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Nitrogen losses from agricultural areas

A fraction of applied fertilizer and manure (FracLEACH)

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Summary:

The current IPCC guidelines define an estimate for the fraction of mineral fertilizer and animal waste (manure) lost to leaching and runoff (FracLEACH). The FracLEACH default is 30 %. The main purpose of this study was to give an updated estimate of nitrogen (N) leaching in relation to the amounts of N applied in agriculture (FracLEACH) for Norway. The estimates of FracLEACH presented in this report were based on data from the Agricultural Environmental monitoring program (JOVA). The overall FracLEACH estimated in this study was 22 % of the N applied. This value is a median of FracLEACH for each year during the monitoring period and for each of 8 catchments. It covers a variation between sites from 16 % on grassland in Valdres to 44 % in intensive vegetable, potato and cereal production areas in the southernmost part of Norway.

Runoff is the most significant parameter describing 86 % of the variation between catchments, but also production system is important for FracLEACH. It is thus suggested to use different FracLEACH-values for the different production systems and adjust FracLEACH according to average runoff for the region.

Approved

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Project leader

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Preface

The present report presents an updated estimate for the factor FracLEACH defined by the IPCC guidelines. FracLEACH describes the fraction of N application lost to water and is part of the calculated estimate for N gas emissions from agriculture. The FracLEACH default is 30 %. In Norway, 18 % has been used based on calculations made in 1998 (Vagstad et al., 1998). The present report documents an updated estimate of FracLEACH for Norwegian agriculture.

The project was initiated by the Norwegian Climate and Pollution Agency (Klif).

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1. Summary

The current IPCC guidelines define an estimate for the fraction of mineral fertilizer and animal waste (manure) lost to leaching and runoff (FracLEACH). The FracLEACH default is 30 %. In Norway, 18 % has been used based on calculations made in 1998 (Vagstad et al., 1998).

The main purpose of this study was to give an updated estimate of nitrogen (N) leaching in relation to the amounts of N applied in agriculture (FracLEACH). The term losses in this report include both surface and subsurface runoff.

The estimates of FracLEACH presented in this report were based on data from the Agricultural Environmental monitoring program (JOVA). The JOVA-program includes catchment and field study sites representing typical situations in Norwegian agriculture with regard to production system, management, intensity, soil, landscape, region and climate. Data from plot- scale study sites confirmed the level of N leaching from the agricultural areas within the JOVA catchments.

The overall FracLEACH estimated in this study was 22 % of the N applied. This average covers a variation between sites from 16 % on grassland in Valdres to 44 % in intensive vegetable, potato and cereal production areas in the southernmost part of Norway.

The difference in FracLEACH between sites was for 86 % due to differences in precipitation and runoff; but also to factors such as N balance, soil tillage and denitrification potential influenced the site specific FracLEACH. The high FracLEACH for the site dominated by vegetables and potatoes may be explained by the high N application in relation to N uptake in yield (high N surplus), but also high precipitation and intensive soil tillage contributes to high losses of N. The annual variation in FracLEACH for this area was from 28 % to 78 %.

In cereal production areas in Akershus FracLEACH varied from 18-31 %, mainly due to differences in soils and precipitation. Cereal production with livestock production in Hedmark had a FracLEACH of 32 %, ranging from 16 to 57 % on annual basis. Intensive grassland in Rogaland had an average FracLEACH of 17 %, varying from 7 to 22 % and extensive grasslands had average FracLEACH values of 16 and 23 % for Valdres and Nordland, respectively. The average FracLEACH values for each catchment were calculated as a median value since this is the most probable value. The average FracLEACH value for each catchment was calculated as the median of annual values. Median was used since this is the central point of the dataset and it is not sensitive to outliers.

Agricultural mitigation methods aimed at reducing N losses to water include 1) better fertilizing planning and time of applications, 2) increased efficiency of N uptake, 3) reduced soil tillage in autumn and 4) increased denitrification of N.

Both site specific and crop specific factors influence the amount of N lost through surface and subsurface water. The annual variations in FracLEACH for each site were dominated by variations in runoff. In addition, N balance (e.g. low yields because of drought) had an impact on the annual FracLEACH. The calculated values of FracLEACH reflect a large variation in N losses and factors influencing N losses in Norwegian agriculture.

As an alternative method for calculating N losses from agricultural areas, a regression-model based on JOVA-data was evaluated. This model calculates N losses each year, based on statistical information on climate and soil management. These data are used to estimate the Norwegian N contributions to the North Sea. However, in this model the use of N fertilizer is based on information from the JOVA catchments and does not reflect the overall use of N fertilizer in Norway.

Runoff is the most significant parameter for the difference in FracLEACH between catchments. In addition, production system and to some degree soil type are important for FracLEACH. It is thus suggested to use different FracLEACH-values for the different production systems and adjust FracLEACH according to average runoff for the region.

2. Introduction

The fraction of leachate (FracLEACH) refers to the amount of applied nitrogen (N) that is lost through leaching and runoff in agriculture. In this report, the term losses includes N lost through surface and subsurface runoff.

In the IPCC Guidelines for National Green Gas Inventories, estimation of indirect N_2O emissions from managed soils is calculated using FracLEACH. A default value of FracLEACH of 30 % is presented in the IPPC *Guidelines* while Norway is currently using a value of 18 % based on calculations from 1998 (Vagstad et al., 1998). An updated estimate of FracLEACH in Norway and better documentation are needed.

The emission estimate is calculated following the methodology in IPCC: Good Practice Guidance (p. 4.70-4.72 in http://www.ipcc-nggip.iges.or.jp/public/gp/english/). Sources of N application included in the estimate are mineral fertilizer, manure from housed livestock, manure from grazing and sewage sludge. Within the next few years, N in crop residues and N mineralization associated with loss from peat soil will be included in the estimate of N_2O emissions (http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html, eq 11.10), but they are not included in the calculations presented below.

This project includes documentation of a new FracLEACH estimate for nitrogen. All the factors affecting FracLEACH are discussed (type of fertilizer, timing of fertilizer application, mitigation measures, regional variation and weather patterns).

3. The Agricultural Environmental Monitoring program (JOVA)

The calculation of FracLEACH is based upon data from the National Agricultural Environmental Monitoring Program (JOVA). It includes data obtained from 9 agricultural catchments and a field study site (Bye) that represent the main agricultural production systems in Norway; mixed cereal and arable production in the eastern (Skuterud, Mørdre, Kolstad and Bye) and middle (Hotran) parts of the country, intensive vegetable production in the south (Vasshaglona, figure 2.), intensive dairy farming in the western parts (Time and Skas-Heigre), and more extensive grass production in the mountain valleys in the south-east(Volbu) and in the north (Naurstad) (Figure 1). The study catchments also represent typical differences in soils, topography and climate (Table 1) in Norway.

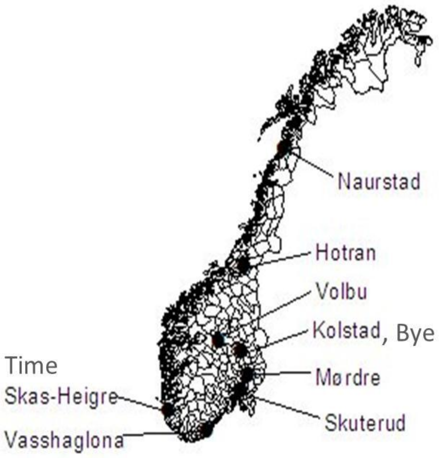

Figure 1. Location of the JOVA monitoring sites

Table 1. Characterization of JOVA monitoring sites

Catchment	Total area (ha)	Agricultural land use (%)	Main crops	Livestock units^1 ha^{-1}	Soil texturale class	Soil P status (mg P-AL 100g^{-1})	Water quality monitoring period
Skuterud	449	61	Cereals	0.3	Silty clay, silty loam	8	1993 – 2011
Mørdre	680	65	Cereals	0.3	Silt, silty clay loam	11	1991 – 2011
Kolstad	308	68	Cereals	0.7	Loam	11	1991 - 2011
Bye	4	100	Cereals	0	Loam		1993 - 2011
Hotran	2000	58	Cereals, grass	1.3	Silty loam, silty clay loam	_	1992 – 2011
Naurstad	146	42	Grass	0.8	Peat soil	9	1994 – 2011
Volbu	166	42	Grass	1.0	Silty sand, silty loam	11	1993 – 2011
Vasshaglona	65	60	Vegetables, potatoes, cereals	1.1	Sand, loam	24	1998 – 2011
Skas Heigre	2830	83	Grass, cereals	1.9	Sand, loam	_	1995 – 2011
Time	91	94	Grass	2.8	Silty sand, gravel	19	1995 - 2011

3.1 Farming practices

Information on agricultural practices has been collected on an annual basis at the field scale for all the catchments except Skas-Heigre and Hotran. The individual farmers' field information includes type of crop, time of sowing/harvesting and yields, time and amount of fertilizer/animal manure application, type and date of pesticide application, type and date of tillage operations and days of grazing.

Figure 2. Monitoring station for Vasshaglona agricultural catchment (left) and an overview over the Skuterud catchment (right) (Photo: Bioforsk)

3.2 Discharge measurement and water quality sampling

In all catchments the water levels in the outlet of the catchments is recorded automatically using a pressure transducer in combination with a Campbell data logger. Composite water samples are collected automatically by a discharge proportional sampling strategy in all catchments (Deelstra and Øygarden 1998, Deelstra et al. 1998). The water samples thus represent a flow- weighted average concentration over the sampling period. The sample container is placed in a refrigerator located in the monitoring station. By default, composite water samples are collected for analysis every fourteen days, but during periods with high runoff conditions samples are collected more frequently. The samples are analyzed for a range of substances, including total nitrogen (TN), total phosphorus (TP) and suspended sediments (SS). More details about the monitoring setup may be found in Bechmann et al. (2008) and on www.bioforsk.no/JOVA.

