeted application of fertilizers and manures, and through adjustments of the crop rotation.

Trends in Danish Agriculture

The agricultural area in Denmark constituted 62 percent (26,470 km^2) of the total land area in 2000. Grasslands constituted 30 percent and cereals 47%, with dairy cattle and pigs dominating livestock production. The cattle population declined by 34 percent, from 2.84 million in 1970 to 1.87 million in 2000; however, milk was almost constant as a consequence of increasing productivity. The pig population increased by 43 percent from 8.36 million in 1970 to 11.92 million in 2000. Most of the animal feed is produced domestically.

During the 1990s fertilizer N declined rapidly (Figure 9.1), resulting in an increase in N recovery efficiency (RE) over the 20-year period of 12 percent based on total N input and of 18 percent based on input of manure, waste, and mineral N fertilizer only.

The change in mineral fertilizer use has been a result of the Danish Action Plan on the Aquatic Environment, which was initiated in 1987 and aimed at reducing N leach-

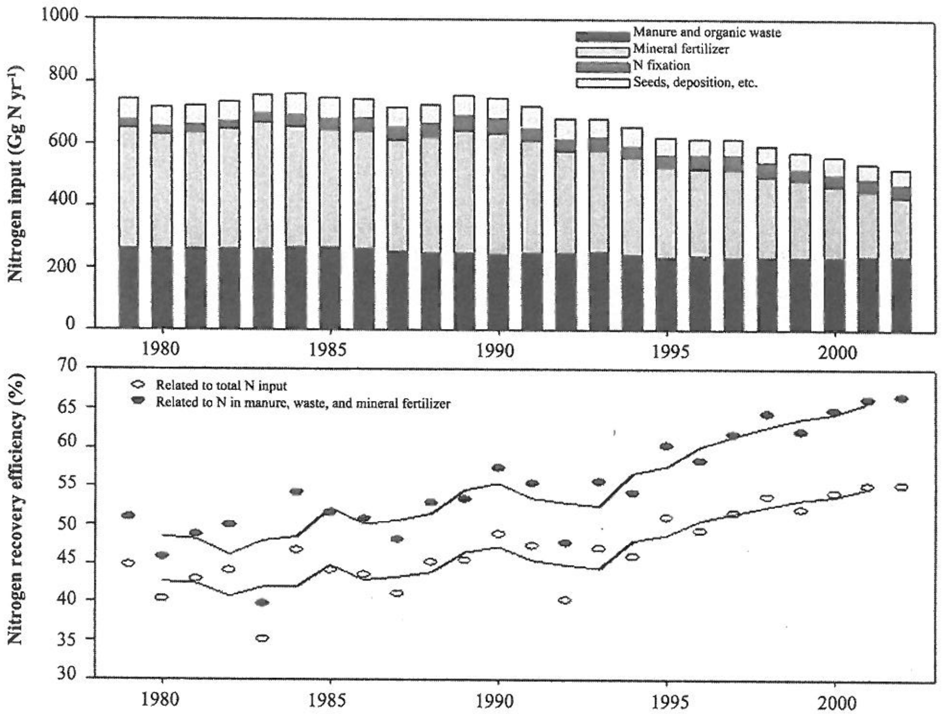

Figure 9.1. Annual N input to fields (top graph) and nitrogen use efficiency estimated as harvested N in proportion of either total N input or N in manure, organic waste, and mineral fertilizer only (bottom graph) (Kyllingsbæk, 2000).

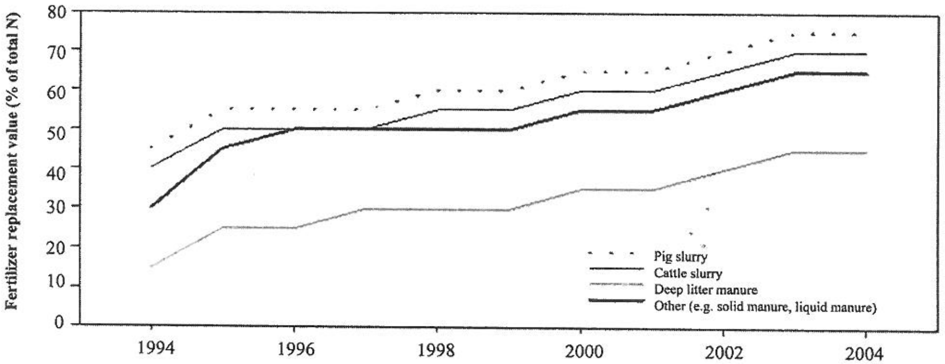

Figure 9.2. Change in fertilizer replacement value of different manure types in the Danish farm-scale fertilizer accounting system.

