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A comparison of disaggregated nitrogen budgets for Danish agriculture using Europe-wide and national approaches

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ABSTRACT

Spatially detailed information on agricultural nitrogen (N) budgets is relevant to identify regions where there is a need for a reduction in inputs in view of various forms of N pollution. However, at the scale of the European Union, there is a lack of consistent, reliable, high spatial resolution data necessary for the calculation of regional N losses. To gain insight in the reduction in uncertainty achieved by using higher spatial resolution input data. This was done by comparing spatially disaggregated agricultural N budgets for Denmark for the period 2000-2010, generated by two versions of the European scale model Integrator, a version using high spatial resolution national data for Denmark (Integrator-DK) and a version using available data at the EU scale (Integrator-EU). Results showed that the national N fluxes in the N budgets calculated by the two versions of the model were within 1-5% for N inputs by fertilizer and manure excretion, but inputs by N fixation and N mineralisation differed by 50-

100% and N uptake also differed by ca 25%, causing a difference in N leaching and runoff of nearly 50%. Comparison with an independently derived Danish national budget appeared generally to be better with Integrator-EU results in 2000 but with Integrator-DK results in 2010. However, the spatial distribution of manure distribution and N losses from Integrator-DK were closer to observed distributions than those from Integrator-EU. We conclude that close attention to local agronomic practices is needed when using a leaching fraction approach and that for effective support of environmental policymaking, Member States need to collect or submit high spatial resolution agricultural data to Eurostat.

Key words: nitrogen; agricultural soils; modelling; budgets; disaggregation; national.

1 Introduction

Spatially detailed information on nitrogen (N) budgets is relevant to identify regions with a high potential to significantly reduce N pollution and increase N efficiency. Moreover, to be relevant for policymakers, there is a need to disaggregate national N budgets, at least to the scale of the administrative NUTS3 regions (Nomenclature of Territorial Units; EC, 2017) that are often responsible for local health and business development and local environmental regulation. Furthermore, disaggregation to biophysical regions such as landscapes and/or catchments is relevant, since implementation of the Water Framework Directive (EC, 2000) and to a lesser extent the Nitrates Directive (EC, 1991) will lead to significant changes in land use and land management at this scale.

Regarding the assessment of agricultural N budgets within a country it is important to identify the most appropriate scale in view of the impact of N inputs on air quality and water quality. For nitrous oxide (N_2O), information on the spatial distribution of the emissions is less relevant, because N_2O is a long-lived gas with strong atmospheric dispersion, leading to an averaging of its concentration. For NH_3 emissions, and related N deposition, and for N leaching and N runoff, accurate information on their spatial distribution is, however, crucial in view of eutrophication impacts on terrestrial and aquatic ecosystems close to its source (Cellier et al., 2011; De Vries et al., 2015; Kros et al., 2013). Here, aggregation of input data for large areas may cause accurate average N deposition and N leaching levels, but a strong deviation in the area exceeding critical N deposition loads or critical N concentrations in ground water and surface water (De Vries et al., 2010). This effect holds for all spatial levels and may especially affect the results of European scale model predictions. For this reason, many countries in Europe have developed modelling tools, at national and sub-national scale.

One model that has been used at European scale to assess N budgets is the model Integrator (De Vries et al., 2011; Kros et al., 2012), which includes the MITERRA model (Velthof et al., 2009) for agricultural regions, modified to include much more spatial detail. Where MITERRA focuses on ca 300 NUTS2 regions, Integrator includes ca 40,000 NitroEurope Classification Units (NCUs), which are unique combinations of soil mapping units (Soil Geographical Database of Europe, SGDBE; Daroussin et al., 2006; EC, 2006) and slope classes (Vogt et al., 2007) within ca. 1300 NUTS3 regions (EC, 2017). These NCUs are composed of polygons, being clusters of 1 km by 1 km pixels. The model includes detailed downscaled information on animal numbers at NCU level, upscaled from 1km by 1km information (Neumann et al., 2011). Despite using this detailed information, the model might be quite inaccurate at the regional level within countries (cf. Kros et al., 2012).

To gain insight in the reduction in uncertainty that could be achieved by using higher resolution input data, spatially disaggregated agricultural N budgets for Denmark for the period 2000-2010 were generated by the European scale model Integrator, using both high spatial resolution national data (Integrator-DK) and data available at the European scale

(Integrator-EU). Here we report the approach and results of this study, focusing on the years 2000 and 2010, for which the quality of the regional Danish input data was considered best. The results provide insight into the quality of European-scale model results at regional scale (within country level). We also compared the results at national scale with those obtained using Danish national data and a Danish modelling approach.

2 Materials and methods

2.1 Integrator EU

The Integrator model uses relatively simple and transparent model calculations based on existing model approaches, combined with high-resolution spatially explicit input data. It includes sub-models for the prediction of ammonia (NH_3), nitrous oxide (N_2O), other oxides of N (NO_x) and dinitrogen (N_2) emissions and N leaching from the root zone (principally nitrate, NO_3^-) and runoff from animal housing, manure storage systems and agricultural soils, based on the MITERRA-Europe model (Lesschen et al., 2011a; Velthof et al., 2009) and from non-agricultural terrestrial systems, including deposition, fixation, (im)mobilisation and emissions and leaching for forests and semi-natural vegetation. An emission and deposition matrix for NH_3 and NO_x, based on the EMEP model (Simpson et al., 2006), is used to assess the interactions through the atmosphere between agricultural and non-agricultural land.

Integrator calculates the total manure production for each NUTS3 region, using Eurostat data on animal numbers at NUTS3 level and excretion rates from the CAPRI model (Britz and Witzke, 2012). The manure production is calculated at the NCU level, using livestock numbers downscaled from NUTS3 level and national values for N excretion per animal type. A division is made between excretion of animals in housing systems and animals grazing pastures, based on data at the country level that is derived from the GAINS model (Klimont and Brink, 2004). Manure produced in housing and manure storage systems at NCU, corrected for nutrient losses (gaseous and leaching) in animal housing and storage systems, is first distributed within a NUTS3 region, until a maximum manure application is reached. If excess manure exists within an NCU, the excess is distributed over nearby NCUs within the same NUTS3 region that have the capacity to utilise more manure. If an excess exists at NUTS3 level, the remaining excess is distributed to nearby NUTS3 regions within the country. There is no manure transport between countries included in the model. When an excess at country level exists, being only the case for a few countries, this manure is removed from the system. More detail is given in section 1 of the Supplementary material (SM).

The maximum amount of manure N applied to agricultural land was set to the 170 kg N ha^{-1} yr^{-1} specified in the EU Nitrates Directive (EC, 1991), except for grassland and other roughage crops in Belgium, Denmark, Germany, UK, Ireland, Italy and Netherlands. Here, values of 230 or 250 kg N ha^{-1} yr^{-1} are used, depending on the derogation received from the EU. These maximum manure applications rates were assigned irrespective of the occurrence of nitrate vulnerable zones (NVZ).