3.3 N content in manures and crops

The information on application of manure in the JOVA-programme was given by farmers in tons/ha/yr of applied manure for each field. The content of N in manure was calculated based on Tveitnes et al. (1993) and the new values from Daugstad et al (2012) (Table 2 and 3). Daugstad et al. (2012) have collected data on N content in manure from 2006 -2011 and they identified new factors for nutrient content in pig and chicken manure.

There have been changes in the intensity of production and fodder quality over the last 20 years which may have caused a change in the nutrient content in manure, especially from pigs and chicken. From 2007, the use of fytase had become common in Norway and it is expected to have caused a change in nutrient content in manure from pigs and chicken. According to Norgesfôr (pers. comm. Harald Hetland) the changes probably happened continuously over the period. The new values have therefore been introduced gradually for the period from 2001 to 2007. In general, there is a great uncertainty in the level of nutrient content in manure. The farmers may add water to the manure and thus reduce the nitrogen concentration. The dry matter content was also based on measured values from Tveitnes et al. (1993) and Daugstad et al (2012). The result from these reports suggests that the average dry matter content of manure also changed in the same period.

Table 2. Values for dry matter and N (%), based on Tveitnes et al (1993), in use up to 2001.

Type of manure	Dry matter	Nitrogen
	%	
Cow, wet	8	0.39
Cow, dry	20	0.46
Pig, wet	8	*0.6**
Pig, dry	20	*0.6**
Sheep/goat, dry	24	0.8
Sheep/goat, wet	12	0.6
Chicken, dry	33	*1.48**
Broiler	50	*1.78**

*Updated values in Table 3

Table 3. New values for dry matter and N content in pig and chicken manure (%), based on Daugstad et al (2012), in use from 2001 -2007.

	2001	2002	2003	2004	2005	2006	2007-	Dry matter
	%							
Pig, wet	0.56	0.53	0.49	0.45	0.41	0.38	0.34	3-5
Pig, dry	0.6	0.6	0.6	0.6	0.6	0.6	0.6	20
Chicken, dry	1.54	1.59	1.65	1.71	1.77	1.82	1.88	50
Broiler	1.92	2.07	2.21	2.36	2.50	2.65	2.79	50

Table 4. Nitrogen content of selected crops used in the calculations of FracLEACH.

Crop	Nitrogen content
	%
Barley	1.75
Oats	1.75
Spring wheat	2
Autumn wheat	2
Autumn rye	1.75
Rape seed	3.4
Peas	3.3
Potato	0.31
Ryegrass	3.2
Intensive pasture	2.5
Extensive pasture	2.2

Nitrogen in yield (kg/ha) was defined by the N content of the crop (Table 4) and its yield level within a specific year. The N content of cereal yields were based on results of analysis supplied by farmers. For grass yield the N content was based on a survey by Daugstad et al. (2011). The content of clover in grass swards was estimated to approx. 5-7 % and the N content was 2.5 % for intensive production and 2.2 % for extensive production (Gustav Fystro. pers. com.). Values for the content of N in vegetable yield were based on Tammelin (1981). Over time the N content in yield may have changed due to differences in e.g. N application rate and these changes may not be reflected in the values used in the presented calculations. However, no new reliable data were available for this report.

3.4 Calculations

Nitrogen losses were calculated simply by multiplying runoff amounts by their N concentration. The loss of N from the agricultural areas was assumed to be 10 times greater than the loss from non-agricultural areas (e.g. forest), as estimated from Uhlen (1989). This standard value has been confirmed by the monitoring results on N losses from a forested area in the Volbu catchment (Nyhaga).

The specific N loss from agricultural areas was calculated using the following equation:

$N_{agr} = N_{tot}/(A_{ag} + A_{nag}*0.1)$

where

$N_{agr} = N_{loss}$ from agricultural area

$N_{tot} = Q * N_{cons}$ (discharge * measured concentration at catchment outlet)

A_{ag} = Agricultural area

A_{nag} = Non-agricultural area

Nitrogen balances are calculated as follows:

$N_{bal} = (N_{mineral\ fertilizer} + N_{manure\ from\ housed\ livestock} + N_{manure\ from\ grazing} + N_{sewage}) - N_{yield}$

N_{yield} = N removed in yield includes removal of both crop and plant residues if they are removed.

FracLEACH is calculated as follows:

$FracLEACH = N_{agr} / (N_{mineral\ fertilizer} + N_{manure\ from\ storage} + N_{manure\ from\ grazing} + N_{sewage\ sludge})$

4. Nitrogen application

Nitrogen application in mineral fertilizer, manure and other organic material is the denominator in the FracLEACH equation. Hence, high N application rate will reduce FracLEACH.

The average application of N in the monitored sites varied between 121 kg TN/ha at Volbu and 329 kg TN/ha at Time including both mineral fertilizer and manure (Figure 3). At Mørdre, sewage sludge was applied in 3 years, whereas at all other sites only application of mineral fertilizer and manure was registered (Figure 3). The site with intensive livestock production (Time) had the highest TN applications (Table 1), but high amounts of N fertilizers and manure were applied also in Vasshaglona, where there was intensive potato and vegetable production (Figure 3).

In the areas dominated by cereal production and low livestock numbers (Skuterud and Mørdre) 109-180 TN/ha/yr was applied on average over the monitoring period. In a cereal dominated areas where livestock density has increased recently (Kolstad), N application has increased due to more manure having been applied in the last few years (average 159 kg N/ha).

The N application to grassland in the mountain valley (Volbu) and in the northern part of Norway (Naurstad) were about the same as those in the cereal dominated area north of Oslo (Mørdre), approx. 120-130 kg TN/ha.

In cereal dominated areas, such as Skuterud, Mørdre and Bye, most of the N is applied in spring (Figure 4). In these areas most, if not all, the N fertilizers was given in mineral form. In grass and pasture dominated areas, such as Naurstad, Time and Volbu, about one third or more of the N was applied during the spring and summer. In these areas, about 40-60 % of the N application was manure from housed livestock and grazing animals, and there was some N application during fall/winter. Similar patterns were found at Vasshaglona and Kolstad (Figure 4).

The average application of total nitrogen (TN) in the form of mineral fertilizers varied between 60 and 157 kg/ha/yr in the monitored sites (Figure 3). On average for all sites and all years, the input of N from mineral fertilizers was 127 kg/ha. The variation between years is considerable (Figure 3), especially for sites with large variations in manure application rate. These variations may or may not result in variation in N leaching.

Application of N in the form of manure varied from year to year, depending among other things upon the weather conditions during the period of spreading and changes in the number of livestock. At two sites (Time and Kolstad), livestock density increased during the monitoring period and accordingly the N application rate. This may contribute to reduction in FracLEACH, depending on the effect of N application rate on N losses. At two other sites, with more extensive agriculture (Naurstad and Volbu), the livestock density decreased over the monitoring period (Figure 3) and accordingly may contribute to increased FracLEACH.

Most N was applied in spring and during the growing season and the utilization was high and the risk of N losses lower compared to spreading in autumn. In the recent years, hardly any mineral fertilizer was applied in autumn/winter (Figure 4). At some sites, however, part of the manure was spread in autumn. At Kolstad and Vasshaglona, up to 25 % of the manure was spread during this period, causing a high risk of nutrient leaching losses. At Naurstad and Volbu, up to 20 % of the manure N was spread during autumn/winter, whereas at Time, with intensive livestock production, hardly any manure was spread after 1st September and accordingly the risk of leaching losses was low.

Increased prices of mineral fertilizers resulted in lower N applications during the last two years (2009-2010) at all sites. This could lead to higher FracLEACH for these years if N losses are not reduced correspondingly.