ing from rural areas by 100,000 t N yr^{-1} (Grant et al., 2000). The measures in the Aquatic Action Plan can be grouped into four main categories: (1) improved use of animal manures, (2) reduced N input, (3) improved crop rotations (including cover crops), and (4) conversion of cropland to permanent grassland or forestry. Fertilizer planning and nutrient accounting are compulsory with a limit on allowable use of N in fertilizers and manures, which has been set at 10 percent below the economical optimal N rate. The required fertilizer replacement value for manures has been gradually increased over time (Figure 9.2), depending on the manure type.

Crop Nitrogen Demand

The crop N demand generally increases with increasing yield. The N demand is affected by soil and climate conditions but also by biotic conditions, such as the occurrence of weeds and diseases. Olesen et al. (2003) showed that the estimated optimal N fertilizer rate for untreated diseased winter wheat was 60 kg N ha^{-1} lower than for crops without disease. The use of fungicides with an efficacy twice that of the particular fungicide type used in the experiment would increase the optimal N rate by about 20 kg N ha^{-1}.

Determining the Crop Nitrogen Demand at Field Level

The software system BEDRIFTSLØSNING is used by most Danish farmers to estimate crop N demand at field level. A simple soil organic matter model is used to estimate the residual effects of previous crops, manure application, and other inputs of organic matter on net soil N mineralization. BEDRIFTSLØSNING is supplied with information on crops grown in the previous 2 years and the expected yield. By subtracting N mineralized and N supplied with animal manure in the actual growing season, the recommended application rate of mineral fertilizer is calculated. The system has been successful in predicting the overall optimal N rate at farm level, but the skill at field level is still rather low.

To improve the estimates of optimum N rate, three biological/chemical methods for determining potentially mineralizable soil N (anaerobic incubation, boiling with KCl, and chloroform fumigation) were tested in Denmark in 2000 and 2001 (Thomsen et al. 2003). The amount of N mineralized by the three methods was compared with the actual crop N uptake in the field. Of the three methods, the anaerobic incubation gave the best correlation between crop N uptake and mineralized N; however, less than 40 percent of the variation in crop N uptake could be explained by the results from the anaerobic incubation.

Determining the Crop N Demand at Sub-Field Level

During 2001 to 2003, field experiments were conducted with the aim of developing algorithms for the redistribution of N based on soil and plant sensors (Broge et al. 2003). Each year plots placed in fields at different sites in Denmark received 60, 120, 180, or

240 kg N ha^{-1} in two dressings. Measurements with plant sensors (ratio vegetation index [RVI]) were made just before the second application, while soil sensors (electrical conductivity) were used either before planting or after harvest. A statistical analysis of the relationship between N-rate, plot yield, and sensor measurements showed a significant relationship for nearly all fields between sensor measurements and optimum N application rate. The relationship was applied for redistributing a certain amount of N fertilizer on a field, such that N fertilizer was moved from areas with low and high RVI values (low and high amounts of biomass) to areas with medium RVI. Regardless of the location, year, and sensor combination, the yield benefit from this redistribution was small and averaged less than 10 kg grain ha^{-1}. Thus the economic gain that can be expected from redistributing N within fields is nearly nil (Berntsen et al. 2002), and the redistribution of an a priori fixed amount of N within fields does not seem to have much prospect in Denmark. The current work on crop sensors and algorithms therefore focuses on monitoring the absolute N status of the crops and need for additional N.

Efficient Use of Manures

First-year Effects and Residual Effects

Most manures are stored under anaerobic or partly anaerobic conditions, and after application to soil, part of the ammonium N is immobilized by soil microorganisms as a result of the presence of easily decomposable compounds in the manure (Kirchmann and Lundvall 1993). Organic N in the manure is also mineralized, and after 2 to 3 months, N mineralization is often equal to N immobilization. Thus, the potential first year N effect of most manures is equivalent to the ammonium content of the manure (Jensen et al. 1999). High N utilization can be achieved only if losses of N by leaching, denitrification, and volatilization are minimized.