The actual manure application rates, being equal to the N excreted minus N emissions in housing systems and by grazing, depends on the crop and grassland type specific weighing factors (see SM section 1 for more details). The N fertilizer application at NCU level is based on the total N crop offtake, the available non-N fertilizer inputs (N inputs by animal manure, crop residues, N mineralization, N deposition and N fixation) and the N use efficiency (NUE) of the effective N input. The results thus obtained were corrected, where needed, by making use of national fertilizer consumption rates for the year 2000 or 2010 (FAO, 2010).

The N crop offtake is calculated as the product of the crop yield (in terms of harvest) and the N content in harvested crops, which in turn is a function of the N input. The total demand in a NUTS3 region is calculated by multiplying the N removal of each crop by the total area of the crops in each NUTS3 region. The areas of crops in NUTS3 regions are derived from CAPRI. The yields of arable crops for each country are derived from FAOSTAT (FAO, 2010). The N contents of harvested crop products and the amount of crop residues and the relation with N input are based on literature (Fink et al., 1999; Greenwood and Draycott, 1989; Velthof and Kuikman, 2000). The N in crop residues is calculated by dividing the N removed in harvest with an N index.

The emission of gaseous N compounds (NH_3, N_2O, NO and N_2) accounted for in the model include emissions (i) from faeces and urine during storage in housing and manure storage systems, (ii) by grazing animals, (iii) after application of manure and fertilizers to agricultural land and (iv) due to atmospheric deposition, N fixation and crop residue input (not included for NH_3).

NH_3 emissions from fertilizer and animal manure applications are calculated by multiplying the application rates of different animal manures and fertilizers by animal and country-specific emission factors (related to application techniques), based on the GAINS model (Klimont and Brink, 2004).

Losses of N from agricultural systems to ground- and surface waters accounted for in the model include: (i) leaching from stored manure to groundwater, (ii) surface runoff to surface waters, (iii) subsurface runoff to surface waters, and (iv) leaching to groundwater.

Surface runoff is calculated as a fraction of the various N inputs, using runoff fractions that depend on slope, precipitation, land cover, soil type and soil depth. The sum of N leaching and subsurface runoff from soils is derived by multiplying the soil N surplus by leaching fractions, which are determined based on soil texture, land use, precipitation surplus, soil organic carbon content, temperature and rooting depth. The remaining fraction is assumed to be denitrified to N_2.

2.2 Integrator DK

For the application of Integrator with high spatial resolution national data for Denmark we made the following changes: (i) adaptation of the boundaries of the NCU, (ii) adaptation of the manure distribution module and (iii) translation of the detailed Danish data to conform with the animal, manure and crop types used in Integrator. This resulted in a new version of Integrator: Integrator-DK.

Based on the boundaries of the municipalities, firstly the NCUs were stretched such that they exactly fill the municipal boundaries. This was only a cosmetic adaptation and does not influence the results (see Figure 1). Secondly, NCUs that crossed a municipal boundary were split, such that all NCUs are then bound by the municipal borders. The overlay with 99 municipalities resulted in 610 NCUs for DK as a whole, an increase of 497 NCUs compared to Integrator-EU (Figure 1).

Although detailed estimates of manure applications rate were available for Denmark, we used the Integrator-EU manure distribution module to calculate the manure distribution. This was done to ensure that all N flows through the manure management system from excretion to application were included. We calculated the animal manure produced within an NCU, based on farm-scale data concerning the number of animals within different livestock categories (e.g. dairy cows, finishing pigs). The manure produced was distributed over the available agricultural land within an NCU, while taking into account the maximum permissible manure application rates, according the Nitrates Directive (ND). The ND became into force in 1991 and the first reporting period was 1992-1995. Because the change in application rates was a gradual process, we implemented the ND, including the derogation for Denmark (i.e. 230 kg N ha^{-1} yr^{-1} for grassland and 170 kg N ha^{-1} yr^{-1} for arable land) as a linear change in maximum manure application rates during the period 1992-2003 (three ND reporting periods). The change was therefore from 340/460 kg N in 1992 to 170/230 kg N in 2003, with 100%

implementation from 2003 onwards. These limits were used for the entire country, because the whole of Denmark is classified as NVZ. During the entire investigated period, 2000-2010, it was always feasible to apply all manure produced in Denmark within the legal boundaries.

2.3 Underlying European and national datasets

In Table 1, an overview is given of underlying datasets used in the original Integrator-EU version and in Integrator-DK. For the incorporation of the detailed Danish data, we translated the Danish categories (such as animal types and crop types) into those used in Integrator.

The Danish data on crop areas and livestock numbers were available for the period 2000-2010 at municipality level. This was first translated into the Integrator types and then assigned to the NCUs. For soil types we used the aggregated European Soil Map categories. An overview of the linkage of the Danish data sets to the Integrator categories is given in section 2 of the SM.

For the mineral fertilizer application, we used the amount of mineral N fertilizer based on statistical data at farm level for the years 2000-2010, that were assigned to the NCUs. The NH_3 emission fractions for housing and storage emission were based on the national average yearly housing type fractions for the period 1990-2010 and a time independent NH_3 emission fraction per housing type (based on Mikkelsen et al., 2011). Therefore we linked the housing systems used within Integrator with those used in Denmark. The yearly (weighted) mean emission fraction (kg NH_3^-N/kg stable excreted N) thus derived for the years 2000 and 2010 are given in the SM (section 3).

Application emission fractions for NH_3 were derived in a similar way. Mikkelsen et al. (2011) provided yearly information at the national level on used application technique (for liquid manure: injection, trailing hose, broadcast spreading, for solid manure: broadcast spreading) and the related emission fraction for the period 1985-2011. Based on this information a yearly weighted mean emission fraction was calculated (see SM section 3 for more details).

Using the derived input data, we performed the following model simulations:

- Integrator-EU simulations with default EU scale data and default emission factors for the years 2000 and 2010
- Integrator-DK simulations with disaggregated Danish data and emission factors for the years 2000 to 2010

3 Results

3.1 Nitrogen budgets at national level

Annual national land N budgets for Danish agriculture for the years 2000 and 2010 based on the original Integrator version ('Integrator-EU'), the version using the more detailed Danish data ('Integrator-DK') and the Danish national budget (Hutchings et al., 2014) ('DK budget') are given in Table 2. The land N budgets include all N inputs to farmland, net N removal by harvest of crops and grass and the loss of excess N to the environment (air and water), both from housing systems and soils. The N surplus (Total output – Offtake) of the farmland budget includes the N losses from housing and manure management systems and soils and is often used as an indicator of agricultural pressure on water and air (De Vries et al., 2011; EEA, 2005).