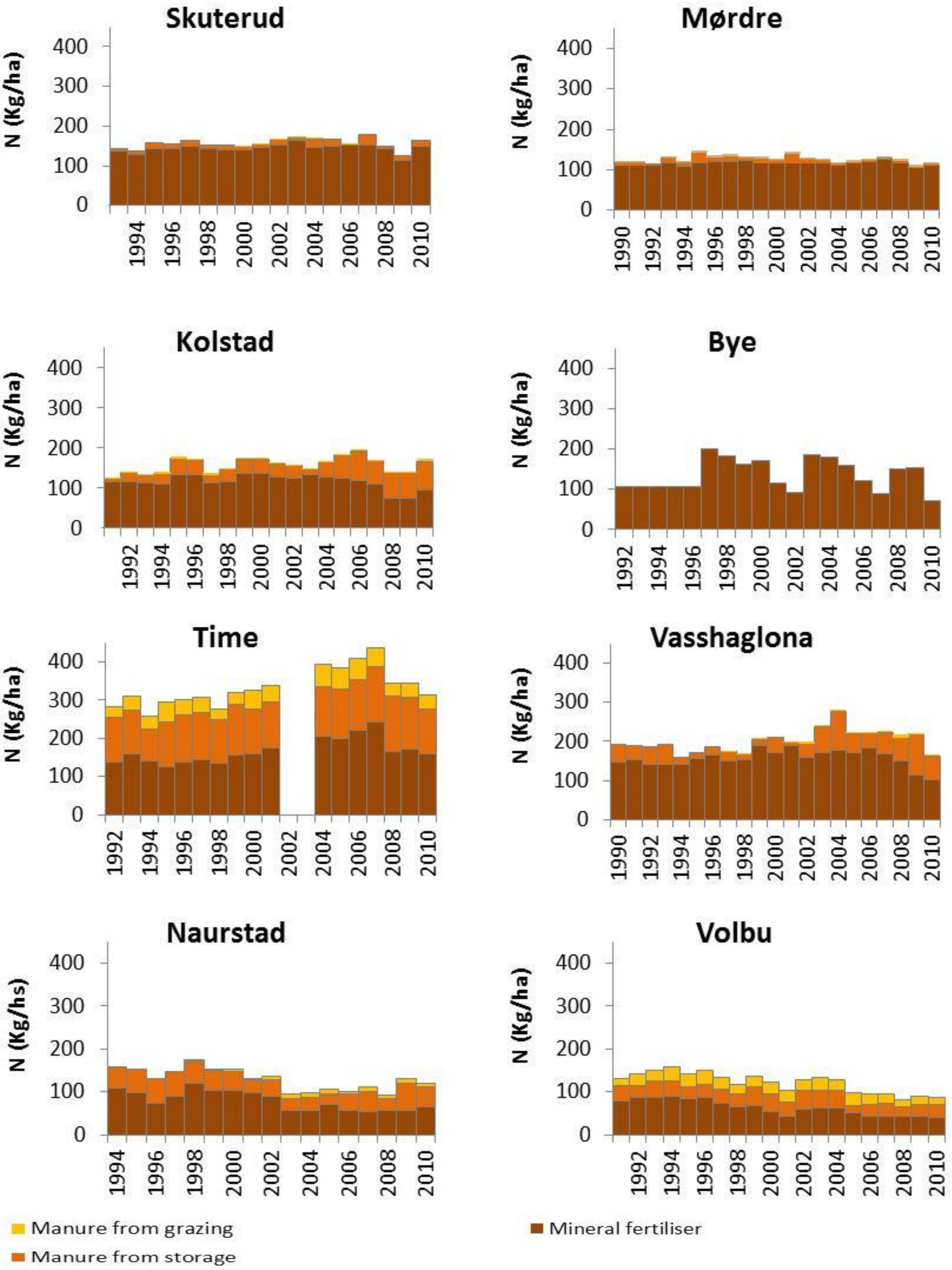

Figure 3. Amount of mineral fertilizer, manure from grazing animals, manure from housed livestock (storage) and sewage sludge (included in storage) used in 8 catchments during the period 1992 -2010. Years are agrological years (1st. may -30th April).

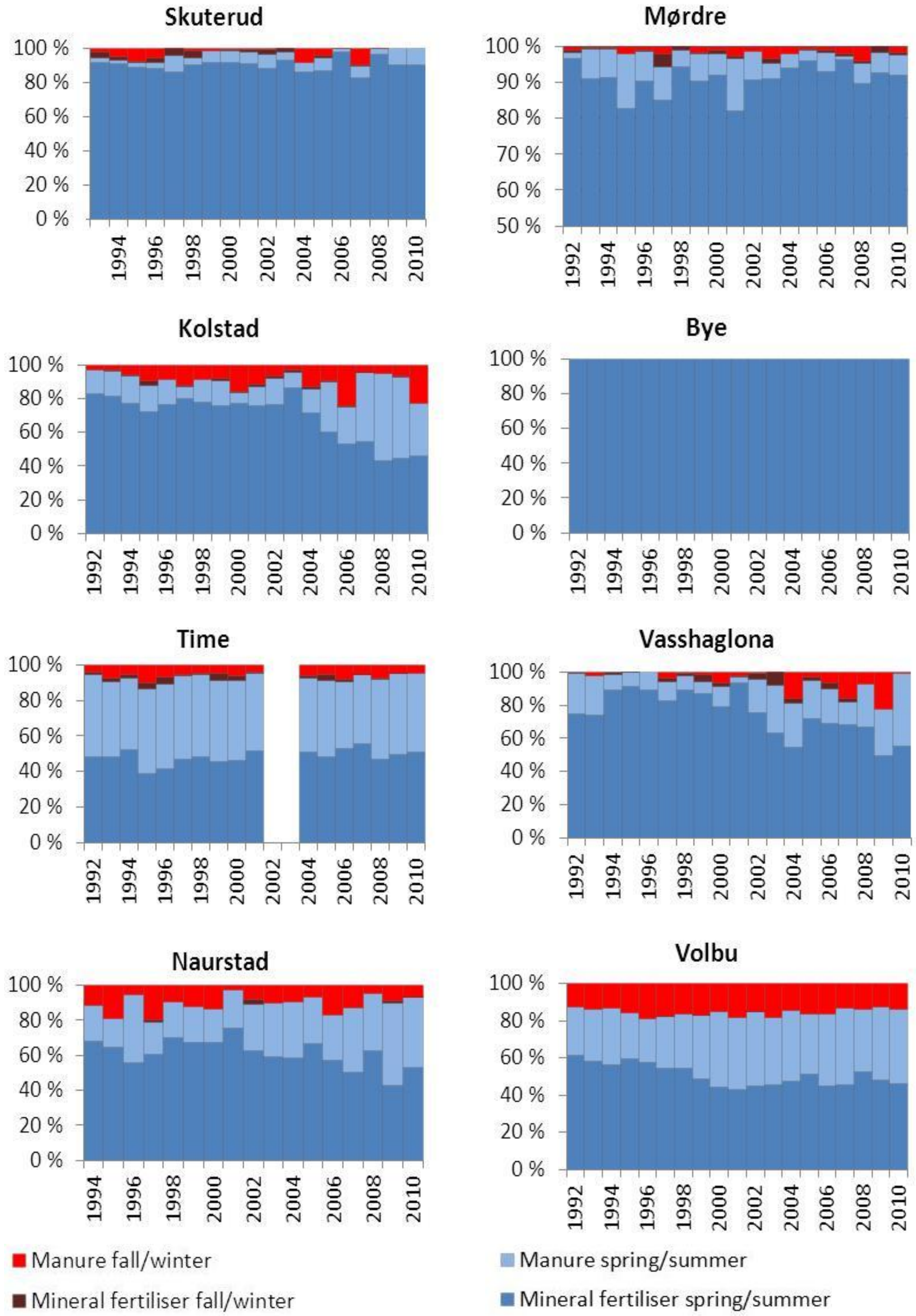

Figure 4. Time of application of mineral fertilizer, manure from grazing animals, manure from housed livestock (storage) and sewage sludge (storage) for 8 catchments during 92 (92/93) -10 (10/11).

5. Nitrogen in yield and nitrogen balance

FracLEACH does not include estimates of N removal in harvested crop products (yield). However, the removal of nutrients is important for the relationship between N application and N losses. Generally, crops with a long growing season remove more nutrients than crops with a shorter growing season. Especially, grass land has the ability to take up nutrients over a longer period than cereal crops. But, for example, winter wheat is also some years able to take up nutrients in late autumn and hence reduce the risk of N losses during winter. Additionally, some crops cover the whole soil surface (e.g. grassland) whereas other crops have roots systems that are only able to take up nutrients from under the plant rows (e.g. onion).

In our study sites, the average removal of N over the monitoring period varied from 83 kg N/ha/yr at Mørdre to about 261 kg N/ha/yr at Time (Figure 5). Mørdre represents an area north of Oslo with cereal production and a relatively cold climate. The growing season at Mørdre is short, approx. 180 days, compared to Skuterud (south of Oslo) with approx 194 days on average and soils differ between these catchments, hence yields differs correspondingly. The N surplus at Mørdre and Skuterud were similar (42 and 45 kg N/daa/yr), but the production was lower at Mørdre (Figure 6).

In Rogaland (Time), the growing season was estimated to be 221 days and N removal by crops is high (260 kg N/ha/yr). The high removal of N by crops corresponds to high application of N. The average N balance was 68 kg N/ha/yr and varied a lot from year to year. It has increased during the monitoring period. Increased livestock density, increased nutrient application and some reduction in yield during recent years, have all contributed to increased surplus of N (up to 158 kg N/ha).

At Vasshaglona the N removal in yield was relatively high in some years, but varied a lot and did not correspond to the high N application levels. The N balance in Vasshaglona was high (67 kg N/ha/yr) on average. Compared to other studies on N balance on areas with vegetable production the Vasshaglona N surplus was very high (Riley and Børtnes, 2010). Also Kolstad (64 kg N/ha/yr) had high N balances (Figure 6) owing to high manure application.

From more extensive grassland areas, the N removal was 93 kg/ha/yr at Naurstad (in Nordland county) and 124 kg N/ha at Volbu (a mountain valley in Oppland county). The lowest N balance was found in Valdres for Volbu (-4 kg N/ha/yr).

The removal of N differed from year to year depending, among other things, upon weather conditions. In the Skuterud and Mørdre catchments, yields in 1994 were very low because of drought and N surpluses were therefore high this year. Nitrogen application rate is often based on the requirement for N for a maximum yield instead of an average yield (Øgaard et al., 2006).

Riley et al. (2011) studied the balance between N supply in mineral fertilizer and N removal in cereal grain and straw. At the average grain yield levels for Norway, the economically optimal N application and corresponding N removal suggested N surpluses of 50-60 kg N/ha/yr when only grain was removed, and of 25-40 kg N/ha/yr when both grain and straw are removed. These values correspond to data from the JOVA-catchments, e.g. Skuterud, Mørdre and Bye.