In a number of Danish experiments, the availability of manure N was measured in small confined plots using ^{15}N-labeled feces and urine from animals fed on ^{15}N-labeled diets. The enclosures used and the applied nutrient application rates allowed normal plant growth. By using labeled and similar unlabeled materials, the contribution from feces, urine, and bedding material to crop N uptake was determined separately. The crop uptake of labeled N in the year of application is highly influenced by the origin of the labeled N (Table 9.1). A significant part of the manure N is still in the soil after harvest of the first crop and is released slowly resulting in both losses and residual N effects during the following years. During the autumn/winter period following manure application to spring barley, 2 to 5 percent of the applied labeled N from both animal manure and mineral fertilizer was lost by nitrate leaching from bare soil after barley harvest (Thomsen et al. 1997). When barley was undersown with a ryegrass cover crop, 1.5 to 6 percent of the labeled manure N was recovered in the cover crop (Jensen et al. 1999; Sørensen et al. 1994; Sørensen and Jensen, 1998).

Table 9.1. Crop uptake of ^{15}N-labeled mineral fertilizer and animal manure components during two or three growing seasons measured in Danish experiments under field conditions

	^{15}N crop uptake (% of input)			
^{15}N-labeled component	*Appl. year*	*1st year*[1]	*2nd year*	*References*[2]
Applied in spring before sowing spring barley				
Mineral fertilizer N	36–57	3–5	1.2–1.5	1–4
Ruminant feces in slurry	12–17	3–6	—	1,2
Ruminant feces in solid manure	9	4.1	1.1–2.0	3
Pig feces in slurry	33	4.2	—	5
Ruminant urine in slurry	32-36	3	—	2
Ruminant urine in solid manure	25–27	3.6	1.3	3
Pig urine in slurry	47	2.5	—	5
NH_4-N in pig and cattle slurry	27–41	3–4	1.8–2.5	4, 5
Bedding straw in solid manure	9–10	3.3	1.1–1.3	3
Applied in August before winter wheat				
Total N in solid manure	8–10	2.6	—	6

[1] First year of residual effects.

[2] 1: Sørensen et al. (1994), 2: Thomsen et al. (1997), 3: Jensen et al. (1999), 4: Sørensen and Amato (2002), 5: Sørensen, unpublished, 6: Thomsen (2001).

In the second year (first residual year), 3 to 6 percent of the labeled N was recovered in barley and grass crops, and in the third year another 1 to 2.5 percent was recovered (Table 9.1). A few months after application, the release rate of residual labeled N is lower for fecal N and straw N than for urinary and mineral fertilizer N (calculated as percentage of residual ^{15}N in soil), but because more N is left in the soil from feces and straw than from urine and fertilizer, the ^{15}N release, calculated as the percentage of applied ^{15}N, is similar for N in the different components (Table 9.1). Manure storage conditions have negligible influence on the release of residual N (Thomsen 2001). Thus, the residual N effect in the years after application of animal manure is mainly determined by the amount of total N applied (manure + mineral fertilizer), not the type of manure.

Table 9.2 shows average estimates of residual N effects after a single and repeated application of standard animal manure types. The estimates are based on ^{15}N and other experiments and show the additional effect of animal manure N compared with soil receiving mineral fertilizer N (Sørensen et al. 2002). When comparing residual N effects in such experiments, it should be recognized that there is also crop uptake of residual fertilizer ^{15}N in the years after mineral fertilizer application. The residual effect

Table 9.2. Estimated residual nitrogen effects of repeated applications of animal manure supplemented with mineral fertilizer compared with soil receiving only mineral fertilizers, expressed as fertilizer replacement value (% of annual manure application)[1]

	Repeated animal manure applications		
Manure type	*1 yr*[2]	*2 yr*	*10 yr*
Cattle slurry	3–5	5–7	10–15
Pig slurry	2–4	3–5	7–10
Solid manure	6–9	8–12	16–24

[1] From Sørensen et al. (2002).

[2] First year with residual N effect.

in the first year after manure application is relatively low, whereas the effect of repeated manure application can be considerable (Table 9.2). A large part of the residual manure N is mineralized during autumn (Sørensen and Amato 2002), and residual effects are therefore higher in crops with a long growing period.

Effects of Manure Treatment, Application Time, and Method

Animal manure can be treated in different ways to modify its characteristics, for example, slurry separation, anaerobic digestion, and slurry acidification. To increase the first-year availability of manure N, it is necessary to remove part of the decomposable carbon in the manure without losing N during the process. After anaerobic digestion of slurry, the content of decomposable carbon is reduced and part of the organic manure N is mineralized, resulting in less N immobilization after application and a higher plant availability of N (Kirchmann and Lundvall 1993).