The N inputs to Danish agriculture estimated by Integrator-DK were generally lower than those by Integrator-EU in 2000, whereas in 2010 the situation was reversed. Most noticeable differences were found in N mineralisation, being 38 kton N lower for Integrator-DK in 2000 and 4 kton lower in 2010. Inversely, N fixation was 13 kton N higher for

Integrator-DK in 2000 and 8 kton higher in 2010. The difference between Integrator-EU and Integrator-DK in total N input amounted -6% in 2000 and +4% in 2010. The total agricultural N inputs estimated by Hutchings et al (2014) were 2-10% higher than both Integrator versions, depending on the version (EU or DK) and the year (2000 or 2010). The estimated values for N fixation in the DK budget were more than twice as high as those of both Integrator versions, whereas the DK budget estimates for N deposition from the atmosphere were lower. For manure excretion, the DK budget estimated value was higher than both Integrator versions in 2000, whereas in 2010 the situation was reversed, although to a lesser extent.

The crop N offtake estimates obtained from Integrator-DK were considerably lower, 28% in 2000 and 12% in 2010) than from Integrator-EU. For NH_3, N_2O and NO_x emissions, the differences between the Integrator versions were smaller (less than 10%). The estimates of N_2 emission, NO_3^- leaching and N runoff were higher from Integrator-DK than Integrator-EU, both in 2000 and 2010, mainly due to the much lower crop N offtake estimated by Integrator-DK. In both years, the DK budget values for crop uptake were in between. The estimated emissions of NH_3 were similar for both Integrator versions and the DK budget in 2000 but DK budget estimates were lower in 2010. For NO_x and N_2O emissions, the DK budget estimates were substantially higher. The estimates of N_2 emissions from Integrator-DK were substantially higher than those in the DK budget for both years, whereas the sum of NO_3^- leaching and runoff from both Integrator versions was substantially (up to a factor 2) lower than those from the DK budget for both years. Integrator separately estimates N leaching and runoff, whereas no distinction was made between leaching and runoff in the DK budget. As with the total N input, the cumulative N output estimated by both Integrator versions was 5-10% less than the estimated output by the DK budget in both years.

3.2 Nitrogen inputs and losses at regional level for the year 2010

3.2.1 Comparing Integrator-EU and Integrator-DK results at NCU level

Figure 2 presents XY-plots based on a comparison of the 113 plots of Integrator-EU versus the mean of the corresponding Integrator-DK plots.

The differences between the two models at NCU level can be rather large. Results show a reasonable correspondence ($R^2 \geq 0.4$) for N_2O emission and N leaching, but poor correspondence for N fertilizer, N surplus and N runoff ($0.2 < R^2 < 0.4$) and very poor correspondence for N manure application, NH_3 emission and N offtake ($R^2 \leq 0.2$).

The very poor correspondence for manure application and NH_3 emission is due to the difference in livestock distribution (see section 2 of the SM for more details), indicating that the data and spatial allocation method used in Integrator-EU needs to be improved. The very poor correspondence for N offtake is caused by both a difference in spatial distribution (low correlation) and at almost all locations, higher Integrator-EU values than Integrator-DK values. This is caused by the higher yields used by Integrator-EU for fodder maize and grass (see section 2 of the SM for more details). Despite the large deviations in both N manure application and N offtake, the correspondence is reasonable for N leaching. The points with very high N surpluses (> 250 kg N ha^{-1} yr^{-1}) refer to peat soils with high N mineralisation rates (> 400 kg N ha^{-1} yr^{-1}).

3.2.2 Comparing maps with disaggregated inputs and losses of Integrator-EU and Integrator-DK

The spatial distribution of animal manure application for the year 2010 as modelled by the two approaches appeared to be reasonably comparable (Figure 3, top), with the highest application levels in the central and western areas and lower levels in eastern areas. However, the distribution of the areas with high manure inputs (> 100 kg ha^{-1}) are quite different. This is likely due to differences in the spatial distribution of animal numbers. This difference is also reflected in the NH_3 emission (Figure 4, top).The areas with high NH_3 emissions are located quite differently by Integrator-DK and Integrator-EU. Maps showing the NH_3 emission from housing and application separately are given in the SM (section 5). Furthermore, the Integrator-DK emission values are on average 10% higher (see Table 2). The spatial distributions of N fertilizer inputs (Figure 3, bottom), as modelled by both methods, differ less than those of N manure inputs, as also reflected by the XY-plot (Figure 2, a slightly higher R^2). Nevertheless, the differences can be large, especially in the north western part of Jutland. For N_2O emissions (Figure 4, middle) the differences in spatial distributions are smaller, as reflected by the XY-plot. Showing a relatively high R^2 (0.50) and a slope close to 1 (0.90). However, differences in spatial distribution of N_2O are of lesser importance because its adverse environmental impact is related to global warming and not local pollution. The two spatial distributions of NO_3^- leaching flux to groundwater and surface water show relatively large differences (Figure 4, bottom). Moreover, Integrator-DK estimates more than 30% higher NO_3^- leaching fluxes, due to lower predicted N offtake (40 kton N less) and higher gaseous N emissions (5 kton N more) than Integrator-EU (see Table 2). This is despite the reasonable correspondence based on the R^2 of the XY-plot (see Figure 2).

4 Discussion

4.1 Plausibility of various modelled nitrogen fluxes

The effect of using national data sources on the N flows predicted by Integrator at the national scale were important, particularly for some items. The differences between Integrator models in N fixation and crop N uptake are due to more accurate crop data (crop mixture and yields) whereas the difference between Integrator-DK and the DK budget with respect to N fixation reflects differences in the underlying models. The difference between Integrator versions with respect to N leaching and emissions of N_2O from the soil illustrate the importance of obtaining good crop yield data to support the calculation of crop N uptake, since these flows are a function of the difference between N inputs and N removed in crops (both in the models and in practice). The large difference in N leaching between Integrator-DK and the DK budget reflects differences in how the two models partition the residual soil N balance (N input – crop N offtake – (NH_3+N_2O+NO_x) emissions); in both 2000 and 2010, the residual N balance is identical but the partitioning varies considerably.

The use of more detailed national data appears to generate more plausible results. The use of national yield data is likely to give more plausible estimates of the crop N offtake (Table 2) than those based on values from FAO (FAO, 2010), which mean that the Integrator-EU crop N offtake values were too high, especially for the year 2000. Moreover, detailed national data also results in more plausible spatial distribution of livestock densities and manure application. As a result, the national total of the Integrator-DK modelled the sums of N leaching and runoff are closer to those of DK budget, both in 2000 and 2010. However, there are also N flows where the difference between the national totals of the Integrator results and the DK budget increased when using Integrator-DK rather than Integrator-EU e.g. N deposition. In this case, it is because N deposition and NH_3 emission are connected within Integrator, so differences in NH_3 emission between the Integrator versions feed through N deposition.