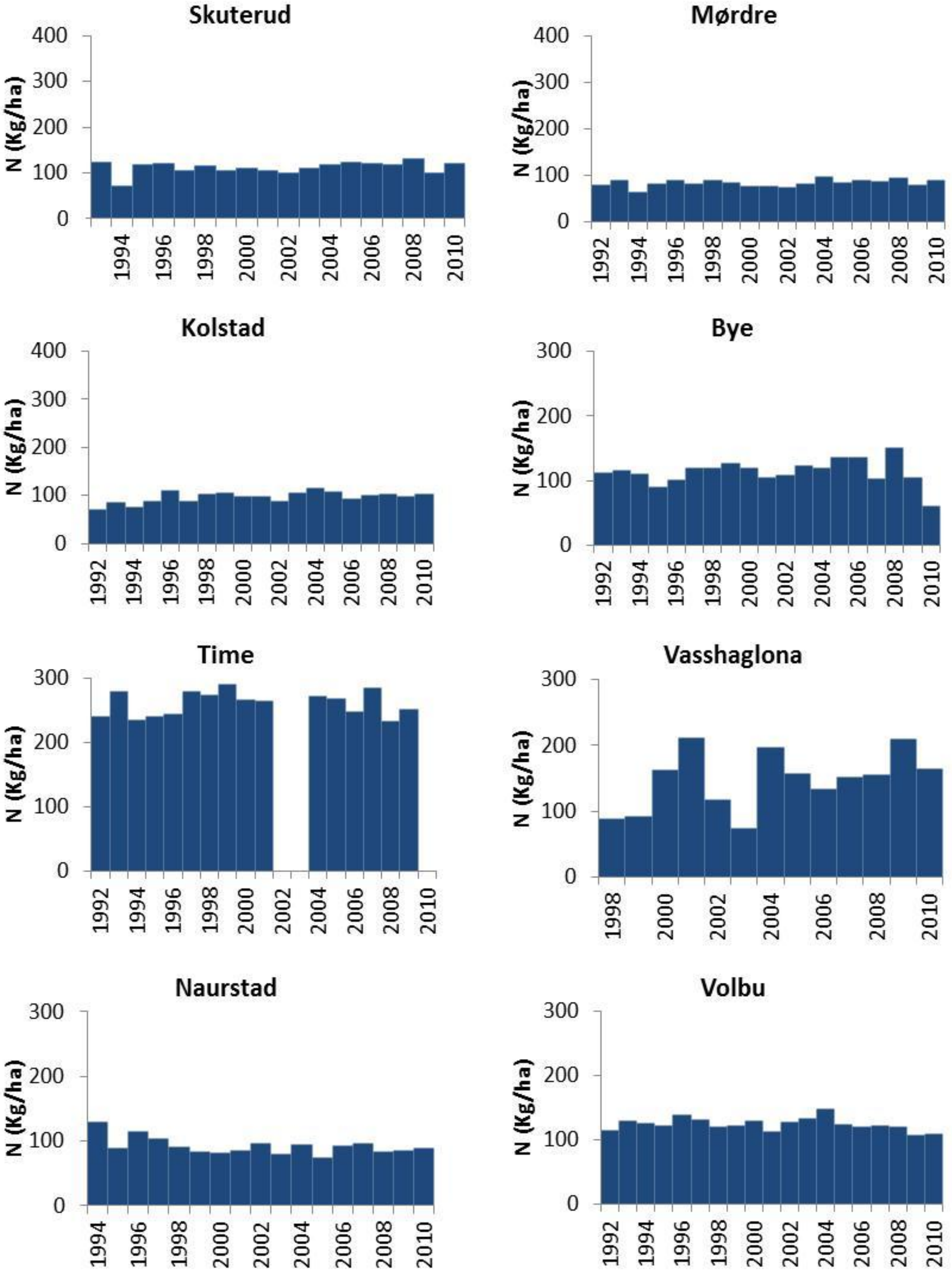

Figure 5. Nitrogen removal in yield and removed residues from 8 catchments in Norway during the period 1992-2010. Years are agrological years (1st. may -30th April).

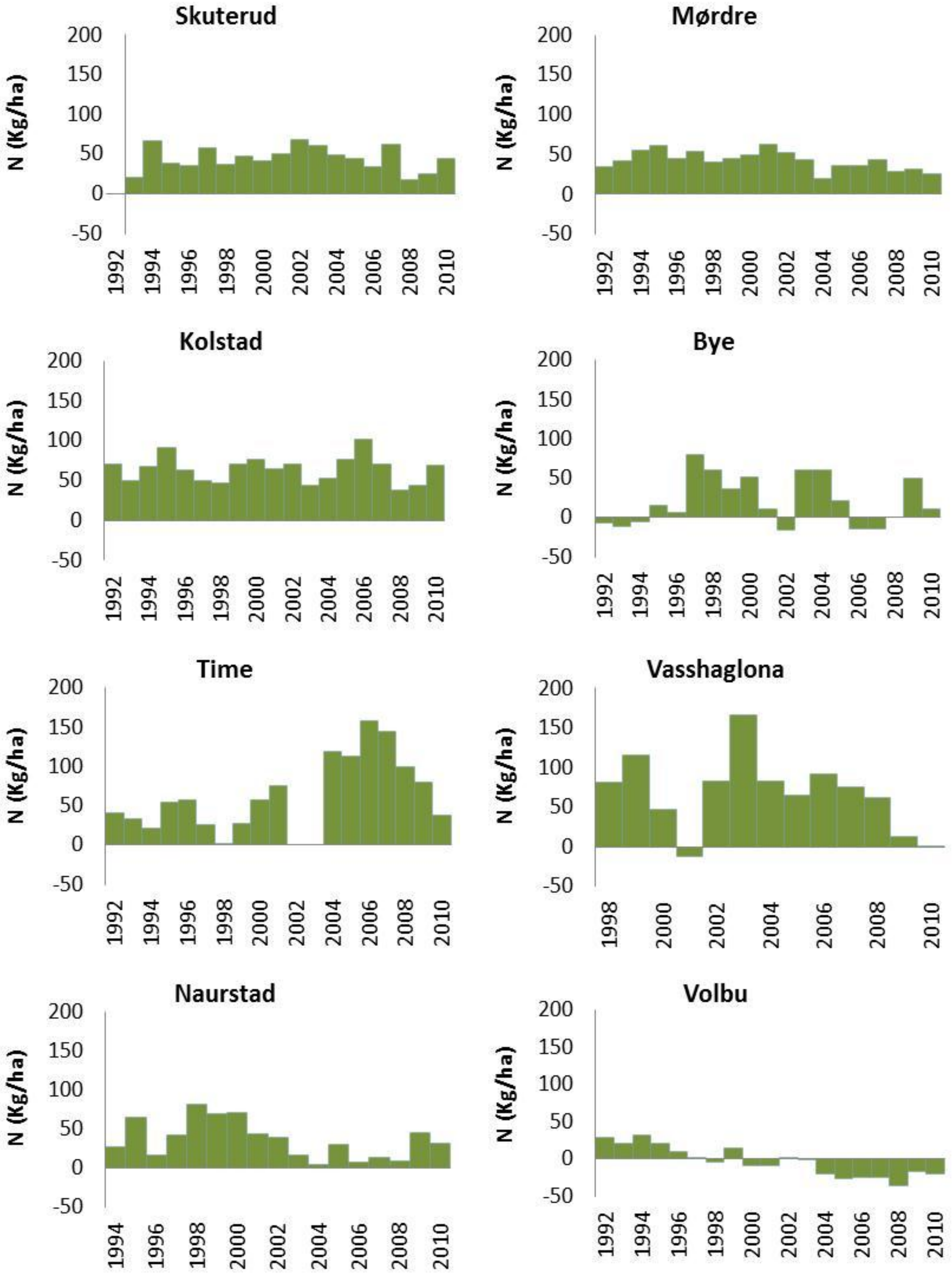

Figure 6.Nitrogen balance (N input-N in yield) at 8 catchments in Norway during the period 1992-2010. Years are agrological years (1st. may -30th April).

6. Nitrogen losses to water

Nitrogen loss is the numerator in the FracLEACH equation and in the JOVA-programme, nitrogen loss is measured in the stream and represents the sum of subsurface leaching and surface runoff. Average total nitrogen (TN) losses during 1992-2010 were highest from vegetable/potato production in Vasshaglona (100 kg/ha/yr) and lowest for grassland in Volbu (21 kg/ha/yr) (Figure 7). The TN losses for Vasshaglona correspond well with other studies on N losses from areas dominated by vegetable production in Norway (Riley and Børtnes, 2010).

From the cereal dominated areas (Skuterud, Mørdre, Kolstad and Bye), average losses of TN varied from 23 to 56 kg/ha/yr. Kolstad showed higher (56 kg/ha/yr) average losses than Skuterud, Mørdre and Bye (48, 23 and 29 kg/ha/yr), possibly due to higher manure application partly occurring in autumn, especially the recent years (Figure 3 and 4). Additionally, differences in soils between Kolstad, Mørdre and Skuterud influence the risk of N losses. However, at Bye the N application was generally lower and losses of TN correspondingly lower than those from Kolstad. Losses of TN also differed a lot between Mørdre and Skuterud. There was higher precipitation and runoff at Skuterud than at Mørdre (Figure 9) and there was a close relationship between precipitation, runoff and TN losses in the Skuterud stream (Figure 10). The low TN losses from Mørdre may possibly be explained by the fact that higher denitrification losses are likely there, due to the nature of its soil. However, this has not been investigated.

Norwegian studies at field and plot scale in areas dominated by cereal production were reported by Kværnø and Bechmann (2010) (Figure 8). Average TN losses over the monitoring periods (differing between sites) varied from 14 to 48 kg/ha/yr. The highest TN losses were measured from sites with manure (Enerstujordet) and high soil organic matter (Syverud). The Holt and Vandsemb sites are situated in the same area as the Mørdre site and average TN losses from these sites (23 kg/ha/yr) were the same as for agricultural areas at Mørdre (23 kg/ha/yr), despite the differences in monitoring periods. The Apelsvoll plot study is comparable to Kolstad and Bye in terms of location and soil. Apelsvoll and Bye show comparable TN losses (Figure 8).

The average TN losses from the grassland sites (Time and Skas-Heigre) in Rogaland were 53 and 41 kg/ha/yr, respectively (Figure 7b). High livestock density and correspondingly high N application with manure, contribute to the high TN losses, but high precipitation and high runoff also contributes to the high leaching losses in this region (Figure 10).

Total nitrogen in the JOVA-programme consists of nitrate-N and other N-forms as presented in Figure 8. The average percentage of nitrate N (NO_3-N) in the runoff was highest at Bye (88 %) and lowest at Naurstad (35 %). In the monitoring period the proportion of NO_3-N has decreased in several of the studied areas.

