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Reestimation and further development in the model N-LES, N-LES$_3$ to N-LES$_4$

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1. Introduction

This model N-LES_4 is the fourth version of an empirical model for prediction of nitrogen leaching from arable lands. The first version was published by Simmelsgaard et al. (2000) and the previous version (N-LES_3) was described by Kristensen et al. (2003). The model predicts the leaching based on nitrogen applications and crops in the year of leaching, the crops in the previous year, the average nitrogen applications through the last five years and information on soil type and drainage during the last two years. The model is developed in cooperation between The Faculty of Agricultural Sciences (DJF) and National Environmental Research Institute (NERI), both part of the University of Aarhus – and based on data collected by both these institutions. This report describes the results of this latest version of N-LES together with information on how it deviates from previous versions. In addition, the report describes some of the effects and gives a preliminary evaluation of the model.

2. Data

This model version uses the same data sources as previous versions, i.e. data from the agricultural catchment monitoring programme – the LOOP programme - (collected by NERI), data from series of drainage water measurements collected by DJF and data from field experiments carried out by DJF. However, previous sources have been updated with more recent data when possible. Data from monitoring catchment 5 (LOOP5) together with one observation from catchment 1 (LOOP1) and one from catchment 3 (LOOP3) have been excluded because these sites are atypical for Danish agriculture and are no longer part of the monitoring programme.

The more recent data show leaching levels and ranges that are generally somewhat lower than those previously used. Average leaching and standard deviation of leaching used in N-LES_2 were thus, respectively, 74 and 62 kg N ha^{-1}, those in N-LES_3 were 64 and 57 kg N ha^{-1}, respectively, while they in the present version were 52 and 45 kg N ha^{-1}, respectively. The range of leaching in the data used in the present version has become smaller because of some very extreme observations in the excluded data, so the smallest and largest leaching levels recorded are now 0 and 341 kg N ha^{-1} compared to 0 and 446 kg N ha^{-1}, respectively, in the data used for N-LES_3. In total, 1467 observations were used for estimation of the parameters, while in the N-LES_1, N-LES_2 and N-LES_3 models the numbers of observations were 598, 596 and 1299, respectively. The number of observations together with the year span and the level of leaching for each source of data can be found in Table 5.

Calculation of drainage and thus leaching were done using rainfall corrections and evaporation with the Makkink formula and crop coefficients (K_c) that may exceed the value 1 (Plauborg et al., 2002). The monthly drainage was estimated using the model DAISY

(Abrahamsen and Hansen, 2000) and the yearly leaching, defined as from 1April in the year of harvesting the summer crop to 31 March the following year, was then calculated.

The amount of nitrogen (N) fixed by a main crop, and any catch crop, has for the NERI data been calculated using the Danish farm planning program "Bedriftsløsningen" from the Danish Agricultural Advisory Service (Hvid, 2004), while nitrogen fixation for data from DJF has been calculated according to Høgh-Jensen et al. (2004). The latter requires information on the dry matter content of harvested legumes, which is usually included in the experiments at DJF, but not in the NERI data from the monitoring programme. A comparison of the two methods (Vinther, unpublished) shows that at typical clover levels (about 20 %), the same fixation level was obtained with the two methods, while at high or low levels of clover content the best estimate was achieved using the method of Høgh-Jensen et al. (2004).

3. Choice of model type and explanatory parameters

The basic structure in the model is the same as in previous versions (Simmelsgaard et al., 2000 and Kristensen et al., 2003). This means that the model comprises both additive and multiplicative parameters. The model has, however, been modified in a number of areas on the basis of new knowledge and discussions with users of the model. The most important modifications are:

- The effect of crop is now included as an additive effect. The previous crop is included as an additive effect in order to describe their effect on variation in residual N levels in the soil. Both the crop and previous crop are now subdivided into a summer crop (main crop) and a winter crop (sub crop). The winter crop can be the same as the summer crop and/or the crop of the following year – or it can be an under sown grass for fodder or a catch crop used to reduce leaching. The grouping of crops has been changed.

- In the modelling process the difference between commercial farms and experimental stations is now included as an additive effect.

- The effect of organic matter in the soil is now included both as an additive effect and a multiplicative effect. The additive effect describes the nitrogen leaching from the organic matter taking into account the relation between N and C and how this influences the degradation and thus release of N (Thomsen et al., 2008). The multiplicative effect describes the extent to which organic matter retains mineral nitrogen and water in the soil and thus reduces leaching.

- The effect of nitrogen removed in harvested crops is no longer included in the model as the effect was very low. This effect was only included in some of the previous models.

- A technology effect, which describes any significant development in leaching over time, is included. This effect describes the changes over time that are not included in the model, such as changes to crop rotations, soil tillage, use of pesticides and varieties, etc.

- All additive effects that directly or indirectly describe added or removed N are now summed before they are raised to a power. This makes the effect of a specific source of N dependent on how much is added/removed by the other sources. For example, the effect of 1 kg spring-applied plant-available N will be larger if the N level is 200 kg N than if it is 150 kg N. Similarly, the effect will depend on crop, previous crop, and other nitrogen sources. If the sum of the additive effects describing added or removed N becomes negative, it is set at a very small value and some of it is additionally transferred to the part of the additive effects that are not raised to a power. This is done in order to ensure a slope on the N response curve also at low N levels.

- In this version of N-LES the drainage has been made up on a monthly basis instead of on a yearly basis as used in previous versions. Effect of yearly leaching is now calculated for the period from 1 April to 31 March and the drainage for all fields is now calculated using the model DAISY. In previous versions the model EVACROP (Olsen and Heidmann, 1990) was used for some of the data. The Daisy model yielded lower drainage values, hence the calculated N leaching values were lower than previously.

- An effect of previous year's drainage is included in order to incorporate the leachable N that may remain in the soil from previous years.

- The effect of both the drainage in the year of leaching and in previous year has now been subdivided into three periods: A summer period (April-August), an autumn period (September-December) and a winter period (January-March) in order to take into account the differences in importance of drainage in the different periods.

- The N level is calculated as the average amount of N added in the five years previous to the actual year of leaching. When information about the five previous years is not available, average N values from the first five years with recordings have been used.

- The newest methods for calculating water drainage and N fixation have been adopted (Plauborg et al., 2002; Høgh-Jensen et al, 2004).

In connection with the setup of the model, several explanatory variables were investigated but not included. These were the effects of spring and autumn-applied organic N in animal manure as separate parameters (they are included in the N level), but the effects were noninterpretable and thus not retained in the model. The effect of farm type (crop, cattle and pigs in combination with organic farming) was investigated as additive effects, but the effects were relatively small and thus not retained. The effect of temperatures, in three-four separate periods, was investigated as additive effects, but the effects were not so clear and seemed to be correlated with each other and other effects already included in the model.