Trail-hose application (surface-banding) in spring in established cereal crops is widely used in Denmark. A well-established crop canopy reduces ammonia volatilization, but significant volatilization may still occur when slurry is surface-banded in a crop (Sommer et al. 1997). The ammonia emission can be further reduced by direct injection, but crop damage by injector tines and more traffic in the field by injection is a problem in established crops, and can reduce yields.

A high N utilization is obtainable after direct injection of slurry before sowing in spring. The high N utilization is partly due to reduced volatilization and partly due to lower N immobilization when the slurry is placed in a band in the soil (Sørensen and Jensen 1998). Sørensen et al. (2003) found higher denitrification losses after direct injection, but this loss was counterbalanced by the lower N volatilization loss. If slurry

injection is followed by wet soil conditions the loss of N by denitrification can be significant (Thompson et al. 1987).

Efficient Use of Nitrogen in Crop Rotations

Effects of Previous Crops

Fertilizer N standards are enforced for farmers and growers in Denmark. The standards are field and crop specific and based on average N response curves from field trials carried out primarily on farmers' fields. The fertilizer standards are made for individual crops and are made as specific as possible for different soil types and previous crops. The largest experimental base is available for winter wheat, and this has made it possible to distinguish between different previous crops.

An analysis of the data for winter wheat shows that the economic optimum N application rate may vary considerably within years and sites (Petersen 2002). The optimum N rate ranged from 0 to 300 kg N ha^{-1} within a single year. One of the important aspects was the previous crop grown on a field, with grass–clover and alfalfa having a residual effect that reduced optimum N rate by 60 kg N ha^{-1} (Petersen 2002). Even the crop grown 2 years previously had an effect if the crop was grass–clover or alfalfa, where optimum N rate was reduced by 50 kg N ha^{-1}. The effect of winter rape as the previous crop was a reduction in optimum N rate of about 45 kg N ha^{-1} and that of spring rape and pulse crops was a reduction of about 35 kg N ha^{-1}.

Residual Effects of Grasslands

In grasslands, a considerable buildup of N may take place. As a consequence of this buildup, the cultivation of grasslands is followed by a rapid and extended period of N mineralization that may often exceed the requirement of the subsequent arable crop (Francis 1995). The residual effects of six 3-year-old grasslands on yield and nitrate leaching in the following three cereal crops were investigated on a loamy sand in Denmark (Eriksen 2001). The grasslands were unfertilized grass–clover and fertilized ryegrass subject to cutting or continuous grazing by dairy cows with two levels of N in feed supplements. In the first year the residual effect of the grazed grasslands was sufficient to obviate the need for supplementary fertilizer, but in the following years gradually more fertilizer N was required to obtain economic optimal yields. A residual effect (N fertilizer replacement value) following grass–clover was at least 115 kg N ha^{-1}. The residual effect of grazed ryegrass was 90 to 100 kg N ha^{-1}, while for cut ryegrass it was only 25 kg N ha^{-1}. In the second year after grassland cultivation, the residual effects were 60 kg N ha^{-1} after grass–clover, 40 kg N ha^{-1} after grazed ryegrass, and negative after cut ryegrass. In the third year, the residual effects were either very small or nonexistent.

The residual effect is a combination of non-N and N effects. The N recovery of grass–clover and grazed and cut ryegrass in the first year was 50 to 70, 40 to 50, and less than 0 kg N ha^{-1}, respectively.

Effect of Cover Crops

Cover crops are grown between main crops with the purpose of reducing nitrate leaching from soil during autumn and winter when the soil would have been bare. The commonly tested cover crop in Denmark is perennial ryegrass (*Lolium perenne* L.) undersown in spring barley. The N uptake may vary with soil type and N application rates in the specific field, but the average N uptake in a ryegrass cover crop grown after spring barley is about 24 kg N ha^{-1} (Hansen et al. 2000c). Uptake of N from ryegrass material incorporated in autumn ranges from 10 to 19 percent, 2 to 4 percent, and 1 to 2 percent in the first, second, and third year, respectively (Jensen 1992; Thomsen and Jensen 1994). N derived from the cover crop may accordingly amount to 2 to 5 kg N ha^{-1} in the first growth season after incorporation. If the N taken up by the cover crop would not have been completely lost by leaching during winter, however, the cover crop, through its uptake of soil N, may effectively reduce the soil N pool available for initial uptake of the subsequent crop (Thorup-Kristensen 1993). Because a ryegrass cover crop may contain 3 to 9 kg N ha^{-1} at the time of harvest of the main crop (Jensen 1991), an immediate positive residual value may not be obtained if determined in barley grown repeatedly with a cover crop.