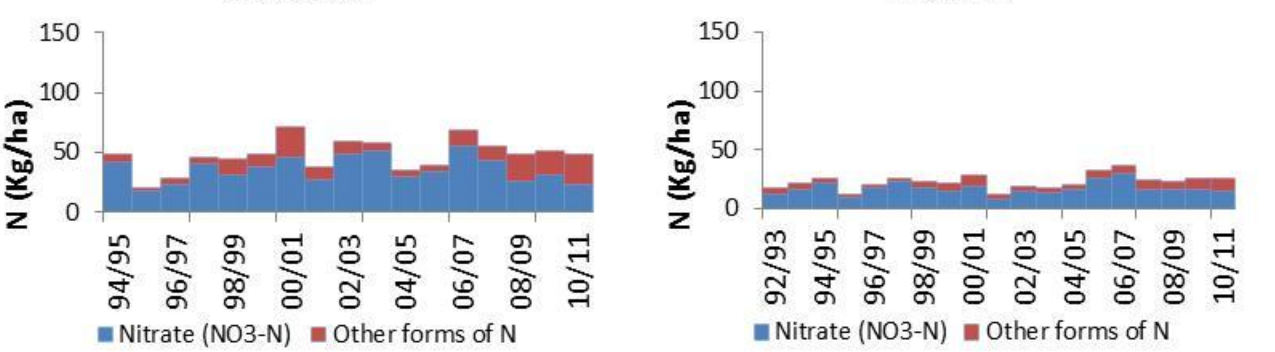

Figure 7a. Total losses (leaching and surface runoff) of nitrate N (NO_3-N) and other forms of N; kg/ha agricultural land) from 2 sites in Norway during the period 1992-2010. Years are agrohydrological years (1st. May -30th. April).

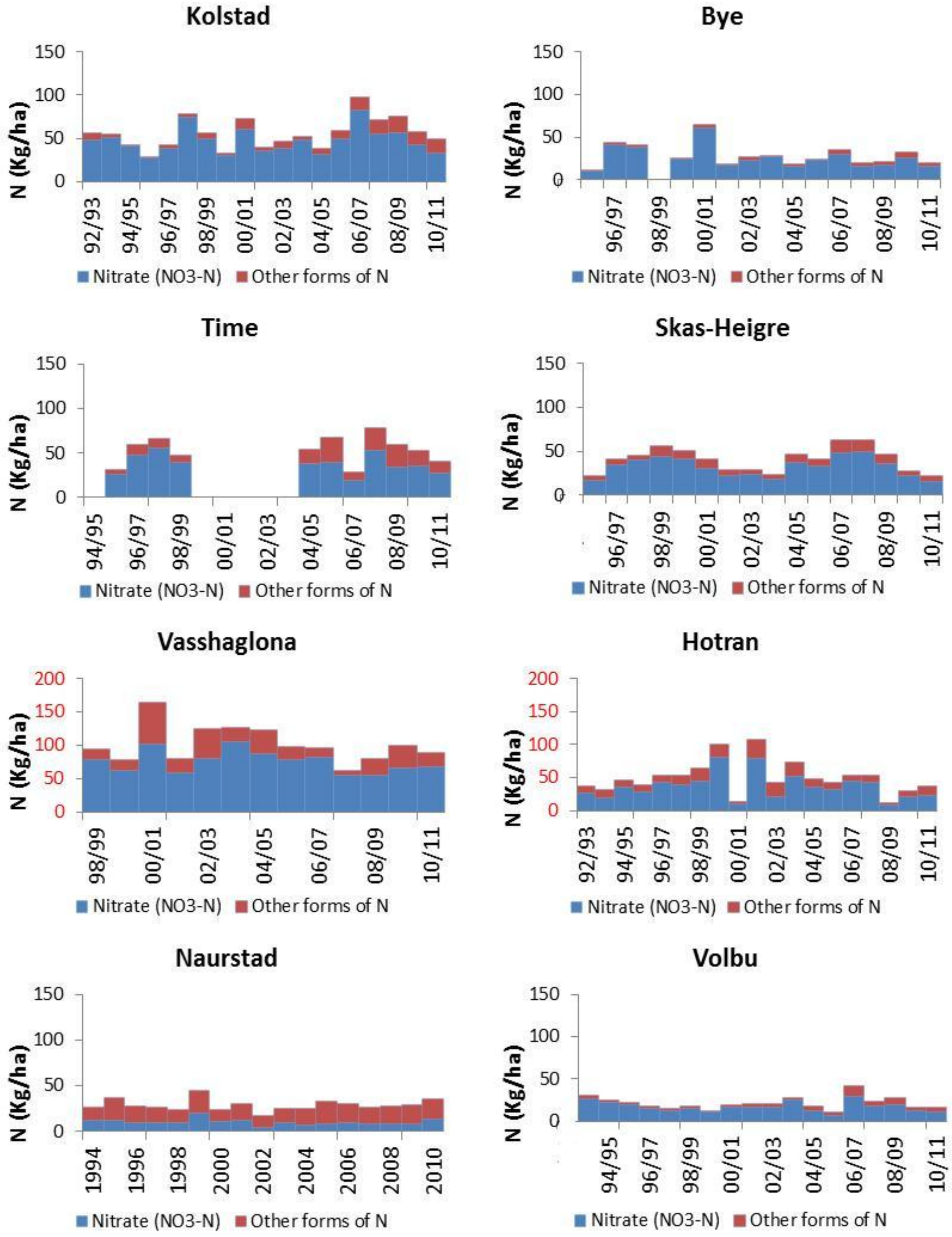

Figure 7b. Total losses (leaching and surface runoff) of nitrate N (NO_3 N) N and other forms of N; kg/ha agricultural land) from 8 sites in Norway during the period 1992-2010. Years are agrological years (1st. may -30th April).

There were no significant trends in total N losses during the monitoring period. However, the annual variations were large and mainly depended on amount of runoff (Figure 10). In Kolstad and Time the annual variations tended to reflect the variations in livestock density and hence manure application rate (Figure 3).

Losses of nitrogen measured in plot scale studies in south-east and mid-Norway were within approximately the same range as those from the catchments (Figures 7 and 8). From the plots, most nitrogen is lost with subsurface runoff.

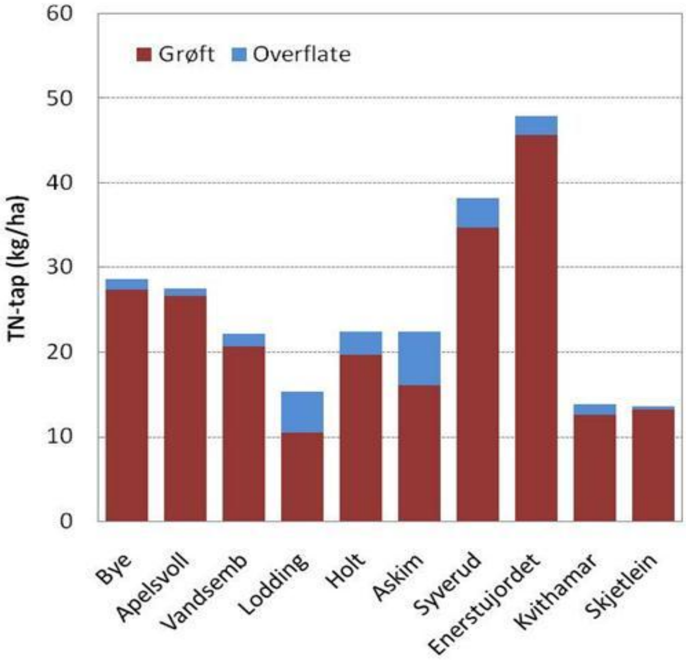

Figure 8. Losses of total nitrogen in surface ('overflate') and subsurface ('grøft') runoff reported in a number of Norwegian plot studies (Kværnø and Bechmann, 2010)

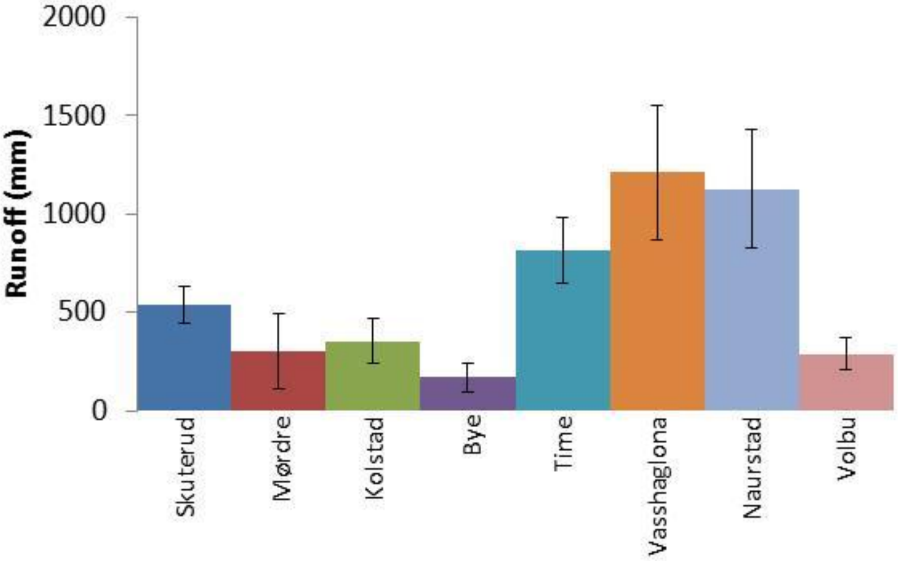

Figure 9. Runoff (mm yr^{-1}) from 8 sites in Norway during the period 1992-2010. Years are agrohydrological years (1st. May - 30th. April).

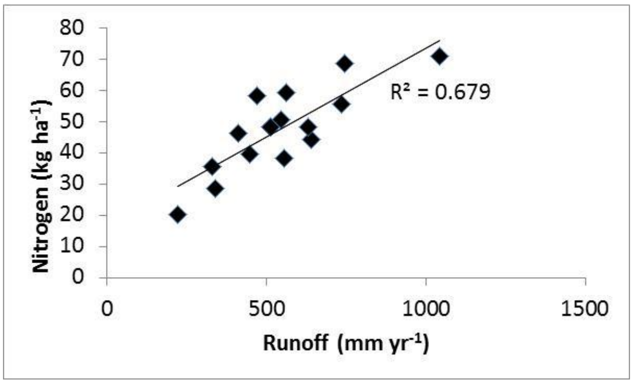

Figure 10. Runoff (mm) and N losses (kg ha^{-1}) in the Skuterud stream.

