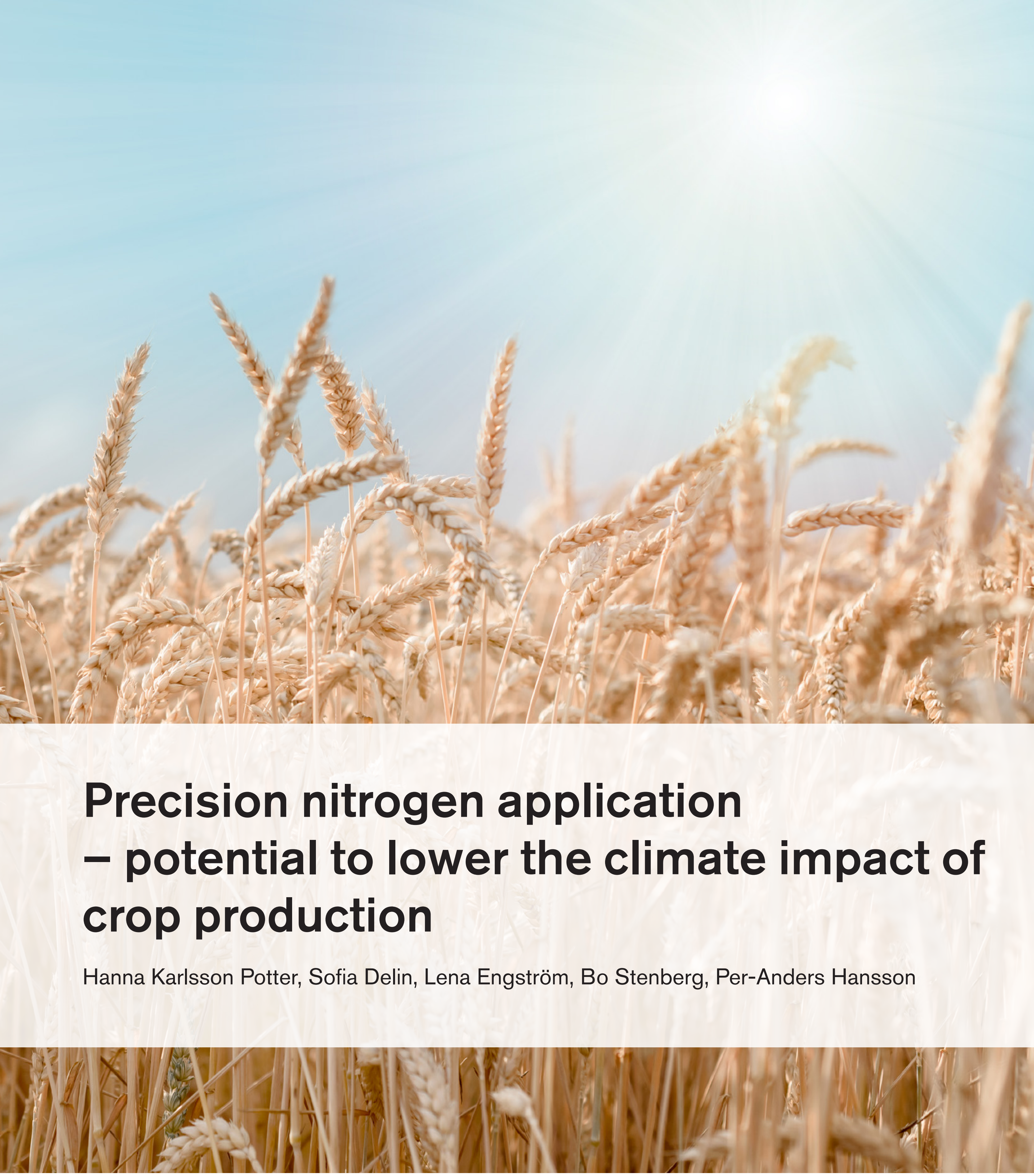

Precision nitrogen application – potential to lower the climate impact of crop production

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Precision nitrogen application – potential to lower the climate impact of crop production
Precisionsgödsling – potentialen att minska klimatpåverkan från spannmålsodling

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The overarching vision of the programme Mistra Food Futures is to create a science-based platform to enable transformation of the Swedish food system into one that is sustainable (in all three dimensions: environmental, economic and social), resilient and delivers healthy diets. By taking a holistic perspective and addressing issues related to agriculture and food production, as well as processing, consumption and retail, Mistra Food Futures aims to play a key role in initiating an evidence based sustainability (including environmental, economic and social dimensions) and resilience transformation of the Swedish food system. This report is a part of Mistra Food Future's work to identify agricultural systems with potential to make agriculture net-zero, one of the central issues within Mistra Food Futures.