The N content of soil is raised after long-term use of cover crops (Thomsen 1995) and thereby also the amount of mineralizable N. Extra N mineralized from cover crops may either be taken up by a crop or lost by nitrate leaching. After 24 years of repeated use of cover crops, Hansen et al. (2000a) found that the average increase in leaching over 4 years corresponded to 14 kg N ha^{-1} yr^{-1}; however, the amount of plant-available N was also increased, thereby reducing the need for N fertilization by up to 27 kg N ha^{-1} yr^{-1} (Hansen et al. 2000b).

Cover crops have been implemented in Danish agriculture with a compulsory use on 6 percent of the area grown with winter and spring cereals, field peas, and rape. Among the allowed cover-crop species are grasses, crucifers, and chicory. The application of mineral fertilizer in the following year is reduced by 12 kg N ha^{-1} to account for increased soil N mineralization.

Crop Rotation Effects

Efficient utilization of crop rotation effects is particularly important in low-input farming systems, such as organic arable farming, where there is a much larger dependency on N_2-fixing crops, including pulses, green-manure crops, and cover crops.

Olesen et al. (2002) showed that rotations without a whole-year green manure crop produced the greatest total yield. Dry matter yields and N uptake in grains in this rotation were about 10 percent higher than in the rotation with a grass–clover ley in one year of four. Therefore, the yield benefits from the grass–clover ley could not compensate for the yield reduction as a result of leaving 25 percent of the rotation out of production.

The yield response from applying manure was the same with and without a green-manure crop. The RE_N of harvested grain for ammonium–N applied in manure was about 37 percent for cereal crops. A similar RE_N of 41 percent was found on average for an application of 50 kg of fertilizer N to winter wheat in on-farm fertilizer experiments carried out during 1991 to 1998 (Knudsen et al. 1999).

Winter wheat has a relatively high N demand, which in low-input farming systems can be partly supplied by a green-manure crop before the winter wheat. In the crop-rotation experiment, winter wheat and winter rye were grown just after the grass–clover green-manure crop. This gave quite different results at the different sites and years. A regression of wheat grain N uptake on accumulated N in the aboveground biomass when the green-manure crop was cut gave slopes of 0.04, 0.07, and 0.10 for the coarse sand, loamy sand, and sandy loam soils, respectively. The number of cuts varied from two to four, and if it is assumed that the N accumulation is less than half the aboveground N at the time of cutting as a result of internal recycling, then the recovery of the N in the green manure varies between 10 and 25 percent in the first year after the green-manure crop. The variation is probably linked with N leaching during the winter after sowing the winter wheat because the highest N leaching was found for the coarse sand (120 kg N ha^{-1} yr^{-1}) and the lowest for the sandy loam (35 kg N ha^{-1} yr^{-1}).

The aboveground N in the cover crop and weeds was measured by sampling in early November in the year before the spring barley. A multiple regression analysis was performed for spring barley grain N uptake against N in the biomass in November with manure application and previous crop as additional class variables. The cover crop's RE_N was taken as the slope of this regression. The results indicated greater RE_N for the coarse sand (72 percent) compared with the other soil types (49–49 percent) in rotations 1 and 2, where non N-fixing cover crops were used (ryegrass and chicory). The N recovery efficiency was greatest in the rotation, where a red and white clover was used in combination with ryegrass as a cover crop (70–77 percent). The use of aboveground biomass as an indicator of cover crop N probably overestimates the N utilization because there is often a substantial below-ground component in cover crops (Hansen et al. 2000c).

Conclusions

Over 15 years, the N surplus in Danish agriculture has been reduced by 235 Gg N yr^{-1} without reducing productivity. The result has been an increase in the overall N recovery efficiency from 42 to 52 percent, achieved primarily through a higher utilization of N in animal manures and a better consideration of pre-crop effects on yield potential and N supply. The lower N rates have led to a slight reduction in cereal grain protein content, but because the grain is used primarily for animal feed, this does not constitute a general problem.