An analysis of factors affecting N losses to water was carried out for the JOVA-sites (Eggestad et al., 2001). The Jovanest-model has been used annually to estimate total N losses from agricultural areas in Norway to the North Sea (Selvik et al., 2006). According to their study, the losses of N from agricultural catchments in Norway could be explained by factors related to runoff (Q), soil organic matter, N balance, soil tillage and temperature. They have set up the following equation:

N_{loss} = 0.01355Q − 1.5 pSOM + 0.04522 N_bal_pos_tilled − 0.004197 Q_t3
+ 0.01765 tilldays + 0.002493 temp_sum_t1 − 0.01385 aharv_Q_meadow + 0.311

where

Q=amount of runoff (mm)
N_{loss} = Nitrogen losses (kg daa^{-1}, 1 daa = 0.1 ha)
SOM = Soil Organic Matter (%)
N_bal_pos_tilled = Nitrogen balance on tilled fields (non-grassland): difference between applied fertilizer plus manure plus Nitrogen precipitated and plant uptake (kg daa^{-1}, 1 daa = 0.1 ha)
Q_t3 = runoff in the period January through April (mm)
tilldays = number of days with the mean temperature above zero between soil tillage (harrowing or ploughing) and 1. May
temp_sum_t1 = sum of daily mean temperature above zero in the period May through August
aharv_Q_meadow = runoff from grassland after grain harvest (runoff ×grassland area ÷ crop land area) (mm)

According to this analysis, runoff (Q) explains 60 % of the variation in N leaching. Therefore FracLEACH is highly influenced by runoff and accordingly precipitation each year. Annual FracLEACH-values could be developed to reflect these variations. However, the purpose of FracLEACH is to give an estimate of the effect of changes in agricultural practice on N losses and hence, average runoff for a normal period would be more representative.

According to the model, the area of soil tillage within a catchment was the most reliable agricultural factor and in addition, manure application in autumn had significant influence on N leaching (Eggestad et al., 2001). The N balance contributed to variation between catchments, but was not significant for variation between years. Under conditions with no difference in soil and climate, Korsaeth (2000) found, based on plot scale studies at Apelsvoll (Oppland) that the N balance for arable cropping systems predicted 86 % of the variation in N loss.

A study at Rothamsted (Goulding et al., 2000) in the UK showed that applying more N than needed for optimum yield greatly increases losses of N by leaching. However, even where no fertilizer N was applied there was some leaching loss (5-10 kg ha^{-1}yr^{-1}). Other studies have shown similar relationships between nitrogen loss and runoff amount, N application, soil type (% clay) and crop (Simmelsgård, 1998). Simmelsgård found, corresponding to the JOVA-data, decreasing N losses with increasing length of growing season. Uhlen (1989), in his plot study in south east Norway, found that leaching losses of N from grassland was about 10 % of the leaching losses from bare soil.

A comparison of N losses from agricultural areas in the Nordic countries showed that the highest losses occurred in Norway (Vagstad et al., 2001). Amount of precipitation, length of growing season and intensity of drainage systems may explain part of the variation between countries. Denitrification processes are important for the final risk of N losses to water.

FracLEACH is used to characterize the risk of N losses from N applied to agricultural areas. According to the general results, the most important factors determining N losses from agricultural areas include runoff, N balance, soil tillage, plant cover, soil organic matter and soil type. These factors were included in the regression model (Jovanest) (Eggestad et al., 2001), but this model partly requires annual input data from JOVA-catchments and may not be used to estimate N losses directly based on statistical data.

7. Mitigation methods to reduce N losses

Mitigation methods to reduce N leaching should focus on the most important sources and processes. Factors of importance for N losses are runoff, fertilizer or manure application, soil organic matter and soil tillage. Increased denitrification and/or crop uptake will reduce N losses. Improved methods and time of N application may contribute to increased uptake of N in crop.

Based on these N loss factors, mitigation methods should focus on:

- Improved efficiency of N application for crop growth
- Increasing soil organic matter
- Minimum soil tillage (as it may reduce N losses in autumn)
- Increased plant uptake (green soil cover, e.g. catch crop)
- Increased denitrification (e.g. wetlands, controlled drainage)

Improved efficiency in use of N fertilizer or manure may be obtained by nutrient management planning for average yield instead of maximum yield, split fertilizer application or by use of precision agriculture by which methods farmers more specifically apply N according to spatial variation in crop need within a field. In these ways, N application may be reduced while yields are maintained. All of these methods will reduce risk of N losses, however, N losses may not decrease as much as the amount of N applied.

Application of manure in autumn will also increase the risk of N losses and hence manure application in spring and during the growing season is an important mitigation method to reduce N losses and also reduce FracLEACH.

The application method for nitrogen also influences the risk of leaching. Applying manure on soil surface will increase the losses of N to air by ammonia volatilization and denitrification and therefore the relative losses of N to water may not increase compared to incorporation of manure. However, to apply N for crop needs then requires additional application of N in fertilizer.

Soil tillage has been shown to increase the concentration of nitrate in soil and hence the risk of N losses. Mineralization of organic matter contributes to the leaching of N after harvest when no crop uptake avoids losses. In Sweden, subsidies are given for no soil tillage in autumn because of its effect on N leaching.

Catch crops, as used in Norway, consist of Rye grass sown together with the cereals in spring and left to grow after harvesting the cereal crop. In this way plant uptake of N will continue for longer than for a cereal crop alone. A prerequisite for the effect of catch crops in the long term is that N available in the catch crop plant material will be taken into account in the N applications made in the following season. Experiences on the effect of catch crops on FracLEACH could be derived from the JOVA monitoring (Figure 11). In the Mørdre site, catch crops were introduced in 2000 by giving economic subsidies. The area of catch crops was large during the next 3-4 years and then, because of reduction in the subsidies, decreased again to a small area (Bechmann et al., 2008).

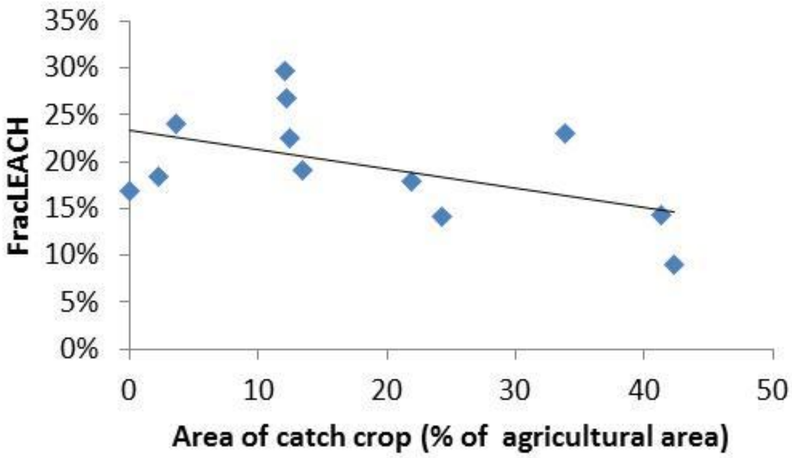

Figure 11. FracLEACH in relation to the area of catch crops (%) at the Mørdre site during the period 1992-2010.

In a mild climate, winter wheat and catch crops can take up nitrogen during winter. However, most years in Norway, the uptake of N in autumn by winter cereals is relatively small. Grassland will also be able to take up N during part of the winter, when temperatures are high enough for plant growth, e.g. some years at Jæren.

8. FracLEACH estimate

The overall FracLEACH calculated based on 8 Norwegian study sites was 22 % (table 5). The highest average FracLEACH values were found at Vasshaglona (44 %) and Kolstad (32 %) and the lowest at Time (17 %), Mørdre (18 %) and Volbu (16 %). Precipitation and runoff are important for N leaching and for FracLEACH. However, as shown in Figure 12, there was no unique relationship between runoff and FracLEACH for all sites. This is due to influence of agricultural practices and regional variations in soil and temperature. Since some years and some catchments show very high or very low values for FracLEACH, iIt is suggested to use median values for FracLEACH instead of mean. Median is the central point of the dataset and it is not sensitive to outliers. The median shows the most probable value of FracLEACH and this will be more appropriate in this case (Table 5).

Table 5. Fraction of leachate (FracLEACH) (N in runoff / N fertiliser) in 8 catchments in Norway from 1992-2010. Median values (1992-2010) are included in the last line of the table.

	Skuterud	Mørdre	Kolstad	Bye	Time	Vasshaglona	Naurstad	Volbu	Average
	%								
1992		15	40						28
1993		17	40					20	20
1994	35	22	30				17	15	20
1995	13	8	16	10	11		24	16	14
1996	18	15	24	40	20		21	12	21
1997	28	19	57	20	22		18	11	20
1998	29	17	38		17	56	14	16	17
1999	32	17	19	15		37	29	9	18
2000	47	23	41	38		78	15	16	31
2001	24	9	25	15		40	23	20	22
2002	36	14	29	30		63	13	16	23
2003	34	14	35	15		53	27	21	24
2004	21	18	23	11	14	44	25	14	18
2005	24	27	32	15	18	44	31	11	27
2006	44	30	50	29	7	43	30	43	30
2007	31	19	42	23	18	28	23	24	23
2008	32	18	54	14	18	37	30	33	30
2009	40	24	41	21	16	45	22	18	22
2010	29	22	29	28	13	54	29	19	28
Average	31	18	32	20	17	44	23	16	22

The high FracLEACH in the Vasshaglona catchment is due the high application of mineral fertilizers and a relatively large amount of manure applied. Part of the manure was applied at an unfavorable time during autumn/winter when the plant uptake is low and the risk of runoff high. In Time, N application was also high, but here the grass cover was able to take up N nearly all year round and the FracLEACH was thus very low compared to Vasshaglona. Manure spreading at Time occurs in spring or during the growing season contributes to the low values for FracLEACH. Furthermore the high yields and therefore the low N balances contribute to the low FracLEACH. On the other hand, areas with intensive vegetable and potato production at Vasshaglona, had high N application rates and only moderate removal of N, resulting in high surpluses of N. In addition to plant uptake, there was a difference between the two catchments regarding soil tillage. Soil tillage contributes to N-leaching by increasing mineralization. There is much less soil tillage in the Time catchment than in the Vasshaglona catchment and therefore lower N-losses and a relatively lower FracLEACH. The Kolstad catchment also had a high FracLEACH. The morainic soil at Kolstad, favors N leaching processes rather than surface runoff, and additionally, a high content of soil organic matter contributes to higher risk of N losses there.