4. Results: N-LES$_4$ model

For given values of the explanatory variables the prediction model can be written as:

$$\hat{Y} = \{U + V^{\hat{\kappa}}\}M\hat{c}$$

Where

$\hat{Y}$ is the predicted leaching

T is the sum of direct and indirect N effects

U is an additive effect of a temporal development (technology effect) and a mathematical expression that ensures a slope to the N response curve also at low N levels

V the positive values of T that are raised to an exponent

$\hat{c}$ is a constant to ensure same mean of leaching for predicted and observed values,

$$U = \begin{cases} \hat{\theta}_0 + \hat{\theta}_1 /(\mathring{a}r - \hat{\theta}_2) & \text{hvis } T \geq 0 \\ \hat{\theta}_0 + \hat{\theta}_1 /(\mathring{a}r - \hat{\theta}_2) + \varphi T & \text{hvis } T < 0 \\ \text{min } 0 \end{cases}$$

$$V = \begin{cases} T & \text{if } T > 0 \\ 0 \ \ (0.001) & \text{if } T \leq 0 \end{cases}$$

$$T = \hat{\beta}_0 + \hat{\beta}_1 N_{level} + \hat{\beta}_2 (N_{sping} + N_{fix}) + \hat{\beta}_3 N_{excretion} + \hat{\beta}_{4j} N_{autumn} + \hat{\beta}_5 f_{c/n} C_{total}$$
$$+ \hat{\gamma}_{summer\ crop} + \hat{\gamma}_{winter\ crop} + \hat{\lambda}_{previous\ summer\ crop} + \hat{\lambda}_{previous\ winter\ crop} + \hat{\eta}_{experimantal\ station}$$

$$M = [1 - \exp(-\hat{\delta}_{1a} A_{0aa} - \hat{\delta}_{1a} A_{0sd} - \hat{\delta}_{1b} A_{0jm})] \exp(-\hat{\delta}_{2a} A_{1aa} - \hat{\delta}_{2b} A_{1sd} - \hat{\delta}_{2b} A_{1jm}) \exp(-\hat{\delta}_3 H) \exp(-\hat{\delta}_4 L)$$

A_{0aa}, A_{0sd} and A_{0jm} are the drainage in the months April-August, September-December, January-March in the actual year. A_{1aa}, A_{1sd} and A_{1jm} are the drainage in same months of the previous year

other parameters are defined in tables 1-3.

4.1 Parameter estimates

Tables 1, 2 and 3 show the parameter estimates for the model together with an approximate standard error. With the chosen parameter estimates, the level of leaching, *Y,* can be predicted for given values of the explanatory variables using the equation above.

Table 1 shows the additive effects that comprise the effect of added N, *N level*, *N-spring*, *N-autumn, N-excretion* and *N-C in soil.*

Table 1. Parameter estimates and standard errors for additive non-classification variables.

Parameter	Description		Estimate	Approximate StdErr
κ	Power		1.50	0.10
θ_0	Intercept		175	67
θ_1	Technology effect		2878	1
θ_2	Technology effect		1968	2
β_0	Intercept in T		31	10
β_1	N-level		0.115	0.026
β_2	N-spring and N-fixation		0.094	0.023
β_3	N-excretion		0.103	0.052
β_{4s}	N-autumn	Sandy soil	0.374	0.176
β_{4l}	N-autumn	Clay soil	0.167	0.071
β_5	N-C in soil		0.728	0.160
φ	Effect of negative T		0.5	-

Intercept: can be interpreted as the leaching of N from a hypothetical cereal crop field followed by bare soil with a cereal followed by bare soil as previous crop and with a clay and organic matter content of 0%, where no N has been added and where drainage has been, respectively, infinitely large and zero in the current and previous leaching years.

Technology effect: The variable is the specific year when the leaching year starts. Year 2001 is, for example, the leaching year that starts in April 2001 and finishes March 2002. The technology effect explains the changes (which cannot be explained by the input variables) in leaching that took place over the years. This could be the effect of new crop varieties, changes in soil management or crop protection. Changes in temperature and increasing CO_2 levels can, however, also have an effect. The technology effect is largest in the 1970s and reduces over time. As the technology effect cannot in any sensible way be extrapolated to coming years, it is recommended that in the future application of the model the year 2004 is used – the last year of the data material.

N-level: Has been calculated as the average addition of N (measured in kg ha^{-1} $year^{-1}$) in the five years of leaching prior to the actual year of leaching (where no information on the five previous years is available, average N levels from the first five years of data are used). Added N comprises the sum of total-N in artificial fertilizer, animal manure, deposition from animals on grass and biological N fixation.

N-spring: Is the amount of added mineral N in artificial fertilizers and animal manure (measured in kg ha^{-1} $year^{-1}$) in the period between 15^{th} February and 1^{st} September.

N-fixation: Is the amount of fixed N (measured in kg ha^{-1} $year^{-1}$) by crops grown in the year of leaching. For fields without legumes a fixation of 2 kg ha^{-1} $year^{-1}$ is assumed.

N-excretion: Is the total amount of N (measured in kg ha^{-1} year^{-1}) deposited on the field during grazing.

N-autumn: Is the autumn-applied artificial fertilizer and winter-applied (1.9 – 15.2) ammonium-N (measured in kg ha^{-1} year^{-1}) in animal manure on either sandy soil (Jb 1-4) or clay soil (Jb 5-8).

N-C in soil: Is the effect of the amount of N in soil organic matter (based on tonne C ha^{-1} and the C/N relation in the top 0-25 cm). The parameter β_5 describes the effect after the total amount of C has been corrected by a factor that depends on the relation between C and N (Thomsen et al., 2008). The factor varies between 0.35 and 1.00 for the soils used here and is given by the expression $f_{C/N} = \min(56.2 \times CN^{-1.69}, 1.0)$, where CN is the relation between C and N in the top 0-25 cm.

Table 2 shows the additive effects that comprise the effect of crop, previous crop and cultivation on an experimental station when compared to a commercial farm.

Table 2. Parameter estimates and standard errors for additive classification variables.

Parameter	Description	Estimate	Approximate StdErr
	Summer crop		
γ_{s1}	Grass[a] + Peas + Cereal/clover	18.6	6.2
γ_{s2}	Beets + Potatoes	-29.3	6.7
γ_{s3}	Cereal + Grass for seed production + Legume/spring cereal	0	-
γ_{s4}	Rape	23.2	14.4
γ_{s5}	Maize	28.4	15.0
	Winter crop		
γ_{v1}	No crop (bare soil)	0	-
γ_{v2}	Grass for seed productions + Grass[a]	-100.6	16.5
γ_{v3}	Undersown grass + Winter rape + Autumn-sown catch crop	-43.6	7.8
γ_{v4}	Autumn-sown cereal	-11.5	4.6
	Previous summer crop		
λ_{s1}	Grass for seed productions + Beets + Potatoes + Peas + Maize +Legume/spring cereal	-17.7	4.6
λ_{s2}	Grass[a] + Rape + Fallow	5.0	3.2
λ_{s3}	Cereal + Cereal/clover	0	-
	Previous winter crop		
λ_{v1}	No crop (bare soil)	0	-
λ_{v2}	Grass for seed productions	-51.6	18.5
λ_{v3}	Grass[a] + Under sown grass + Autumn-sown cereal	-9.1	3.2
λ_{v4}	Winter rape + Other autumn-sown crop	-15.9	9.3
	Location of observation		
η	Experimental station	-24.9	6.7

a) Includes pure grass as well as grass-clover mixtures

Summer crop: The effect of a crop group is estimated as being either larger or smaller than group 3 (*Cereal + Grass for seed production + Legume/spring cereal*). Group 5 had the largest indirect N effect of 28.4. Crops in group 5 therefore – all other things being equal – produced the largest level of leaching. The lowest leaching levels were obtained with crops in group 2.