Mistra Food Futures is a transdisciplinary consortium where key scientific perspectives are combined and integrated, and where the scientific process is developed in close collaboration with non-academic partners from all parts of the food system. Core consortium partners are Swedish University of Agricultural Sciences (SLU), Stockholm Resilience Centre at Stockholm University and RISE Research Institutes of Sweden.

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Abstract

The agriculture sector is a significant contributor to global greenhouse gas emissions, especially methane (CH_4) and nitrous oxides (N_2O). Nitrous oxide emissions originate primarily from nitrogen fertiliser production and use. A nitrogen fertilisation rate close to crop demand is desirable for several reasons, *e.g.* it limits fertiliser use per unit of crop produced and reduces the risk of N_2O emissions and nitrogen leaching.

This study estimated the impact of two different measures for more accurate nitrogen fertilisation, *field-specific nitrogen fertilisation* (accounting for between-field variation) and *variable-rate nitrogen application* (accounting for within-field variation), compared with a uniform fertilisation application. Effects on nitrogen leaching, N_2O emissions, grain yield and nitrogen balance were analysed. Calculations of leaching and N_2O emissions were based on different examples of within- and between-field variation on two soil types, represented by two experimental fields in south-west Sweden from which measured data on grain yield and N_2O emissions were obtained. Climate impact in a life cycle perspective, including fertiliser production and use, was calculated. The results for N_2O emissions were compared with the results of simulations using the IPCC model for N_2O emissions and a nitrogen balance-based model.

According to the results, the climate impact from field N_2O emissions was reduced by around 5% when using field-specific nitrogen fertilisation. An additional reduction of 1-10% (depending on in-field variations in nitrogen demand) was achieved when using variable-rate nitrogen application. The amount of fertiliser used was very important for the overall climate impact of crop production, indicating that measures which increase nitrogen use efficiency and keep nitrogen fertiliser doses below the optimum rate are preferable in a climate impact perspective. The commonly used IPCC model for predicting field N_2O emissions failed to predict reductions in N_2O from better nitrogen use efficiency. The nitrogen balance-based model performed better in predicting field N_2O emissions in relation to what could be expected based on measured N_2O emissions, but the estimated reduction was not as high as that predicted from field measurements.

Keywords: Precision fertilisation, nitrous oxide emissions, nitrogen fertilisation rate, nitrogen fertiliser recommendations

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1. Introduction

The agriculture sector is a significant contributor to global greenhouse gas (GHG) emissions, especially methane (CH_4) and nitrous oxides (N_2O) (Shukla *et al.*, 2019). Agriculture and forestry together account for approximately 80% of global N_2O emissions and 44% of global CH_4 emissions (IPCC, 2020). Use of mineral fertilisers and nitrogen (N)-fixing crops in agriculture has dramatically increased the amount of reactive N in the biosphere. This has several environmental consequences (Foley *et al.*, 2011), such as eutrophication of surface waters and impacts on biodiversity.

In a systems perspective, production of fertilisers, for which fossil energy is often used, and application of the fertiliser in the field both give rise to GHG emissions. When N fertiliser is applied in the field, losses occur to water (run-off and leaching) and to air in the form of N_2O, nitrogen gas (N_2) and nitrogen dioxide (NO_2). Emissions of N_2O are currently attracting most attention (Wang *et al.*, 2021), as it is a strong greenhouse gas. Therefore, sustainable management of nutrients, especially N, is central in improving the environmental performance of agriculture.