The differences between Integrator versions with respect to both N_2O emission and NO_3^- leaching partly relate to the livestock distribution (so manure applied) and partly to the fertiliser distribution. The differences between Integrator and the DK-budget is due to the use in Integrator of spatially distributed N_2O emission fractions, which depend on soil type, precipitation, pH etc. In contrast, the model used for the DK-budget uses a standard IPCC Tier 2, so emissions are just a proportion of the N applied to soil. With regard to the higher N leaching estimates obtained using Danish methods, we can conclude that this is in part due to differences in modelling N_2 emissions. Both Integrator versions use the leaching fraction concept, which is applied spatially at NCU level and depends on factors such as soil texture, soil organic carbon content, precipitation surplus, temperature, land use and rooting depth, all of which are specified at that scale. In contrast, the method underlying the DK-budget estimated NO_3^- leaching at the field scale. To do so, farm-scale data on livestock numbers, manure management systems and fertiliser, and field-scale data on cropping were used to distribute manure and fertiliser within each farm. A complex model (DAISY, Hansen et al., 1990) was used to calculate drainage water and then all the field-scale data were used as input into an empirical NO_3^- leaching model (N-LES4, Kristensen et al., 2008).

For the modelling of NH_3 emissions, Integrator-EU uses the activity data and emission factors from the GAINS model (Klimont and Brink, 2004) and this model has been adjusted by IIASA to match the Danish national emission values reported under CLRTP (UNECE, 1994). However, in case of Integrator-DK, we used the downscaled livestock populations, housing types and the emission factors related to the DK housing types, all based on Danish national data. Apparently, this caused a substantial difference in total emissions as calculated by the two Integrator versions (from Integrator-EU to Integrator-DK: 63 to 58 in 2000 and 56 to 61 in 2010), but this even increases the difference (from 5 kton (+10%) to 10 kton (+20%)) in 2010. This difference is mainly caused by the increase in of housing emission (see Table 2), as a result of higher (+5%) excretion and the difference in NH_3 emission fraction (see section 3 of the SM). Here it should be noted that although the Integrator-DK and DK budget models use the same activity data and the same method for estimating emissions (activity × emission factor), and the Integrator-DK emission factors were adapted to Danish conditions (see section 3 of the SM), the model used in the DK budget uses a much larger range of animal housing and manure storage categories.

4.2 Plausibility of spatial distribution of N losses to air and water

From this study it is clear that the current procedure of livestock downscaling in Integrator is a substantial source of uncertainty. The question is whether the livestock distribution model within Integrator can be improved? The errors are mainly associated with the distribution of pigs and poultry, since in Europe, the distribution of cattle can be associated with the distribution of grassland (see SM section 2). This has also been reported by Neumann et al. (2011), who concluded that the contrary to cattle, the mechanisms behind the spatial allocation of pigs and especially poultry are not well understood. This makes it difficult to improve the model and this would suggest that data on the distribution of livestock should be made available in the EU scale at a higher spatial resolution than at present. In many cases, the national data are collected at a higher resolution than is reported to Eurostat so in the first instance, these data could be made available.

Most of the N losses calculated by Integrator-EU and Integrator-DK differ quite considerably at the NCU scale. This is mainly because inaccuracies in the distribution of livestock in Integrator-EU version lead to inaccuracies in the distribution of manure N (see Figure 3). Manure N accounts for about half the total N supplied to crops (Table 2) and plays an important role in all soil N losses, particularly NH_3 emission. This indicates that the use of detailed spatially distributed Danish data significantly improved the plausibility of the Integrator results.

There are limited or no empirical data available to compare with the national or spatially detailed model predictions. For NH_3 and NO_x, the networks of measurements are too sparse (although adequate for detecting trends) and there is no network for N_2O. For NO_3^-

concentrations, measurements are available for the fjords but these are also responsive to processes occurring below the rooting zone and in surface waters. Likewise, data from drinking water boreholes, since measurements are from older water and water extracted well below the rooting zone (Hansen et al., 2011) and are affected by nearby conditions (Hansen et al., 2016). The best that can be claimed is that the measurements show higher concentrations in Jutland than in the rest of the country (Schullehner and Hansen, 2014), despite higher rainfall here, and that this corresponds to the higher predicted NO_3^- leaching (Figure 4, bottom).

The differences between the Integrator and DK budget estimates of NO_3^- leaching is an indication that the leaching fractions used in Integrator are too low for Danish conditions, where most agricultural soils are free-draining, with low denitrification rates. In order to gain more insight into the reliability and validity of the spatial distribution of N leaching results of Integrator-DK, we compared the Integrator-DK results with the spatially distributed N-LES4 results of Kristensen et al. (2008) at NCU level. Given that it was recognised that the leaching fractions (LF) used in Integrator are too low, we made a comparison with Integrator-DK results while using enhanced leaching fractions. Based on De Vries et al. (2003) we used a generic leaching fraction for grassland (0.85) and for arable land (1.0) (see SM section 6). We compared those model results with the corresponding N-LES4 results at NCU level (Figure 5, left) and at municipality level (Figure 5, right). From this comparison at NCU level of both modelling results, it appears that enhancing the leaching fraction yields to Integrator-DK results that are more in line with the N-LES4 and this holds even more for the comparison at municipality level, where the underlying spatial variability of NCUs within municipalities is levelled out (compare Figure 5, right and the corresponding maps in Figure 6). Furthermore, this comparison shows that the underestimation mainly occurs in municipalities dominated by grassland (green dots in Figure 5, right), whereas it is overestimated in municipalities dominated by arable land (brown dots in Figure 5, right). In summary, we conclude that the Integrator-DK model with an adapted leaching fraction, provides a reasonable representation of the spatial variation in N leaching in Denmark.

4.3 Improving the flow of information to policymakers

To be of value for policymaking, predicted flows of N need to be realistic regarding their magnitude, geographic variation and origin (i.e. activity driving flows). The relative importance of these three characteristics varies depending on the compound in question. The origin is important if action needs to be taken to reduce losses. For N_2O emissions, the magnitude is important whereas the geographic location is not, since the regulatory limit is at a national scale. For NH_3 and NO_3^- leaching, the magnitude and location are both important. National NH_3 emission is regulated under the Convention on Long-range Transboundary Air Pollution and EU NEC Directive (EC, 2001), and the location of the NH_3 emissions is important for the estimation of N deposition to sensitive ecosystems and secondary particulate matter concentrations. For NO_3^- leaching from the root zone, the magnitude at the national scale is irrelevant but important at higher spatial resolutions, as this information is an input to models that calculate NO_3^- concentrations in drainage water (regulated under the Nitrates Directive; EC, 1991) and NO_3^- inputs to aquatic ecosystems (regulated under the Water Framework Directive; EC, 2000). Errors in model predictions of N losses can be from two sources; model error (inability of the model to reflect the processes driving N flows) and errors in input and parameter data. In the work reported here, the focus has been on the latter source.