Winter crop: The effect of a winter crop group is estimated as being either larger or smaller than group 1 (*No crop, i.e. bare soil*). All winter crops had a negative value and they thus produced less leaching than bare soil – all other things being equal. The lowest leaching levels are achieved when the soil was covered with a grass crop (group 2).

Previous summer crop: The effect of a previous crop group is estimated as being either larger or smaller than group 3 (*Cereal + Cereal/clover*).

Previous winter crop: The effect of a previous winter crop group is estimated as being either larger or smaller than group 0 (*No crop, i.e. bare soil*). All winter crops reduced leaching in the following leaching year when compared to bare soil and with all other things being equal.

Experimental station: The effect of the field being located on an experimental station is estimated as being either larger or smaller than a field on a commercial farm. The estimate shows that – all other things being equal – the leaching from a field on an experimental station was smaller than for a similar field on a commercial farm.

Table 3 shows the parameter estimates of multiplicative variables that comprise the effect of drainage and soil type and the correction factor.

Table 3. Parameter estimates and standard errors of multiplicative variables.

Parameter	Description	Estimate	Approximate StdErr
δ_{1a}	Drainage in year of leaching April-December	0.000382	0.000112
δ_{1b}	Drainage in year of leaching January-March	0.000659	0.000201
δ_{2a}	Drainage in previous year April-August	0.000549	0.000390
δ_{2b}	Drainage in previous year September-March	0.000424	0.000118
δ_3	Amount of Humus, %	0.1866	0.0237
δ_4	Amount of clay, %	0.0494	0.0064
c	Correction factor	1.256	-

Drainage in the leaching year: The drainage is calculated using the exponential function. Drainage has a very strong effect on leaching. At very large drainage events (where leaching is not limited), a multiplication factor of 1 is used. If the drainage is 0 the multiplication factor is 0 and for all other drainages the factor varies between 0 and 1. A given drainage event had a larger effect in the winter period (January-March) than in the rest of the year.

Drainage in previous leaching year: The drainage is calculated using the exponential function. It has a less important effect on leaching than drainage in the leaching year. At low drainage events (where leaching the previous year was virtually non-existent) the factor is close to 1 and becomes smaller with increasing levels of drainage in the previous year.

Soil type: Is characterised by percentage of organic matter and clay in the topsoil. Leaching reduces with increasing soil organic matter content and clay content. An increase in soil organic matter content from 2% to 4% thus reduces leaching by approx. 31%. An increase in soil clay content from 6% to 10% correspondingly reduces leaching by approx. 18%.

Correction for skewness: In order to obtain the same average for the predicted leaching as for the measured values, all values are multiplied by the factor 1.256. The correction factor was calculated after all other effects were estimated.

4.2 Random effects and coefficient of determination

Table 4 shows the contribution to the variability of ln(*Y*) for each of the random effects, the coefficient of determination (R^2) and the standard deviation.

Table 4. Number of observations, variance components, coefficient of determination and standard deviation on differences between observed and predicted values.

Parameter	Description	Estimate
n	Number of observation	1467
σ_L^2	Location [a)]	0.0419
σ_Y^2	Year	0.0221
σ_1^2	Residual, DJF	0.2593
σ_2^2	Residual, DMU without grassing animals	0.3965
σ_3^2	Residual, DMU with grassing animals	0.6350
R^2	Coefficient of determination [b)]	0.526
Std	Standard deviation [c)]	33.3

[a)] Field on farmlands or on experimental station

[b)] Based on sum of squares for predicted and observed leaching

[c)] Based on differences between observed and predicted leaching, kg N ha^{-1} $year^{-1}$

Variance: The residual variance on ln(*Y*) corresponds to a coefficient of variation on leaching of approx. 50-70%. If random effects are included, the coefficient of variation is 60-90%. Residual variance includes several components. The most important are: 1) uncertainty relating to concentrations in water in suction cups due to, e.g., soil variation, variation in the application of fertilizer, etc., 2) uncertainty in the explanatory variables such as applied fertilizer, nitrogen excretion, etc, and 3) the inability of the model to explain all the details.

The coefficient of variation therefore depends on the observation type, as many relations must necessarily be more uncertain when the explanatory variables are based on interviews rather than on experimental data, likewise the uncertainty relating to application of fertilizer will be larger when some of this originates from grazing animals. The random variation of location and year describes the additional variation from location to location (field to field or treatment to treatment) caused by e.g. soil variation not explained by percentage organic matter and clay and the farmers' choice of management. In this version, this component of variation was clearly reduced when compared to the previous versions, which is most probably mainly caused by the exclusion of some fields (more extreme ones). The random variation of year describes the additional variation from year to year caused by e.g. climate differences from year to year.

Coefficient of determination (R^2): About 50% of the variation in the observed leaching was explained by the model. The value is about the same as in the previous model, but somewhat lower than in N-LES$_1$ and N-LES$_2$, which is due, among other things, to the number of observations increasing steeply from about 600 to about 1300-1500 and the new observations being less extreme than earlier data.

Standard deviation (Std): describes the average deviation between recorded and predicted leaching. The value of 33.3 corresponds to approx. 60% of the average leaching in the data. This may seem to be a rather high value. However, even with the best models, the standard deviation cannot be less than the standard deviation of recorded leaching. It is associated with a large level of uncertainty and in some experiments with measurements in replicated plots in the same field it has been found to vary between approx. 1-200% with an average value of around 40%. On this background the model is judged to give a good description of the utilized data.

5. Model validation

The model has not been validated using independent data or any kind of cross-validation. The previous version was validated using cross-validation (Larsen and Kristensen, 2007) and similar methods may be used to validate this model. The following shows a number of tables and figures that can be used for a preliminary validation of the model.

Table 5 shows the measured and predicted leaching for each locality and/or experiment. A good agreement between recorded and modelled leaching can be seen. However, in a few series predicted leaching deviated considerably from measured leaching. This could be due to the effect of variables that the model does not take account of. Some experiments may, for example, have taken place in a period with cold autumns and winters, which is expected to reduce mineralization in the leaching period.

Table 5. Observed and predicted leaching for each locality or experiment. Only fixed effects have been used to predict the leaching (i.e. without including the random effect of the individual field or year).

Locality/experiment	Years	No. obs.	Observed kg N/ha			Predicted kg N/ha		
			Avg.	Min	Max	Avg.	Min	Max
Loop nr 1	1991-2004	81	31	0	109	39	0	109
Loop nr 2	1991-2004	82	80	0	284	78	0	183
Loop nr 3	1991-2004	56	57	6	341	65	8	204
Loop nr 4	1991-2004	84	39	0	127	53	0	123
Loop nr 6	1991-2004	106	101	1	334	87	6	231
Drainage water	1973-1996	94	67	7	240	65	6	165
Supplementary square grid	1989-1993	73	65	1	192	52	17	145
Increasing N	1974-1990	103	44	3	169	50	12	113
Ploughing of grass-clover	1990-1994	30	77	52	108	90	72	112
Catch crop, tillage and N	1988-1991	64	52	4	160	53	20	95
Long-term catch crop	1994-1996	24	51	19	117	45	12	108
Organic matter input	1990-1992	44	50	12	129	50	21	85
Low input rotations	1990-1992	31	46	7	121	56	30	131
Fodder crop rotation	1990-1992	24	38	12	73	51	22	75
Organic cereal rotations	1998-2004	294	44	3	248	41	8	121
Organic fodder crop rotation	1995-2001	168	29	0	144	27	4	71
Residual effect of grassland	1998-1999	36	23	4	80	23	16	32
Drainage water, continued	1998-2004	33	45	5	140	61	18	123
Slurry and catch crop	1988-1989	12	80	15	232	70	29	111
Low input fodder crops	1998-2000	28	49	16	155	45	16	120
All	1972-2004	1467	52	0	341	52	0	231

Table 6 likewise shows measured and estimated leaching for 20 groups of crop. Large deviations were found for fields with first year and older grass, with winter rape/winter cereal, with maize and especially with other crops, but here there were only two observations and both were atypical agricultural crops (winter rape with under sown grass and summer rape followed by bare soil). For the remaining crops the averages of observed and predicted leaching seemed to be reasonably close. The maximum predicted values were in most cases smaller than the observed maximum and the minimum predicted values were in many cases larger than the observed minimum. This is expected because the model aims at finding the best predicted value for a given field.