Precision agriculture (PA) aims at optimising agricultural measures with respect to temporal and spatial variability, for improved resource use efficiency in agricultural production. Precision agriculture is defined as a management strategy that gathers, processes and analyses temporal, spatial and individual data and combines it with other information to support management decisions according to estimated variability, for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production (ISPA, 2022). Many of the measures suggested to decrease environmental impacts of agriculture, including GHG emissions, while maintaining or increasing productivity could also benefit farm finances (Balafoutis et al., 2017). This win-win situation is because nutrients efficiently used by the crop are not available for impacts on the environment. Economic optimum N fertilisation is defined as the rate giving the optimal yield return. At lower fertilisation rates, the yield response is nearly linear, but around the optimum the yield response to adding more N gradually decreases. The economically optimum N rate is taken as the rate where the yield increase per unit added fertiliser equals the price ratio between the two. Since prices of grain and fertiliser tend to fluctuate, an average over several years may be used. Up to now, 1 kg fertiliser nitrogen has usually been 7-10 times the price of 1 kg grain. As long as the ratio is within this interval, differences in optimum N rate due to price ratio are usually small. However, during this past year prices on fertilizers have increased more than for grains which means prices ratios above 10.

Due to the upstream emissions from mineral fertiliser production, manure handling and the emissions associated with spreading fertilisers, variable-rate nutrient application, specifically of N, has been suggested as a measure to decrease GHG emissions from agriculture (Mahmud *et al.*, 2021; Balafoutis *et al.*, 2017; European Union, 2015; Smith *et al.*, 2008).

It is worth noting that before employing variable-rate N application (VRNA), large improvements in nutrient use efficiency compared with general fertiliser recommendations (step 1 in Figure 1) can be achieved by adjusting fertilisation to yearly variations at the regional scale, based on the situation at a few farms (step 2 in Figure 1). As the next level (step 3 in Figure 1), variations at the field scale can be considered from measurements of soil N delivery using 'zero-N plots' (Delin *et al.*, 2015). Apart from improving the precision further to step 4 (Figure 1), the chances of correctly estimating the average optimum fertiliser rate for an individual field can be increased if all parts of the field have been estimated and accounted for by VRNA.

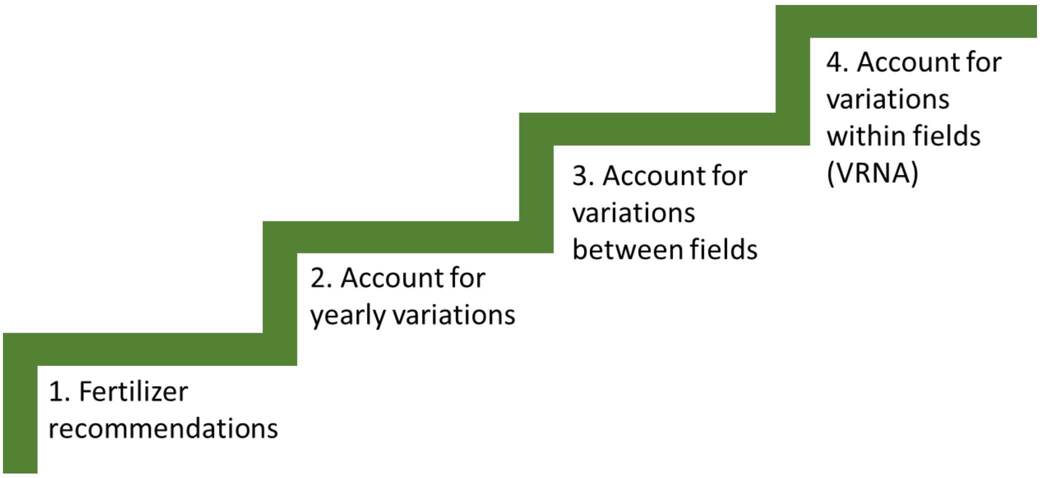

Figure 1. Four steps for more accurate nitrogen application, starting with (1) general recommendations from the Swedish Board of Agriculture based on experimental data in previous years and moving on to (2) adjustment based on current-year observations in experiments in the same region, (3) more precise adjustment according to observations in the individual field or farm and (4) further adjustment to variations within the individual field (variable-rate nitrogen application, VRNA).