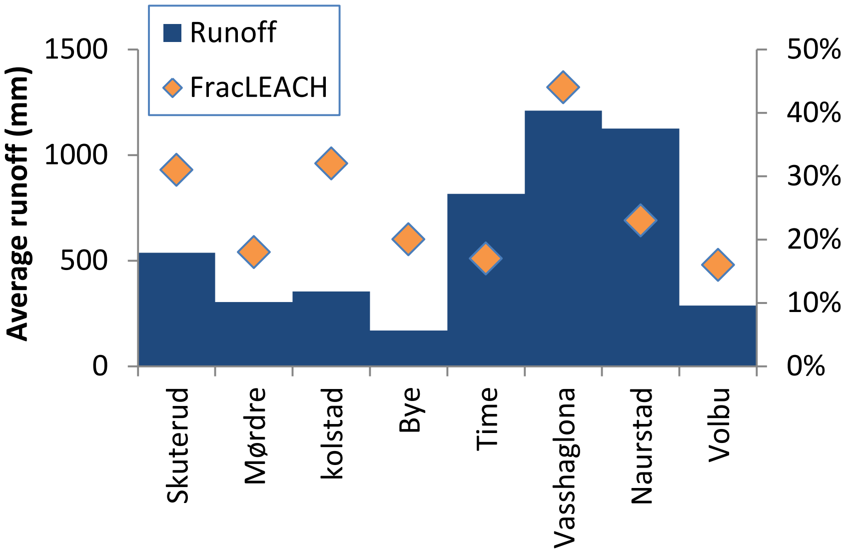

Figure 12. Average runoff during the monitoring period and FracLEACH for 8 sites.

For the cereal areas of south east Norway, Skuterud and Mørdre, the average FracLEACH values were 31 and 18 %, respectively (Table 2). The large difference between the two sites can be explained mainly by the amount of runoff. But the differences between soils, crops and landscape of the two sites also have some influence. The silty soils at Mørdre have a greater potential for denitrification and there are also differences in soil tillage, with more tillage in autumn at Skuterud. Both these factors may contribute to higher N losses.

For the more extensive agriculture at Volbu and Naurstad, the average FracLEACH values were 16 and 23 %, respectively (Table 2).

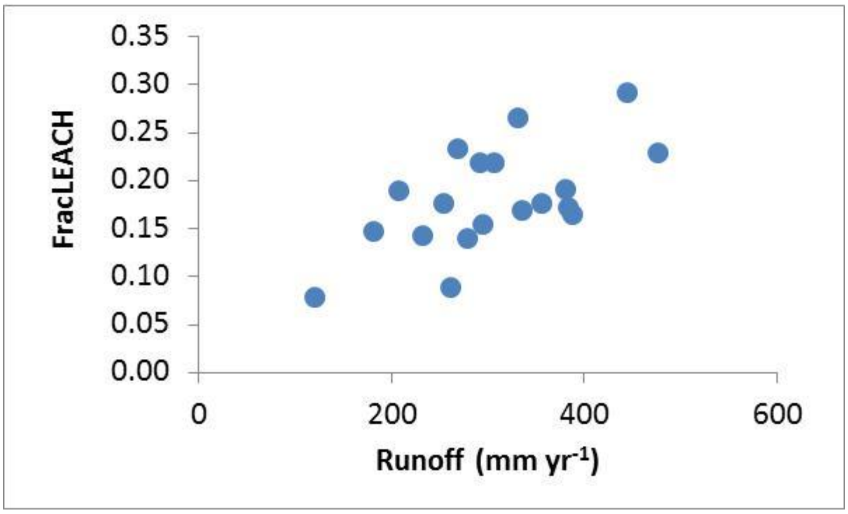

Figure 13. Relationship between runoff and FracLEACH for Mørdre

There was a considerable annual variation in FracLEACH at all the sites (Table 2) caused among other things by variation in runoff (Figure 13). In the south-east (Skuterud, Mørdre, Kolstad, Bye and Vasshaglona), FracLEACH was high in the year 2000 when extreme precipitation occurred in the autumn, causing high N losses. The high FracLEACH-values in 2006 were also caused by high runoff and high N losses in most of the sites in the south-east. By contrast, cold and dry weather conditions during winter resulted in low FracLEACH values in 1995.

At the site in Romerike, Mørdre, the FracLEACH was very low in 2001 and the catch cropping reached its maximum area covering 45 % of the catchment area during autumn of that year.

At the two extensive grassland sites (Naurstad and Volbu), there was a slight increase in FracLEACH values during the monitoring period. At Volbu in Valdres, this trend was even significant. Runoff in Volbu increased less than FracLEACH, and there was no trend in N losses. The upward trend in FracLEACH was owing to the decreasing trend in N application. The last 7 years the N balance was even negative in Volbu.

The FracLEACH estimate is a difficult concept to evaluate since N application is the denominator of FracLEACH. Therefore increased efficiency in use of N fertilizer (reduced N application) may increase FracLEACH. Increased efficiency in use of N fertilizers and hence reduced N application in agriculture, by for example nutrient management planning for average yield instead of maximum yield or by introducing precision agriculture, may lead to reduced N application and in turn reduced N leaching. However, it may not necessarily result in reduced FracLEACH, since N application is not the main parameter influencing risk of N losses. A more comprehensive approach would include a simple regression model to estimate the risk of N losses to water.

8.1 International comparison

Most of the estimated values for FracLEACH, which have been documented in international literature, seem to be lower than the default of 30 %. The current default of 30 % was based on the general knowledge of the expert group that met in Geneva, Switzerland in 1995 to develop the 1996-revised IPCC methodology. The default uncertainty range of 10-80 % was justified on the basis of the global-scale modeling study of N loading in rivers by Seitzinger and Kroeze (1998).

The current default for FracLEACH of 30 % was critically examined by Weed and Kanwar (1996) in 6 case study areas in the Midwest of the USA. In general, the 6 Midwestern case studies found that the inorganic nitrogen loading in nearby rivers was typically equivalent to about 20 % of N inputs to agricultural fields. Some variation was observed between till and no-till systems and between crop types (deep rooted crops tended to reduce leaching loss), but by far the most significant factor determining interannual variability in leaching loss was precipitation. Low leaching and accumulation of inorganic soil N tended to occur during dry years, followed by large leaching losses in subsequent wet years. In one study, the fraction of N inputs leached ranged from 3–70 %, depending on interannual variability in rainfall (Weed and Kanwar, 1996). The range of FracLEACH presented in this case study corresponds very well to the range in FracLEACH values estimated for Norway.

In the Netherlands, Velthof and Mosquera (2011) used the STONE-model to calculate FracLEACH values for three periods from 1987-2008. The FracLEACH values showed a change from 14 to 12 % during this period. In the Norwegian data, there was a high interannual variation but the overall trend in FracLEACH was increasing.

Other values for FracLEACH have been estimated for other European countries. In an EU-project (EU-27), FracLEACH values were estimated by using 4 models (INTEGRATOR; IDEAg, MITERRA and IMAGE) for 27 EU countries (Vries et al., 2011, Velthof et al., 2009). The estimated values for FracLEACH were 14, 30, 12 and 28 % for the 4 models, respectively.

In New Zealand, FracLEACH values for a range of typical farming systems were compared with estimates obtained using the OVERSEER® nutrient budget model calibrated for New Zealand conditions (Thomas et al., 2005). The comparison suggested that FracLEACH for New Zealand is too high for dairy and sheep and beef farming systems. In contrast, the FracLEACH values estimated for arable and intensive vegetable systems using the OVERSEER® model were much closer to 30 % (the IPCC default value). Also in Norway, FracLEACH for intensive production arable systems tends to be higher than for grassland farming systems. For New Zealand, however, Thomas et al. (2005) suggested FracLEACH to be 7 % as an average for the country because of the large areas of extensive grasslands.

The Norwegian estimates for FracLEACH are generally higher than values estimated for the rest of Europe and especially compared to the suggested values for New Zealand. The length of the growing season may explain part of the difference in FracLEACH values between countries, but also high amount of precipitation contributes to increased leaching of applied nitrogen and accordingly to increase in FracLEACH.

8.2 New guidelines from IPCC on residues and organic soil

In a few years, new guidelines will be introduced by the IPCC. These new guidelines will include N in crop residues and N from agricultural use of peat land (http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html, eq 11.10).

Straw residues left on soil will add organic matter high in C/N ratio. This is food for the microorganisms, and when the C/N ratio is high, N will be assimilated in the microorganisms. This has two effects: 1) there will be less nitrate in soil water and thus reduced N leaching; and 2) decomposition continues the following growing season(s) and will compete with the crop in taking up N. Therefore it has been recommended to add an extra 10 kg N ha^{-1} in fertilizer. Accordingly, FracLEACH will decrease, since N application increases while the N leaching is reduced.