Table 6. Observed and predicted leaching for each combination of summer/winter crop. Only systematic effects have been used to predict the leaching (i.e. excluding the random effect of the individual field or year).

Crop summer/winter	No. obs.	Observed kg N/ha Avg.	Observed kg N/ha Min	Observed kg N/ha Max	Predicted kg N/ha Avg.	Predicted kg N/ha Min	Predicted kg N/ha Max
Grass for seed production	21	23	1	59	24	10	51
First year grass/grass	96	43	1	248	31	4	113
Older grass/grass	87	52	0	319	40	4	121
Grass/winter cereal	61	75	6	341	75	17	204
Winter cereal/under sown grass	29	33	7	88	31	9	83
Spring cereal/under sown grass	341	37	0	221	36	4	184
Fodder beets/bare soil	68	55	6	184	56	8	208
Sugar beets/bare soil	43	39	2	106	49	1	109
Potatoes/bare soil	3	52	50	55	45	42	51
Cereal/winter cereal	141	52	0	174	55	0	137
Cereal/other crop	36	43	8	127	41	17	79
Cereal/bare soil	378	63	0	240	66	0	172
Spring rape/winter cereal	5	92	14	171	91	37	143
Peas/winter cereal, other crop	43	55	0	201	63	0	182
Winter rape/winter cereal	17	66	3	162	86	3	165
Maize/winter cereal	2	66	25	107	43	37	48
Maize/bare soil	24	114	28	334	120	17	231
Cereal-mixture/under sown grass	34	29	6	185	30	10	53
Cereal-mixture/bare soil	36	60	14	235	57	21	111
Other crops [a)]	2	143	109	178	77	74	81
All	1467	52	0	341	52	0	231

[a)] Winter rape with under sown grass and spring rape with bare soil.

Figure 1 shows the observed leaching plotted against predicted leaching. The plot shows that the variation between predicted and observed leaching was much smaller when the leaching was small than when the leaching was large.

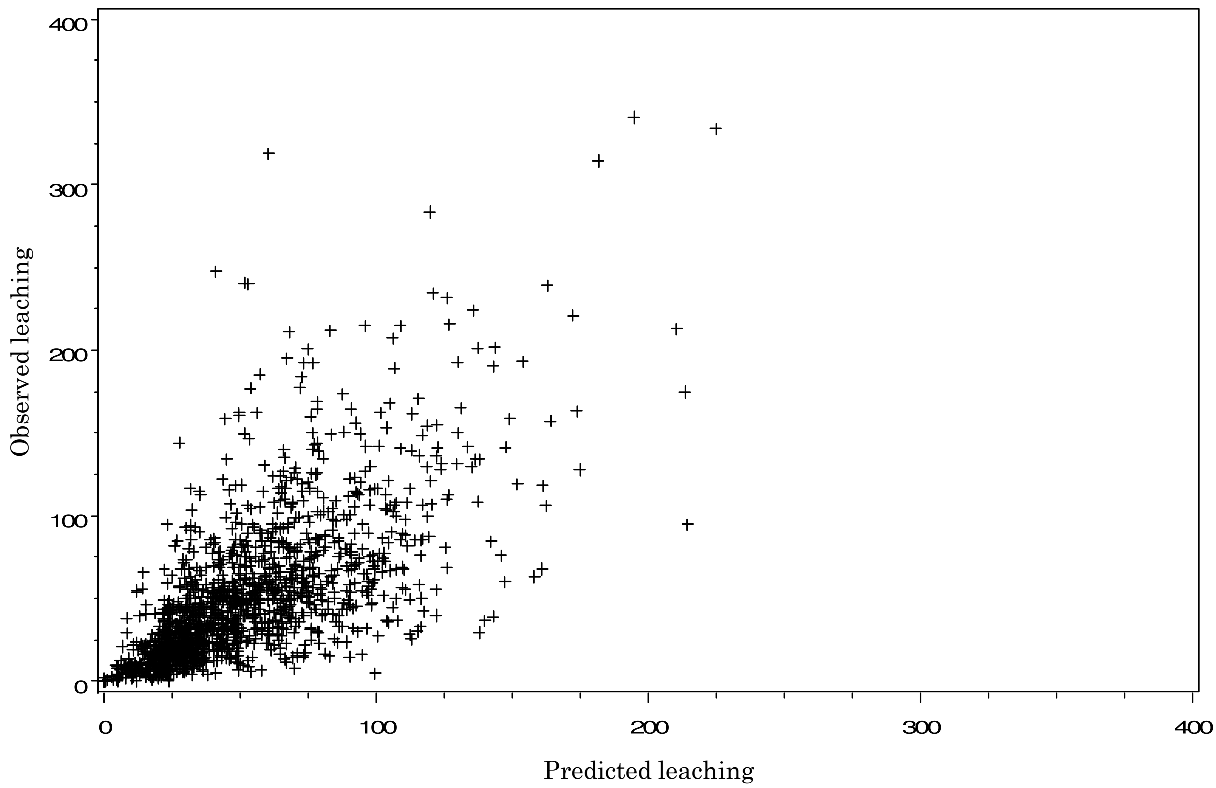
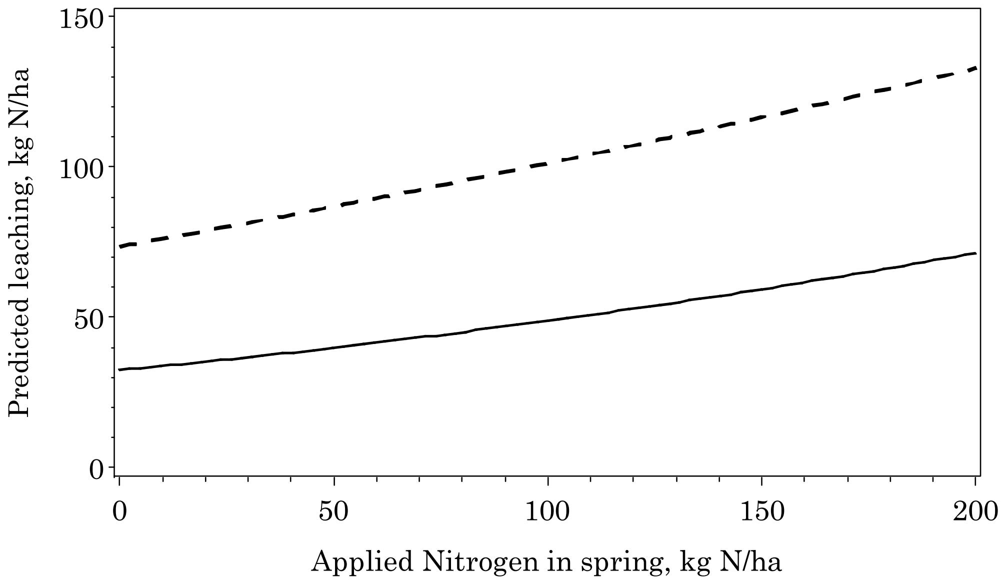


Figure 1. Plot of observed leaching against predicted leaching.