This study has shown the importance of having data on livestock type and population, and manure management, available at a high spatial resolution for estimating losses of N to the environment, both at the national and local scales. This is particularly important for losses as NH_3 and NO_3^-. For NH_3, high spatial resolution data are needed to calculate N deposition to sensitive ecosystems (and so within Europe, compliance with the Habitats Directive; EC, 1992) and the formation of secondary particulate air pollution (and so in Europe, the Clean Air Directive; EC, 2008). For NO_3^- losses, these data are necessary to show compliance with the Nitrates and Water Framework Directives. In many cases, these data are available at the national scale but would require additional effort for data harmonisation, data collation and database management for them to be available at the EU scale. Moreover, livestock N excretion factors are as important as livestock numbers to arrive at reliable animal manure inputs, although these are generally collected at the national scale. Nevertheless, the way how these factors are derived differ per country and per policy (Velthof et al., 2015). There is therefore a need for a harmonisation of the procedures used. Ideally, distribution data should be collected for all livestock types but where this is not feasible, priority should be given to non-ruminant species, since it is more difficult to derive spatial distributions using other means than is the case for ruminants. In the meantime, we need to acknowledge that deviations between methods increase with an increase in spatial resolution (see e.g. Zhu et al., 2016). The challenge we have is to find an optimal balance between the current data availability and the spatial scale on which research results must be represented to support policy makers and legal authorities.

5 Conclusions

Large differences exist for the national N budgets calculated by the Integrator-EU and Integrator-DK versions of the model. Differences in spatial distribution between Integrator-EU and Danish national results are mainly due to differences in the spatial distribution of livestock and the resulting manure distribution. This causes large differences between EU and

DK versions in the spatial distribution of NH_3 emission and N leaching. Furthermore, differences in crop N offtake and the leaching fractions used in Integrator causes larges differences in N leaching and runoff, indicating the need to take greater account of local agronomic practices.

This comparative study between spatially detailed data based and generic national data based N budgets illustrates the importance of good spatial resolution in input data. There is clearly a need for the collection of high resolution data from all Member States or Member States should submit their own existing (high) spatial distribution data to Eurostat. Furthermore, there is a need for a harmonisation of the procedures used to collect detailed national data such as those proposed by the Expert Panel on Nitrogen Budgets (see Leip et al., 2016). Given that Member States take decisions based on model estimates of N pollution that have major economic and social consequences, the cost of more detailed, spatial agricultural data would be a good investment.

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Table 1 Overview of the underlying data sources for use at NCU level as used in the standard Integrator-EU model and in Integrator-DK.

Input data	Integrator-EU		Integrator-DK	
	Data sets/ Data source	Resolution	Data sets/ Data source	Resolution
		113 NCUs		630 NCUs
Land cover	CLUE model predictions, based on CORINE 2000 data for grassland and cropland (EEA, 2009), 100m by 100m	NCU	Area of different crops, including grassland and forest, for each field plus rotation for 2000-2010	Municipality level (95) data was downscaled[4)] to NCU and yearly values for the period 2000-2010
Land use (crops arable land)	CAPRI-SPAT disaggregated data on crops (Leip et al., 2008)	Fraction of crops per NCU	see above	see above
Soil	European Soil Database, scale 1:1,000,000 (Panagos, 2006)	Dominant soil type per NCU	As Integrator EU	
Animal livestock numbers	Downscaled FAO data at country level, based on consistent regional livestock statistics for NUTS1, NUTS2 or NUTT3 regions in the Eurostat-Eurofarm database, to 1km by 1km data (Neumann et al., 2009) aggregated to NCU level. Before 2010 FAO data (FAO, 2007) was used while for 2010 Eurostat NUTS3 data was used.	NUTS3/NCU	Data for more than 50 animal types (animal, age, manure management system) were assigned to the Integrator catergories[1]; yearly values for the period 2000-2010	Farm level upscaled[4)] to NCU and yearly values for the period 2000-2010
Housing systems	GAINS types	Country	Fraction of housing and manure storage systems for about 180 types at national level for the period 2000-2010	Housing type fractions upscaled to the Integrator types for the period 2000-2010
Manure application techniques	GAINS types	Country	Used manure application techniques (four types) for the period 2000-2010 on a monthly basis.	Country level
Housing fractions	GAINS types	Country	Generic housing fractions for the about 180 types for the period 2000-2010	Housing fractions were upscaled to the Integrator types for the period 2000-2010
N excretion rates/head	N excretion model scaled to GAINS model data in 2000	Country	Available from production statistics at GAINS types for the period 2000-2010	Yearly mean for the period 2000-2010 at national level assigned to the Integrator categories

N fertilizer application	Calculated by Integrator Using IFA/FAO database (IFA, 2013)	NCU Country	Amount of N fertilizer type at municipality level was used for the years 2000-2010.	Farm level upscaled[4)] to NCU
Biological N Fixation rates	2 kg N ha^{-1} yr^{-1} for arable land 5 kg N ha^{-1} yr^{-1} for grassland. (based on literature)	Generic	Crop specific fixed levels (also for grass clover) except for legumes: yield dependent	As for land use
N deposition	Emission deposition matrix, based on EMEP model, using terrestrial N emission estimates and other emissions from the Integrator and GAINS (Klaassen et al., 2004; Klimont and Brink, 2004) models, respectively.	EMEP-grid (50 km by 50 km)	As Integrator-EU	As Integrator-EU
Crop yields	FAO database (FAO, 2007) at country level; assumed to be equal in each NCU	Country	Crop specific for ca. 30 crop types that were assigned to the Integrator catergories[1]; For roughage (permanent grass and maize) and grain used in own herd, estimates are made assuming that they fulfil animal requirement, knowing the feed import. [2)]	Yearly crop yields for 8 regions/provinces were assigned to the Integrator types at NUTS3 level for the period 2006-2010. For the period 2000-2005 yearly values at the national level was used.
Crop area	Capri crop shares	NUTS3	Area of different crops	Farm level upscaled to NCU
N contents in crops	Crop-specific N contents, with N contents varying with N input, based on Velthof et al (2009)	Country	Data set on N contents per crop (feed) (Yearly statistics on protein contents) [3)]	Yearly crop N contents were assigned to the Integrator types for the period 2006-2010. For the period 2000-2005 values of 2006 were used.
Housing NH_3 emission fraction	NH_3 emission factors: country-specific data from GAINS model	Country	Generic emission fractions for the about 180 types (either as % TAN or % total N)	Housing type fractions weighted mean emission fraction were upscaled to the Integrator types for the period 2000-2010
Application NH_3 emission fraction	See above	Country	Generic emission fractions for the four application techniques on a monthly basis (expressed as % total N)	Application type fractions weighted mean emission fraction were upscaled to the Integrator

				applications types for the period 2000-2010
N_2O and NO_x emission factors	N_2O emission from soils: factors that are a function of N source, application technique, soil type, land use and precipitation based on Lesschen *et al*. (2011b). N_2O emissions from housing and manure storage systems: country specific factors based on GAINS data. NO_x emissions from housing and manure storage systems: 0.3% of N excretion, based on Skiba et al. (1997).	Country	Danish Data	Country level