The behavior of organic soils is very dependent on the degradation degree of the peat and the time of cultivation. In the first years after cultivation, the C/N ratio is high and the competition by microorganisms for N is high. The N fertilizer applications will increase accordingly in order to get satisfactory yields. The N leaching will be low in this phase. As humification processes over time reduces the C/N ratio to below about 15, the situation becomes reverse. The humification processes now gives net release of N, and the N application has to be reduced in order to avoid lodging. In this situation, the N leaching from fields with crops of limited growth period (e.g. cereal) will increase. FracLEACH for organic soils may not sufficiently describe the risk of leaching from these soils.

9. Discussion

Different suggestions regarding the Norwegian FracLEACH estimate could be made from the available data in the JOVA-program. Three different approaches will be discussed.

1. **One average value for FracLEACH for the whole country**. An average value calculated from the existing monitoring catchments (JOVA). The JOVA catchments represent main agricultural regions, production systems, climates and soils and are therefore expected to cover the variation in Norwegian agriculture and factors relevant for N losses. Eight catchments constitute the database, and a median value give the central value of FracLEACH based on available data. The median FracLEACH is then be 22 % for Norway.

2. **Regional values of FracLEACH.** A refinement of this approach could be to develop values of FracLEACH for each of the combinations of precipitation/runoff and production systems. The monitored catchments represent agricultural production systems, soils and climate in Norway and this information could be used to define specific FracLEACH-values for each production system and runoff-level. Runoff was shown to be the most important factor for N losses and FracLEACH could be adjusted to reflect this relationship in the different regions. However, the purpose of FracLEACH is to look at the effect of changes in agricultural management and therefore annual variations in runoff should not be included in the values. Data on average runoff for a standard period are available from NVE for Norway. FracLEACH could then be calculated based on Table 6 for all agricultural areas in Norway.

Table 6. FracLEACH for agricultural productions systems in Norway

Production system	Region	Runoff$_{\text{IN REGION}}$ /runoff$_{\text{JOVA}}$ (mm/mm)	FracLEACH (%)	JOVA catchment
Cereal/Marine	Akershus/Østfold/ Vestfold/Trøndelag	Runoff$_{\text{in region}}$/536	31	Skuterud, Mørdre
Cereal/Moraine	Hedmark/Opland	Runoff$_{\text{in region}}$/346	32	Kolstad, Bye
Intensive grass	Rogaland and others	Runoff$_{\text{in region}}$/733	17	Time
Extensive grass	Opland and others	Runoff$_{\text{in region}}$/285	16	Volbu
Extensive grass	Northern counties	Runoff$_{\text{in region}}$ /1127	23	Naurstad
Potato/vegetable	Whole country	Runoff$_{\text{in region}}$ /1236	44	Vasshaglona

Example: FracLEACH for an agricultural area (e.g. cereal production with 300 mm runoff) could then be calculated as follows:

FracLEACH (%) = 31 * 300/536 = 17 %, where runoff for this area is derived from NVE.

Some agricultural areas in Norway may not be represented in Table 2. An analysis of the dominating production systems in these areas will be the basis for the decision on which FracLEACH to use in these areas. The productions system is more important than the region (Table 2), since the regional differences are mainly reflected in precipitation and runoff.

3. **Calculating N loss by using a Norwegian N-model**. A model (Jovanest, see chapt. 6) was developed for National Reporting in relation to international agreements. This model is used to estimate the contributions of N from agricultural areas to the North Sea. The model is a multiple regression model based on JOVA-data and developed to use input data from statistical sources. It does not consider runoff in individual years, but uses the statistical data available from SSB on crop distribution and soil

tillage. N-application is not available from Norwegian Statistics and therefore information on N-application from the JOVA-catchments is used in the calculations. This model thus gives an estimate of the N-losses for a “normal” year, taking into account the changes in agricultural management that has occurred this year in the JOVA-catchments. Each year N losses from agricultural areas in Norway are calculated with this model and using this model will give the most exact estimate for N loss from agricultural areas. However, it will not reflect the IPCC-guidelines for calculations of N losses.

10. Conclusion

The overall FracLEACH calculated for all sites and years included in this study was 22 %. This average value covers a variation between sites from 16 % to 44 %. The differences in FracLEACH between sites were partly due to differences in precipitation and runoff, but also to factors like soil tillage, N balance, potential denitrification influenced the site specific FracLEACH.

The highest FracLEACH was found in the Vasshaglona catchment, which is characterized by intensive vegetable and potato production with considerable application of livestock manure. The high FracLEACH for this site may be explained by the high N application in relation to yield (high N surplus) and may be caused in part by intensive soil management. The annual variation in FracLEACH for this area was from 28 % to 78 %.

For cereal production areas in Akershus FracLEACH values varied from 18-31 %, due to differences in soils and precipitation.

Cereal production with livestock production in Hedmark had a FracLEACH of 32 %, ranging from 16 to 57 % on annual basis.

Intensive grassland in Rogaland had an average FracLEACH value of 17 % varying from 7 to 22 % and extensive grasslands had average FracLEACH values of 16 and 23 % for Valdres and Nordland, respectively.

Nitrogen losses are not directly related to N application in agriculture. Both site specific and crop specific factors influence the amount of N lost through surface and subsurface water. The annual variations in FracLEACH for each site were dominated by variations in runoff. In addition, N balance (e.g. low yields because of draught) had an impact on the annual FracLEACH.

Agricultural mitigation methods to reduce N losses to water include increased N efficiency, increased plant uptake of N, reduced N balance, reduced soil tillage, manure application during the growing season and increased denitrification of N.

The calculated values for FracLEACH for Norwegian agriculture are generally below the default value in the IPCC guidelines, but the Norwegian values are higher than country specific values documented by many other countries.

According to the guidelines of IPCC, N losses should be calculated based on the concept defined by FracLEACH. We suggest that a regional FracLEACH will give a more exact estimate of FracLEACH compared to one value for the whole country. These regional values should reflect differences in runoff and differences in productions systems/soils.

11. References

Bechmann, M., Deelstra, J., Stålnacke, P., Eggestad, H.O., Øygarden, L., Pengerud, A. 2008. Monitoring catchment scale agricultural pollution in Norway – policy instruments, implementation of mitigation methods and trends in nutrient and sediment losses. Environmental Science and Policy 11: 102-114.

Daugstad, K., Fystro, G., Kristoffersen, A.,Ø., Bergjord, A.K., og Nesheim, L. 2012. Næringsinnhald og gjødslingsverknad av husdyrgjødsel - Fagleg rapport for 2011 til SLF

Deelstra, J., Vagstad, N.H. & Øygarden, L. (1998) Sampling technique and strategy. In: Measuring runoff and nutrient losses from agricultural land in Nordic countries (ed. by L. Øygarden and P. Botterweg) Tema Nord 1998: 575, 27-35. Nordic Council of Ministers, Copenhagen.

Deelstra, J. & Øygarden L., (1998) Measurement of runoff. In: Measuring runoff and nutrient losses from agricultural land in Nordic countries (ed. by L. Øygarden and P. Botterweg) Tema Nord 1998: 575, 13-26. Nordic Council of Ministers, Copenhagen.Eggestad, H.O., Bechmann, M., and Stålnacke, P. 2001.

Goulding, K.W.T. 2000. Nitrate leaching from arable and horticultural land. Soil use and management 16. Pp 145-151.

Kværnø, S.H. and Bechmann, M. 2010. Transport av jord og næringsstoffer I overflate- og grøftevann. Bioforsk rapport 5/30 2010.

Nevison, C. 2000. Review of the IPCC methodology for estimating nitrous oxide emissions associated with agricultural leaching and runoff. Chemosphere - Global Change Science 2, 3–4, pp 493–500

Riley & Børtnes i Acta Horticulturae 2010

Seitzinger and Kroeze, 1998. Global distribution of nitrous oxide production and N inputs in freshwater and coastal marine ecosystems. Global Biogeochem. Cycles, 12 (1998), pp. 93–113

Simmelsgaard, S.E. 1998. The effect of crop, N-level, soil type and drainage on nitrate leaching from Danish soil. Soil use and management 14, 30-36.

Thomas, Stephen; Ledgard, Stewart; Francis, Glyn. 2005. Improving Estimates of Nitrate Leaching for Quantifying New Zealand's Indirect Nitrous Oxide Emissions. Nutrient Cycling in Agroecosystems, Volume 73, Numbers 2-3, pp. 213-226(14).

Uhlen, G. 1989. Nutrient leaching and surface runoff in field lysimeters on a cultivated soil. Nutrient Balances 1974-181. Norwegian Journal of Agricultural sciences, 33-46.

Weed and Kanwar, 1996. Nitrate and water present in and flowing from root-zone soil. J. Environ. Qual., 25 (1996), pp. 709–719

Vagstad, N., Bechmann, M., Stålnacke, Eggestad, H.O., and Deelstra, J. 1998. Rapport fra jordsmonn overvåkingen I Norge. Jordforsk rapport 79/98. pp 26.

Vagstad, N., P. Stålnacke, H.-E. Andersen, J. Deelstra, V. Jansons, K. Kyllmar, E. Loigu, S. Rekolainen, and R. Tumas. 2004. Regional variations in diffuse nitrogen losses from agriculture in the Nordic and Baltic regions. HESS - 8, 4, pp. 597-859.

Vries de, W., Leip, A., Reinds, G.J., Kros, J.,Lesschen, J.P., Bouwman, A.F. 2011. Comparison of land nitrogen budgets for european agriculture by various modeling approaches. J. Environ. Pollut. 159:3254-3268.

Velthof, G.L. and Mosquera, J. 2011. Calculation of nitrous oxide emissions from agriculture in The Netherlands. Alterra report 2151.

Velthof. G.L., Oudendag, D., Witzke, H.P., Asman, W.A.H., Klimont, Z., Oenema, O. 2009. Integrated Assesment of Nitrogen losses from Agriculture in EU-27 using MITERRA_EUROPE. J. Environ. Qual. 38:402-417