Figure 2 shows the effect of N for spring cereal followed by bare soil and cereal followed by winter cereal. The calculation assumed that N level was identical to *N spring* + *N fixed*, that there were no other N allocations to the crop and that the previous crop was cereal flowed by bare soil. The leaching depends on soil type and precipitation and the two figures show two extremes – a coarse sandy soil in a region with high precipitation and a sandy loam soil in a region with low precipitation. The figure shows the increasing marginal effect of applied nitrogen as the level of nitrogen increased and that the leaching – for the same crop – depended very much on where it was grown. The marginal effect seemed to be lower than expected from experimental data (Simmelsgaard and Djurhuus, 1998). The average slope was about 0.30 and 0.15 for spring cereal followed by bare soil in the figure to the left and to the right, respectively.



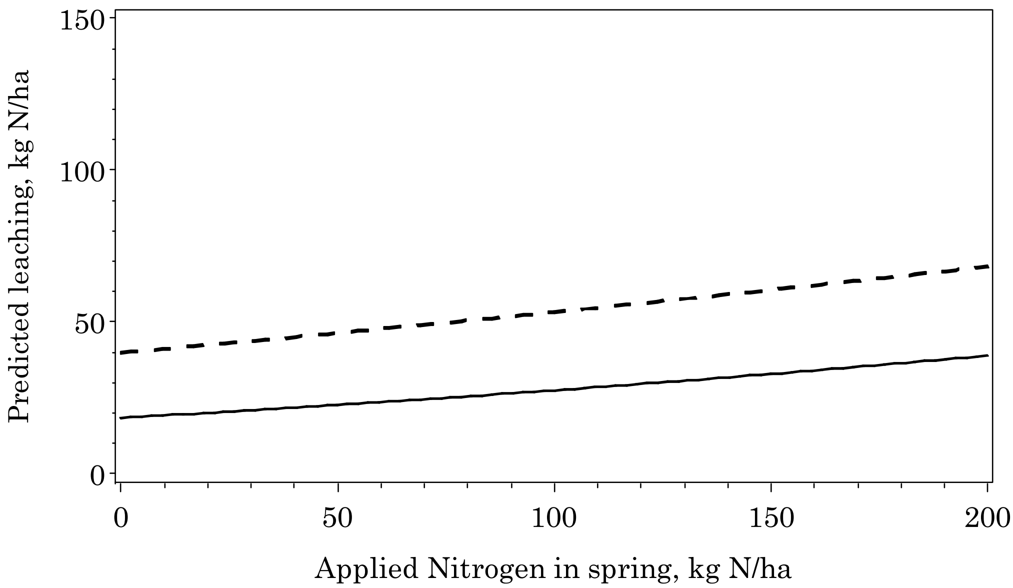


Figure 2. Predicted nitrogen leaching for different levels of spring-applied fertilizer for spring cereal. In each plot with (full line) and without (dashed line) autumn-sown winter crop. Left: on sandy soil (Jb 1) and high precipitation (Jyndevad). Right: Clay soil (Jb 6) and low precipitation (Roskilde). Data are shown in appendix 1.

Similarly rather low values for responses to nitrogen application were found for other crops. In order to investigate whether this could be caused by defects in the model, four different sets of data were selected. In each set the crop, previous crop and soil conditions were made as homogeneous as possible. For each of the sets the leaching was plotted against the level of nitrogen application to the soil, a simple regression analysis was performed and the regression line superimposed on the plot (Figure 3). The figures seemed to show an accordance between the low predicted leaching for increasing nitrogen and the data from which they were estimated.

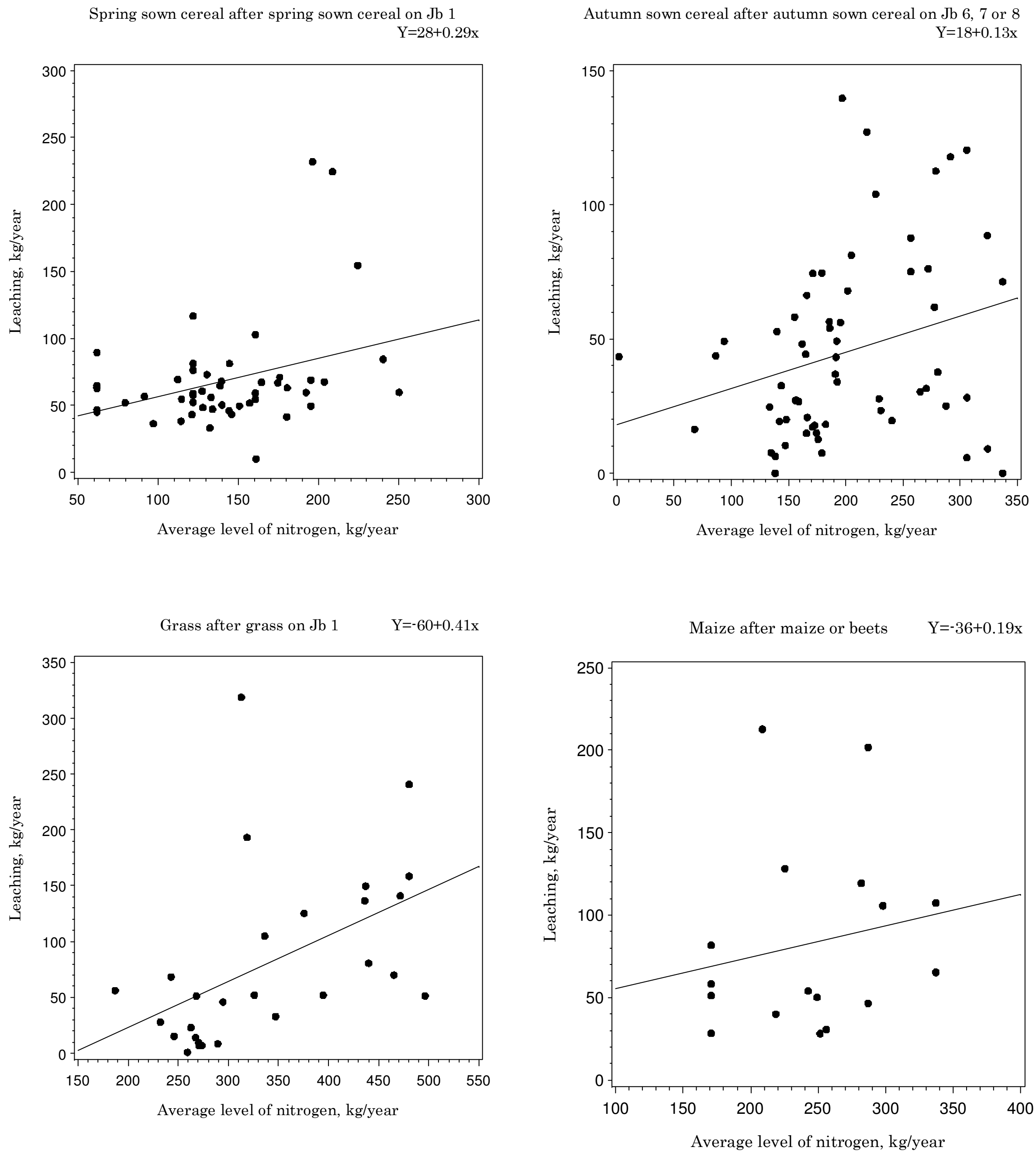


Figure 3. Plot of leaching against average nitrogen level (over five years) for four different crops with the best linear regression line.