[1)] Refers to used database, see Supplementary material.
[2)] Yield is downloaded from Statistics Denmark (Denmark, 2015).
[3)] Nutrient content is based on yearly updated Danish feed table, last published in Møller et al. (2005).
[4)] Based on Kristensen and Børgesen (2015).

Table 2 National N budgets for Denmark in 2000 and 2010 based on Integrator-EU simulations with default European data, Integrator-DK simulations with disaggregated Danish data and a DK budget based on national statistics.

N Source	N budget (kton N per year)					
	Integrator-EU 2000	Integrator-DK 2000	DK budget [1] 2000	Integrator-EU 2010	Integrator-DK 2010	DK budget [2] 2010
Manure excretion	247	232	260	240	251	238
Fertilizer	233	234	234	197	197	198
N biosolids	-	3	9	4	3	7
Deposition	37	34	28	28	35	21
Fixation	17	30	36	13	21	41
Mineralisation	86	48	60 [3]	52	48	77 [3]
Total input [4]	620	580	627	534	556	580
Offtake	383	275	302	323	283	302
Emission NH_3	63	58	61	56	61	51
- Housing	33	33	-	33	39	-
- Application	30	27	-	23	22	-
Emission N_2O	6	6	13	5	6	11
Emission NO_x	3	3	13	3	2	11
Emission N_2	86	115	64	74	106	54
Leaching + runoff	79	123	174	74	98	151
- Leaching	61	84	- [5]	60	76	- [5]
- Runoff	18	39	- [5]	14	22	- [5]
Total output	620	580	627	534	556	580
Area (1000 ha)	3,109 [6]	2,465	2,474	2,584	2,545	2,637

[1] See Supplementary material of Hutchings et al. (2014), note that this refers to year 2001 in order to synchronize the fertilizer use with the Denmark statistics.
[2] See Supplementary material of Hutchings et al. (2014), year 2010.
[3] Hutchings et al. (2014) did not provide mineralisation fluxes, presented values were calculated from the mass balance as net change in soil N: Mineralisation = Total output – (Manure excretion + Fertilizer + N biosolids + Deposition Fixation).
[4] Represents the Land system N budget (De Vries et al., 2011).
[5] No distinction between leaching and runoff was made in Hutchings et al. (2014).
[6] This area includes rough grazing, whereas the other areas do not.

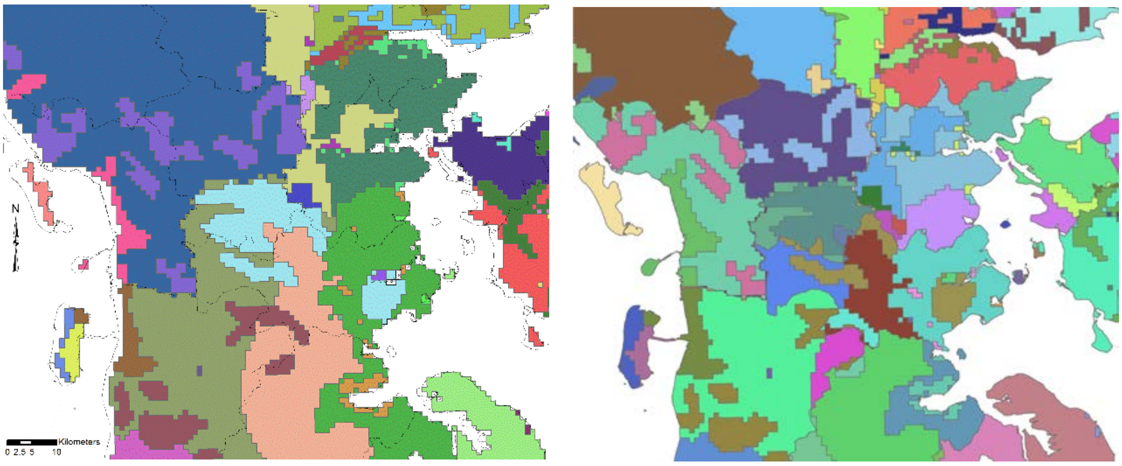

Figure 1. Illustration of the adaptation of NCU boundaries to those of the municipalities, on the left the original situation and right the adapted situation. Boundaries of the original NCUs are indicated by different colours.