The higher utilization of N in animal manure has been achieved by reducing losses during application and by better accounting for efficiency in the application year and in the following years. There is probably little scope for further increasing the NUE of animal manures, although a modest improvement may be obtained through manure digestion, slurry acidification, and improving technologies for slurry injection.

The pre-crop effects of legumes (grass–clover and pulse crops) and cover crops are now included in the Danish fertilizer recommendations. These recommendations are, however, based on average growing conditions of the legumes, and in practice the N fixation and thus the residual N effects vary considerably. There is a need to account for this more clearly in the estimates of crop N demand and also to account for soil and climate differences in the pre-crop effects.

Further improvement of N utilization needs to focus on a better determination of crop N demand at the farm, field, and subfield levels. Individual technologies for properly determining this N demand have failed to provide good estimates. A combination of technologies for measuring soil and crop characteristics with modeling of long-term crop rotation effects on N mineralization may increase the precision in determining optimal N rate and thus further increase NUE.

Literature Cited

Berntsen, J., A. Thomsen, K. Schelde, and O. M. Hansen. 2002. Ny strategi for GPS-gødskning med sensor. *Agrologisk* 3-02:26–27.

Broge, N. H., A. Thomsen, and P. B. Andersen. 2003. Stability of selected vegetation indices commonly employed as indicators of crop development— The red edge inflection point (REIP) and the ratio vegetation index (RVI). Pp. 146–149 in *Proceedings of the seminar on implementation of precision farming in practical agriculture.* DIAS report 100. Foulum, Denmark: Danish Institute of Agricultural Sciences.

Eriksen, J. 2001. Nitrate leaching and growth of cereal crops following cultivation of contrasting temporary grasslands. *Journal of Agricultural Science, Cambridge* 136:271–281.

Francis, G. S. 1995. Management practices for minimising nitrate leaching after ploughing temporary leguminous pastures in Canterbury, New Zealand. *Journal of Contaminant Hydrology* 20:313–327.

Grant, R., G. Blicher-Mathiesen, V. Jørgensen, A. Kyllingsbæk, H. D. Poulsen, C. Børsting, J. O. Jørgensen, J. S. Schou, E. S. Kristensen, J. Waagepetersen, and H. E. Mikkelsen. 2000. *Vandmiljøplan II - midtvejsevaluering.* Silkeborg, Denmark: Miljø-og Energiministeriet, Danmarks Miljøundersøgelser.

Hansen, E. M., J. Djurhuus, and K. Kristensen. 2000a. Nitrate leaching as affected by introduction or discontinuation of cover crop use. *Journal of Environmental Quality* 29:1110–1116.

Hansen, E. M., K. Kristensen, and J. Djurhuus. 2000b. Yield parameters as affected by introduction or discontinuation of cover crop use. *Agronomy Journal* 92:909–914.

Hansen, E. M., A. Kyllingsbæk, I. K. Thomsen, J. Djurhuus, K. Thorup-Kristensen, and V. Jørgensen. 2000c. *Efterafgrøder. Dyrkning, kvælstofoptagelse, kvælstofudvaskning og eftervirkning.* DJF Rapport No. 37. Foulum, Denmark: Danish Institute of Agricultural Sciences.

Jensen, B., P. Sørensen, I. K. Thomsen, E. S. Jensen, and B. T. Christensen. 1999. Availability of nitrogen in ^{15}N-labeled ruminant manure components to successively grown crops. *Soil Science Society of America Journal* 63:416–426.

Jensen, E. S. 1991. Nitrogen accumulation and residual effects of nitrogen cover crops. *Acta Agriculturae Scandinavica* 41:333–344.

Jensen, E. S. 1992. The release and fate of nitrogen from cover-crop materials decomposing under field conditions. *Journal of Soil Science* 43:335–345.

Kirchmann, H., and A. Lundvall. 1993. Relationship between N immobilization and volatile fatty acids in soil after application of pig and cattle slurry. *Biology and Fertility of Soils* 15:161–164.

Knudsen, L., T. Birkmose, R. Hørfarter, O. M. Hansen, H. S. Østergaard, and K. L. Hansen. 1999. Gødskning og kalkning. Pp. 182–238 in *Oversigt over landsforsøgene,* edited by C. Å. Pedersen. Skejby, Denmark: Landbrugets Rådgivningscenter.