It was questioned whether the low response to nitrogen application could be due to a partial confounding with the technology effect because of the decreasing nitrogen application over time from about 1975 to 2005. This was examined by estimating the nitrogen response in a model where the technology effect was excluded. This did not change the response to increasing nitrogen application (Table 7), although the absolute amount of leaching was predicted to be higher (in 2005) when the decline over years was not taken into account.

Table 7. Change in nitrogen leaching in models with and without the technology effect incorporated for selected examples.

				Leaching with N application in model					
Summer crop	Winter crop	Precipitation level	JB-no	**with tech. effect**			**without tech. effect**		
				100*	200*	300*	100*	200*	300*
Grass mixture	none	Jyndevad	1	123	157	194	133	165	201
Grass mixture	Grass mixture	Jyndevad	1	27	32	48	29	39	57
Winter barley	none	Jyndevad	1	88	117	151	97	125	157
Winter barley	none	Roskilde	6	49	64	80	54	68	84
Winter barley	Winter barley	Jyndevad	1	73	101	132	81	108	136
Winter barley	Winter barley	Roskilde	6	41	55	71	46	60	75
Maize	none	Jyndevad	1	117	151	188	128	161	196
Maize	none	Roskilde	6	61	77	94	67	83	99

* kg N/ha

The technology effect was almost the same in N-LES_4 as in N-LES_3 (Figure 4). The shifting position of the lines is caused by the smaller response to nitrogen applications in N-LES_4 than in N-LES_3.

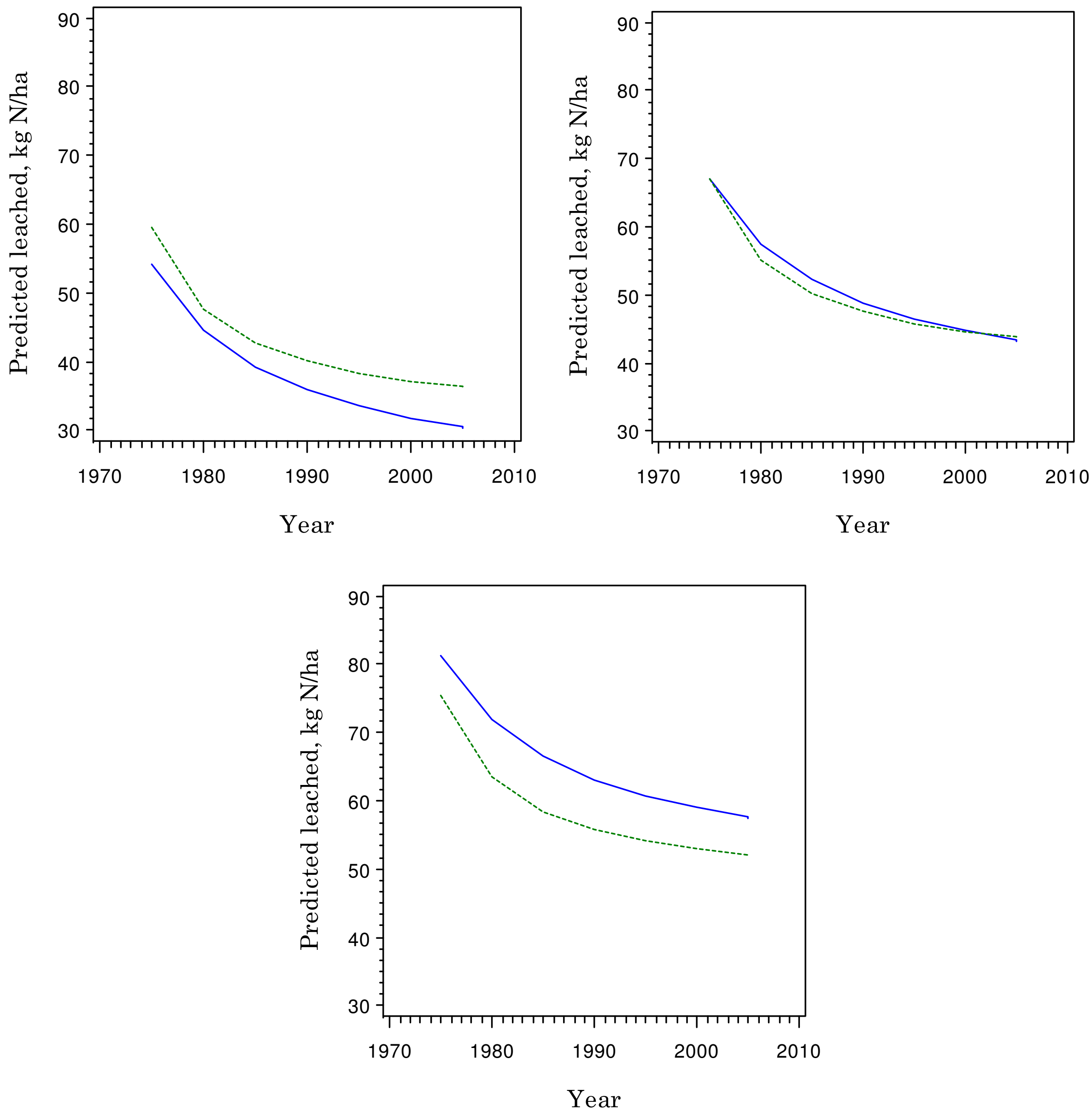


Figure 4. Nitrogen leaching for a cereal crops as a function of year predicted with N-LES$_3$ (blue solid line) and N-LES$_4$ (green dashed line). Top left: Spring cereal with 50 kg applied N. Top right: Spring cereal with 100 kg applied N. Bottom: Spring cereal with 150 kg applied N. The values are predicted means of all combinations of soil type and precipitation. Data are shown in appendix 2.

Comparisons with N-LES_3

The results of the new N-LES_4 were compared with the previous version (N-LES_3) by predicting the leaching by both models:
The average yearly leaching was calculated for five LOOP-areas and compared
The leaching in three standard crop rotations were calculated and compared

The LOOP programme is part of the National Monitoring Programme for the Aquatic Environment initiated in 1990. The LOOP areas consist of five small agricultural catchments (5-15 km^2) varying in soil type, rainfall, and livestock density. The monitoring consists of yearly interviews with farmers regarding farming practices (crops, fertiliser, yields, cultivation, and livestock) and intensive measurement of soil water and groundwater at 5-8 selected sites of each catchment as well as measurement of stream water.

The comparisons for the LOOP areas showed a clear trend of N-LES_4 predicting less leaching than N-LES_3 in the years until about 1997, whereas in the following years the predicted leaching values were almost identical (Figure 5). The discrepancies in the period 1990-97 are due to high levels of N applications and a lower N response in $NLES_4$ than in $NLES_3$.