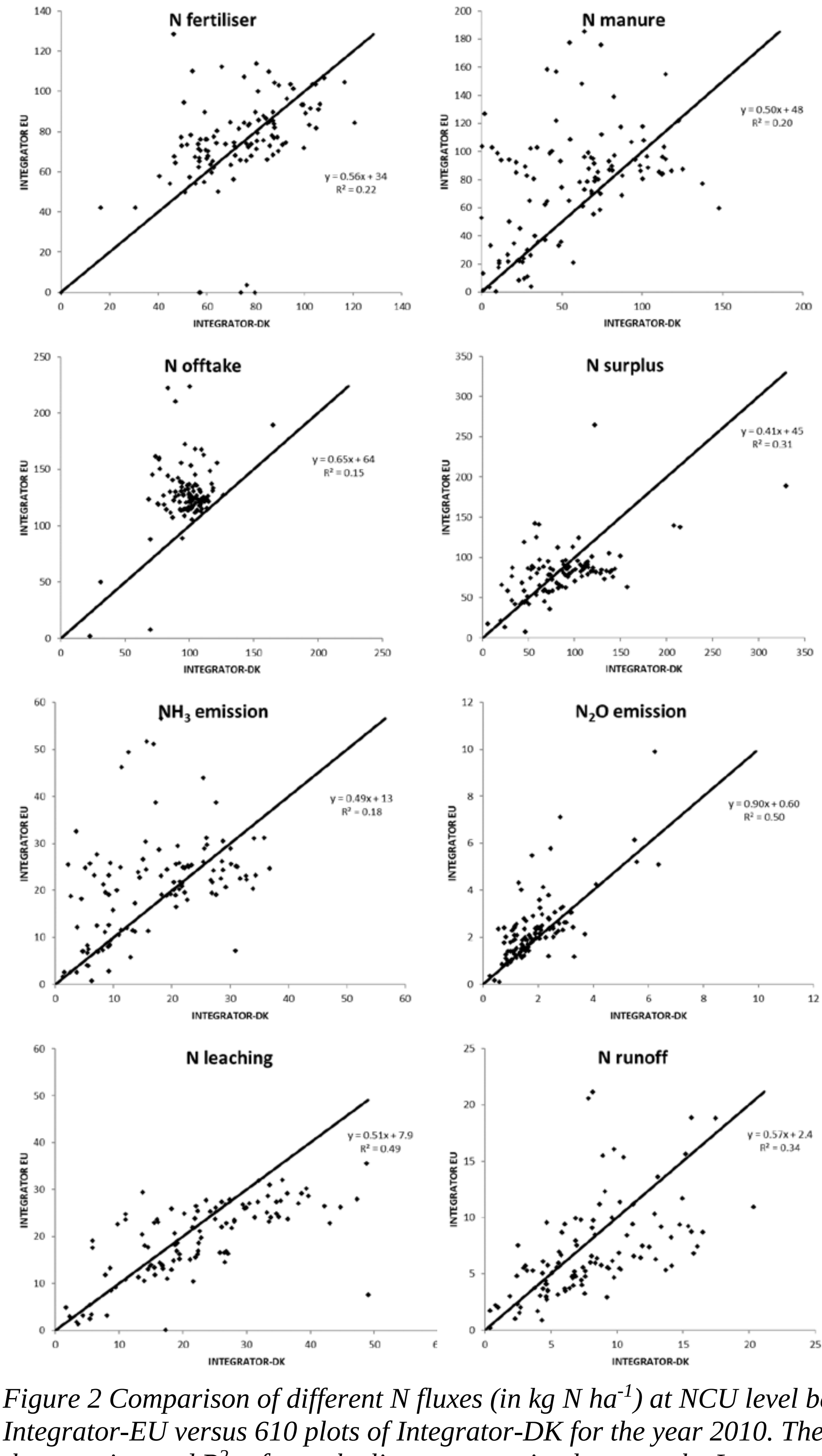

Figure 2 Comparison of different N fluxes (in kg N ha^{-1}) at NCU level based on 113 plots of Integrator-EU versus 610 plots of Integrator-DK for the year 2010. The line represents the 1:1 line, the equation and R^2 refer to the linear regression between the Integrator-EU and Integrator-DK results.

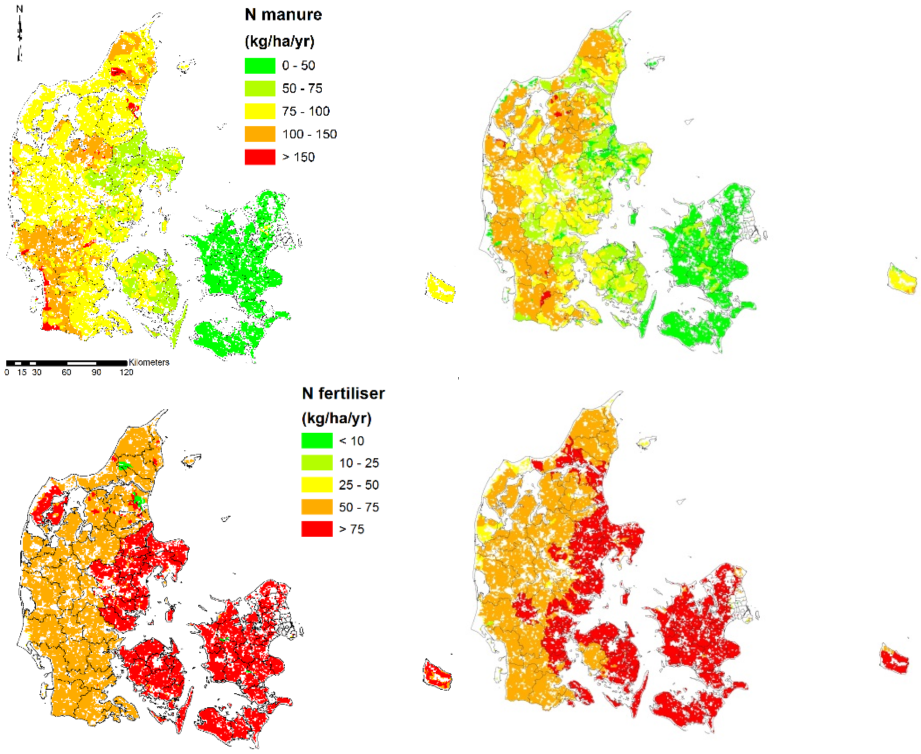

Figure 3 Total N animal manure input (top) and total N fertilizer input (bottom) (in kg N ha^{-1}yr^{-1}) for the year 2010 with Integrator-EU (left) and Integrator-DK (right).