Kyllingsbæk, A. 2000. *Kvælstofbalancer og kvælstofoverskud i dansk landbrug 1979–1999.* DJF Rapport Markbrug no. 36. Foulum, Denmark: Danish Institute of Agricultural Sciences.

Olesen, J. E., L. N. Jørgensen, J. Petersen, and J. V. Mortensen. 2003. Effects of rates and timing of nitrogen fertiliser on disease control by fungicides in winter wheat. 1. Crop yield and nitrogen uptake. *Journal of Agricultural Science, Cambridge* 140:1–13.

Olesen, J. E., I. A. Rasmussen, M. Askegaard, and K. Kristensen. 2002. Whole-rotation dry matter and nitrogen grain yields from the first course of an organic farming crop rotation experiment. *Journal of Agricultural Science, Cambridge* 139:361–370.

Petersen, N. 2002. What is the reason for and the consequences of the variation in N-optimum? Pp. 57–62 in *Optimal nitrogen fertilization— tools for recommendation. Proceedings from NJF seminar 322,* edited by H. S. Østergaard, G. Fystro. and I. K. Thomsen. DIAS report, Plant Production No. 84. Tjele, Denmark: Danish Institute of Agricultural Sciences.

Sommer, S. G., E. Friis, A. Bach, and J. K. Schjørring. 1997. Ammonia volatilisation from pig slurry applied with trail hoses or broadspread to winter wheat: Effects of crop developmental stage, microclimate, and leaf ammonia absorption. *Journal of Environmental Quality* 26:1153–1160.

Sørensen, P., and M. Amato. 2002. Remineralisation and residual effects of N after application of pig slurry to soil. *European Journal of Agronomy* 16:81–95.

Sørensen, P., and E. S. Jensen. 1998. The use of ^{15}N labelling to study the turnover and utilization of ruminant manure N. *Biology and Fertility of Soils* 28:56–63.

Sørensen, P., E. S. Jensen, and N. E. Nielsen. 1994. The fate of ^{15}N-labelled organic nitrogen in sheep manure applied to soils of different texture under field conditions. *Plant and Soil* 162:39–47.

Sørensen, P., I. K. Thomsen, B. Jensen, and B. T. Christensen. 2002. Residual nitrogen effects of animal manure measured by ^{15}N, in *Optimal nitrogen fertilization— tools for recommendation. Proceedings from NJF seminar 322,* edited by H. S. Østergaard, G. Fystro, and I. K. Thomsen. DIAS report, Plant Production No. 84. Tjele, Denmark: Danish Institute of Agricultural Sciences.

Sørensen, P., F. P. Vinther, S. O. Petersen, J. Petersen, and I. Lund. 2003. Høj udnyttelse af gyllens kvælstof ved direkte nedfældning. *Grøn Viden, Markbrug* 281, 1–6. Tjele, Denmark: Danish Institute of Agricultural Sciences.

Thompson, R. B., J. C. Ryden, and D. R. Lockyer. 1987. Fate of nitrogen in cattle slurry following surface application or injection to grassland. *Journal of Soil Science* 38:689–700.

Thomsen, I. K. 1995. Cover crop and animal slurry in spring barley grown with straw incorporation. *Acta Agriculturae Scandinavica* 45:166–170.

Thomsen, I. K. 2001. Recovery of nitrogen from composted and anaerobically stored manure labelled with ^{15}N. *European Journal of Agronomy* 15:31–41.

Thomsen, I. K., and Jensen, E. S. 1994. Recovery of nitrogen by spring barley following incorporation of ^{15}N-labelled straw and cover crop material. *Agriculture, Ecosystems and Environment* 49:115–122.

Thomsen, I. K., V. Kjellerup, and B. Jensen. 1997. Crop uptake and leaching of ^{15}N applied in ruminant slurry with selectively labelled faeces and urine fractions. *Plant and Soil* 197:233–239.

Thomsen, I. K., P. Sørensen, J. Djurhuus, B. Stenberg, H. S. Østergaard, and B. T. Christensen. 2003. Bestemmelse af plantetilgængeligt kvælstof i jord tilført afgrøderester og husdyrgødning. DIAS report, Plant Production. Tjele, Denmark: Danish Institute of Agricultural Sciences.

Thorup-Kristensen, K. 1993. The effect of nitrogen cover crops on the nitrogen nutrition of a succeeding crop. I. Effects through mineralization and pre-emptive competition. *Acta Agriculturae Scandinavica* 43: 74–81.