Comparisons between two crop rotations, a maize rotation and a grass-clover rotation, are shown in Figure 6, and for continuous spring barley in Table 8. No catch crops were included and the spring whole-seed crop was under sown with grass-clover. Liquid cattle manure equivalent to 1.5 animal units per ha was applied to all rotations and supplemented with inorganic N according to the Danish N-norms. N removed by crops was calculated from norm yields and standard N contents. The comparisons were made for a coarse sandy soil (JB1) and a sandy loam soil (JB6) in combination with high and low precipitation, corresponding to a runoff at 1 m depth of 549-575 and 251-279 mm, respectively, depending on crops.

Generally, calculations with N-LES_4 resulted in higher leaching than when calculated with N-LES_3, and the difference was most pronounced with high precipitation. The largest difference between N-LES_4 and N_LES_3, corresponding to 33 kg N/ha, was found for continuous barley on a sandy loam soil and at high precipitation (Table 8).

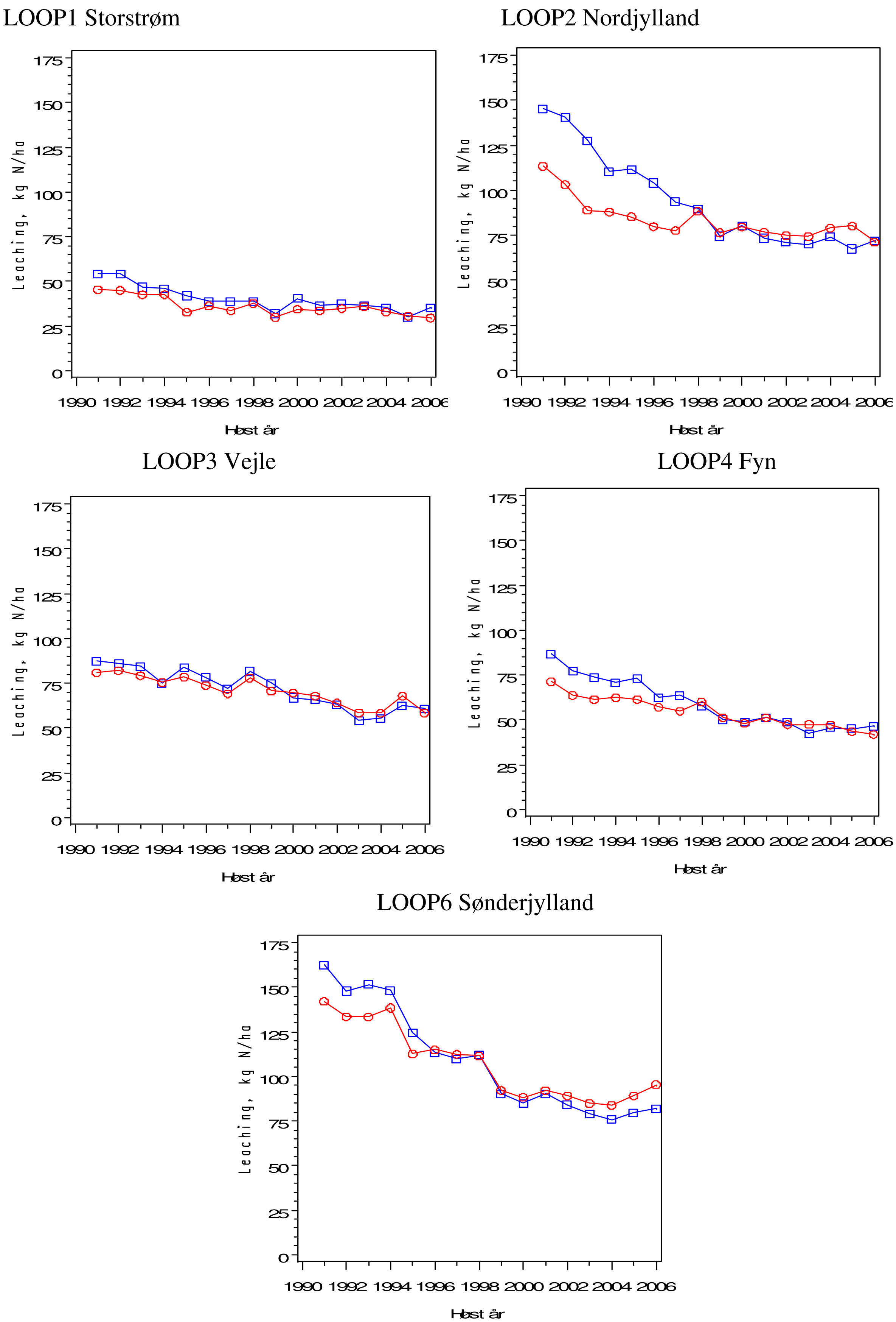


Figure 5. Predicted yearly leaching for each of five loops. Blue squares and lines are for N-LES$_3$ while red dots and lines are for N-LES$_4$. Data are shown in appendix 3.