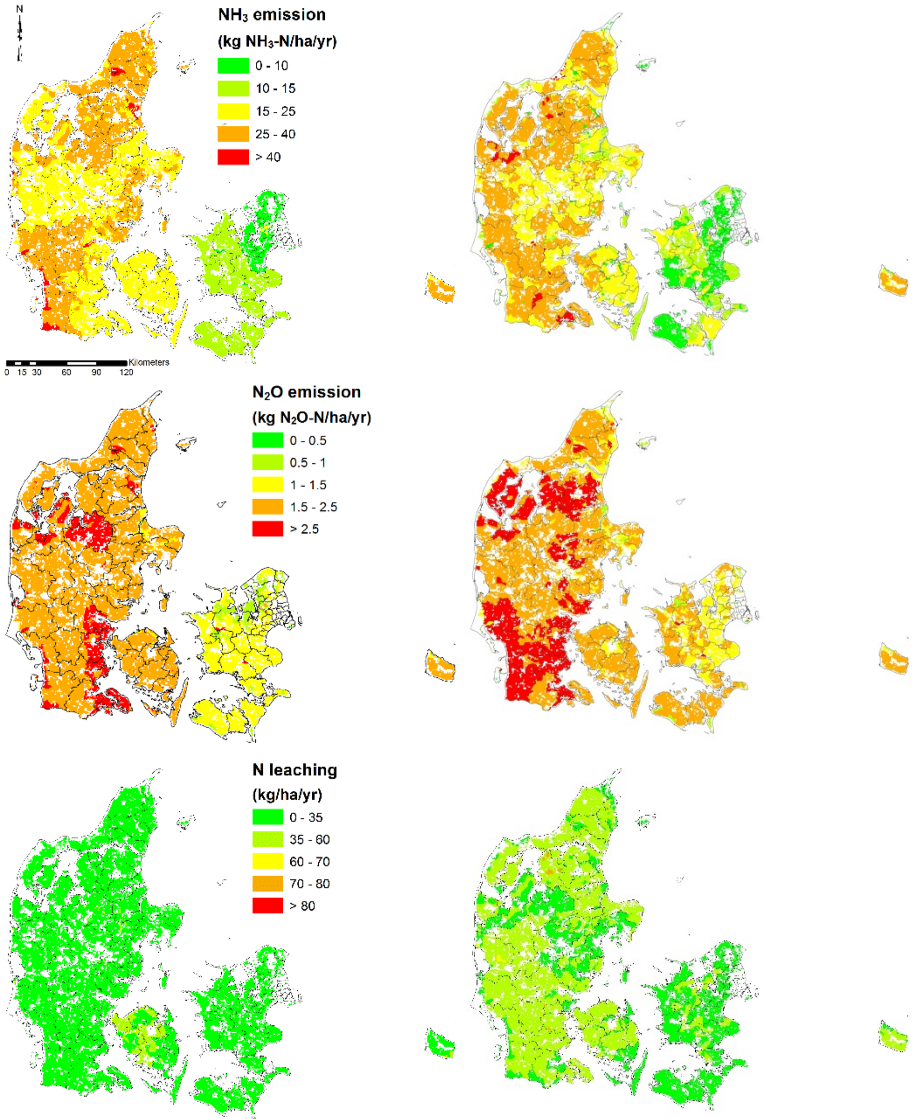

Figure 4 Total NH_3–N emission (top), total N_2O–N emission (middle) and NO_3–N leaching flux to groundwater and surface water (bottom) from agriculture(in kg N $ha^{-1}yr^{-1}$) for the year 2010 with Integrator-EU (left) and Integrator-DK (right).

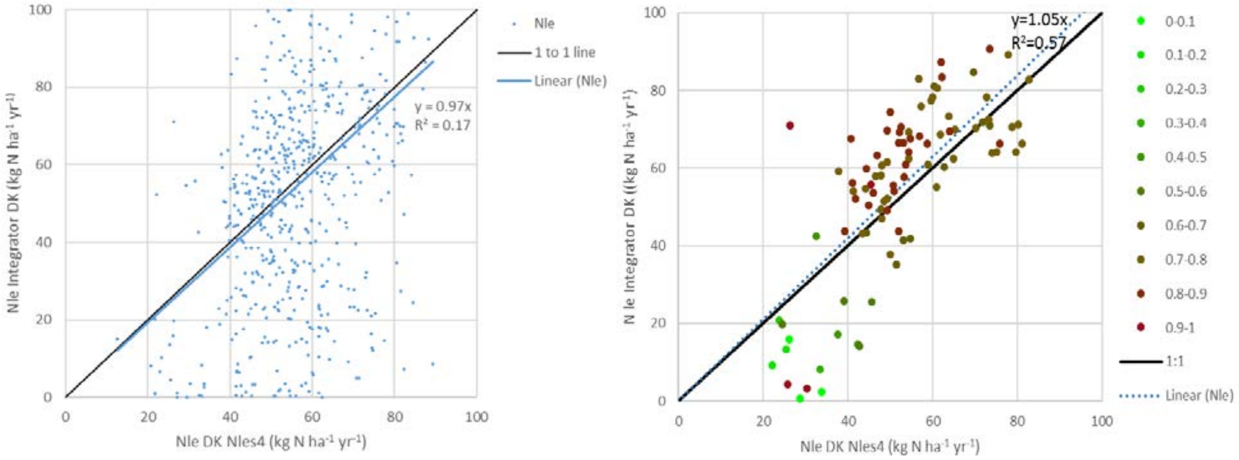

Figure 5 Comparison of the modelled N leaching to groundwater and surface water (Nle) by N-LES4 and Integrator-DK, while using enhanced leaching fractions (see text and SM section 6). Both graphs include the slope and the R^2 of the linear regression between the N-LES4 and Integrator-DK results. The figure left shows the comparison at NCU-level and the figure right shows the comparison at municipality level, where the colour indicates the areal fraction of grassland per municipality (green colour indicates more grassland).

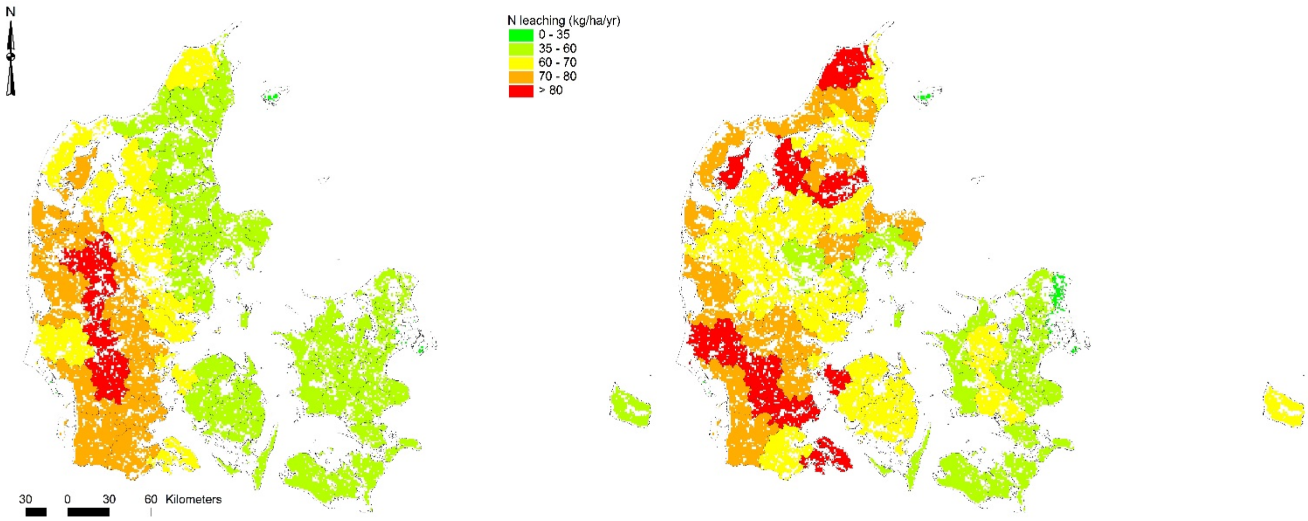

Figure 6 N-LES4 map (left) and Integrator-DK map (right) with N leaching fluxes (sum of leaching to groundwater and runoff to surface water), while using enhanced leaching fractions (see text and SM section 6), at municipality level.