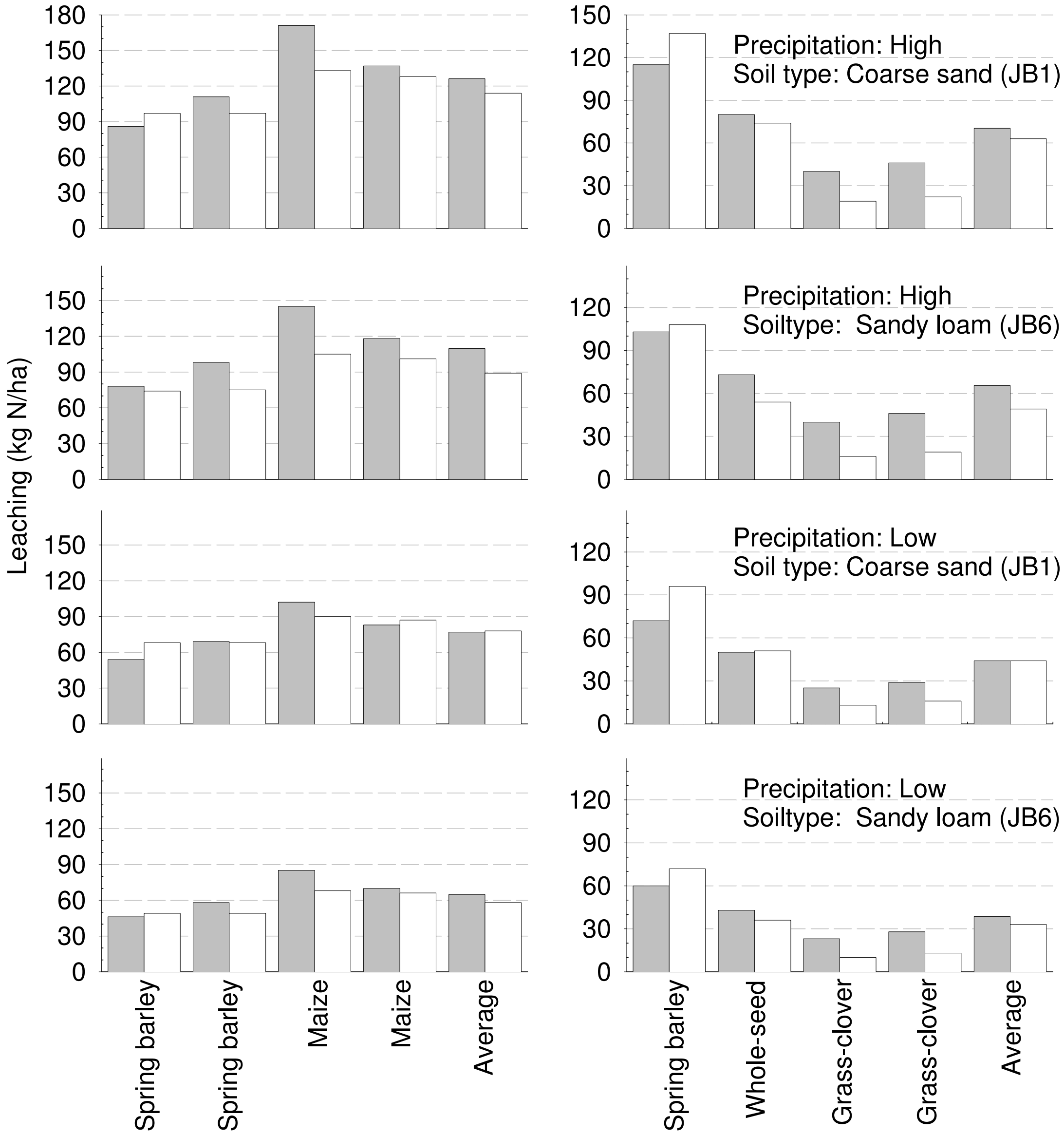


Figure 6. Leaching (kg N/ha) from a maize and a grass-clover rotation at four combinations of precipitation and soil type. Results of N-LES$_4$ calculations are shown with grey bars and N-LES$_3$ with white bars. Data are shown in appendix 4.

Table 8. Leaching (kg N/ha) calculated with N-LES$_4$ and N-LES$_3$ from continuous barley at four combinations of precipitation and soil type.

	High precipitation		Low precipitation	
	Coarse sand	Sandy loam	Coarse sand	Sandy loam
N-LES$_4$	113	101	70	59
N-LES$_3$	86	68	61	45

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Appendix 1 – data used and shown in figure 2

Applied values of variables that do not depend on amount of applied N

All data		Depending on soil and precipitation	Coarse sandy soil, high precipitation	Sandy loam soil, low precipitation
Year of harvest	**2005**			
N-level	See below	C in soil	65 t/ha	55 t/ha
N-spring	See below	C/N factor	0.56	0.98
N-fixation	2 kg/ha	Drainage Apr-Dec	315 mm	109 mm
N-excretion	0 kg/ha	Drainage Apr-Dec	245 mm	138 mm
N-autumn	0 kg/ha	Drainage prev. year Apr-Aug	54 mm	34 mm
Crop	Spring cereal	Drainage prev. year Sep-Mar	517 mm	217 mm
Previous crop	Spring cereal	Amount of humus	3.2 %	2.5 %
Location of obs.	Commercial	Amount of clay	4.7 %	12.7 %

Applied N-level, N spring application and predicted N leaching

Soil type and precipitation	Winter crop	N-level and N spring application				
		0	50	100	150	200
Coarse sandy soil, high precipitation	-	74	87	101	116	133
	+	32	40	49	59	71
Sandy loam soil, low precipitation	-	40	46	53	61	68
	+	18	23	27	33	39

Appendix 2 – data shown in figure 4

Predicted leaching as function of year and applied N for spring cereal with N-LES$_3$ and N-LES$_4$

Year	50 kg N/ha		100 kg N/ha		150 kg N/ha	
	N-LES$_3$	N-LES$_4$	N-LES$_3$	N-LES$_4$	N-LES$_3$	N-LES$_4$
1975	54	60	67	67	81	75
1980	45	48	57	55	72	63
1985	39	43	52	50	67	58
1990	36	40	49	47	63	56
1995	34	38	46	46	61	54
2000	32	37	45	45	59	53
2005	30	36	43	44	58	52

Appendix 3 – data shown in figure 5

Year of harvest	Predicted by N-LES$_3$					Predicted by N-LES$_4$				
	LOOP1	LOOP4	LOOP3	LOOP2	LOOP6	LOOP1	LOOP4	LOOP3	LOOP2	LOOP6
1991	54	87	88	145	163	46	71	81	113	142
1992	54	77	86	141	148	45	64	82	103	134
1993	47	74	84	128	152	43	61	79	89	134
1994	46	71	75	111	149	43	62	76	88	138
1995	42	73	84	112	125	33	62	78	85	113
1996	39	63	78	104	113	36	57	74	80	115
1997	39	64	72	94	110	34	55	69	78	113
1998	39	58	82	90	112	38	60	78	88	112
1999	32	50	75	75	90	30	51	71	76	92
2000	40	49	67	80	85	34	48	70	80	88
2001	36	51	66	73	90	34	51	68	77	92
2002	37	49	63	71	84	35	47	64	75	89
2003	37	42	54	70	79	36	48	59	74	85
2004	35	46	55	74	76	33	47	58	79	84
2005	30	45	63	68	80	31	44	68	80	89
2006	35	47	61	72	82	30	42	59	71	95

Appendix 4 – data used and shown in figure 6

Crop rotation no. and crops	High precipitation							
	Coarse sandy soil (JB1)				Sandy loam soil (JB6)			
	N-level for crop rotation[a]	N-spring[b] + N fixation	N leaching predicted with: N-LES3	N-LES4	N-level for crop rotation[a]	N-spring[b] + N fixation	N leaching predicted with: N-LES3	N-LES4
1. Barley	271	43	115	137	275	45	103	108
1. Whole-seed	271	188	80	74	275	182	73	54
1. Grass-clover	271	290	40	19	275	300	40	16
1. Grass-clover	271	312	46	22	275	322	46	19
2. Barley	177	78	86	97	174	81	78	74
2. Barley	177	78	111	97	174	81	98	75
2. Maize	177	159	171	133	174	148	145	105
2. Maize	177	141	137	128	174	133	118	101
3. Barley	166	110	114	88	169	115	102	70
3. Barley	166	101	112	86	169	103	100	67
3. Barley	166	101	112	86	169	103	100	67
3. Barley	166	101	112	86	169	103	100	67

[a] N level corresponds to average total N applied to the crop rotation.

[b] N-spring corresponds to the amount of inorganic N in manure plus added fertilizer N.

Crop rotation no. and crops	Low precipitation							
	Coarse sandy soil (JB1)				Sandy loam soil (JB6)			
	N-level for crop rotation[a]	N-spring[b] + N fixation	N leaching predicted with: N-LES3	N-LES4	N-level for crop rotation[a]	N spring[b] + N fixation	N leaching predicted with: N-LES3	N-LES4
1. Barley	271	43	72	96	275	45	60	72
1. Whole-seed	271	188	50	51	275	182	43	36
1. Grass-clover	271	290	25	13	275	300	23	10
1. Grass-clover	271	312	29	16	275	322	28	13
2. Barley	177	78	54	68	174	81	46	49
2. Barley	177	78	69	68	174	81	58	49
2. Maize	177	159	102	90	174	148	85	68
2. Maize	177	141	83	87	174	133	70	66
3. Barley	166	110	71	62	169	115	60	46
3. Barley	166	101	70	60	169	103	59	44
3. Barley	166	101	70	60	169	103	59	44
3. Barley	166	101	70	60	169	103	59	44

[a, b]N Notes a and b: see table above