Improvements in N fertilisation approaches to better match field conditions and crop requirements, including VRNA, can be expected to affect yield, N leaching and N_2O emissions, which are all very important for environmental performance. However, the effects, especially on N_2O emissions, are challenging to estimate because the dynamics of N supply from the soil, uptake by the crop and other potential losses vary over time and depend on factors such as soil type, climate and soil organic matter content. Nitrogen losses are dependent on the balance of N supply and crop uptake, but also seasonal variations

(Zhao *et al.*, 2022). For GHG accounting purposes, field N_2O emissions due to N fertilisation are often estimated based solely on N application rate (Hergoualc'h *et al.*, 2019). However, this method risks overlooking yield and N management factors (such as timing and placement) (Eagle *et al.*, 2020). If fertiliser is efficiently used by the crop, less N will be left in soil during the wet autumn-winter period, when soil conditions are usually moist and favourable for denitrification and associated N_2O emissions. Other methods have been suggested for estimating field N_2O emissions, *e.g.* Millar *et al.* (2010) proposed the use of non-linear relationships between N rate and N_2O emissions. Partial nitrogen balance (PNB) or similar has also been suggested as an indicator for N_2O emissions, where PNB equals N application minus plant N uptake (Maaz *et al.*, 2021; Eagle *et al.*, 2020). Several studies have shown that the effect of N application on N_2O losses and N leaching is not linear, but may increase substantially above the economic or agronomic optimum (Wallman, 2021; Delin & Stenberg, 2014; Hoben *et al.*, 2011). This implies that targeting the economic optimum with precision fertilisation should lower the environmental impact.

1.1. Aim

The aim of the present study was to estimate the effect of using more accurate site-specific N fertilisation, compared with national general recommendations, on crop yield, N leaching, N_2O emissions and overall climate impact. Estimates were made using yield and N_2O emissions data and modelling results (N leaching) at field level for two sites in south-west Sweden. The assessment was based on fertiliser adjustment in two steps. The first step involved field-specific seasonal adjustments to account for between-field variations based on measurements of N uptake in plots without N fertiliser (zero-N plots), while the second step consisted of site-specific adjustments using VRNA to account for within-field variations. A life cycle perspective was applied when calculating the overall climate impact of the improved fertilisation approaches (field-specific N fertilisation and VRNA) compared with uniform N application.

The challenges in estimating effects on N_2O emissions when implementing measures for more accurate N application were assessed. The purpose was to generate an estimate of N_2O emissions that takes N use efficiency and residual N into account. The commonly used IPPC model does not consider N use efficiency, so as an alternative a model based on N balance was used.

2. Method

2.1. Scenarios

The climate impact was assessed for three different scenarios:

1) Nitrogen fertilisation adjusted for variation between fields, based on measurements of N uptake in plots without N fertiliser (zero-N plots), compared with fertilisation according to general recommendations without seasonal or site-specific adjustments (Reference fertilisation).

2) Nitrogen fertilisation adjusted for within-field variations, through VRNA, compared with using the same amount of fertiliser with uniform application (Reference fertilisation).

3) Nitrogen fertilisation adjusted for within-field variations, through VRNA, compared with using a uniform application of 10 kg N/ha above the optimum fertiliser rate (Reference higher N rate fertilisation).

2.2. Models

The same method for calculating N leaching and N_2O emissions above and below the optimum N fertilisation rate was used when comparing the effects of field-specific fertilisation and general recommendations, and when comparing VRNA and uniform fertilisation within the field.

2.2.1. Model for nitrogen leaching

Nitrogen leaching was modelled using VERA (Aronsson & Torstensson, 2004). This model estimates different leaching responses to fertilisation depending on soil type, using different factors called Kf values. Calculations were performed for two different soil types, representing two sites (Götala and Lanna) for which data on N leaching that corresponded rather well to modelled values were available (Figure 2). The Götala and Lanna sites are both experimental stations situated in Västergötland County, south-west Sweden. Baseline leaching (that at the economic optimum fertiliser rate) was estimated from average leaching at levels below the optimum in field experiments conducted at the two sites (Delin *et al.*, 2015; Delin & Stenberg, 2014). For Götala, with 5-15% clay, a Kf value of 0.2464 and 36 kg N per hectare baseline leaching were used. For Lanna, with a higher clay content (25-40%), baseline leaching was set to 19 kg N per hectare and the Kf value was set to 0.1584.

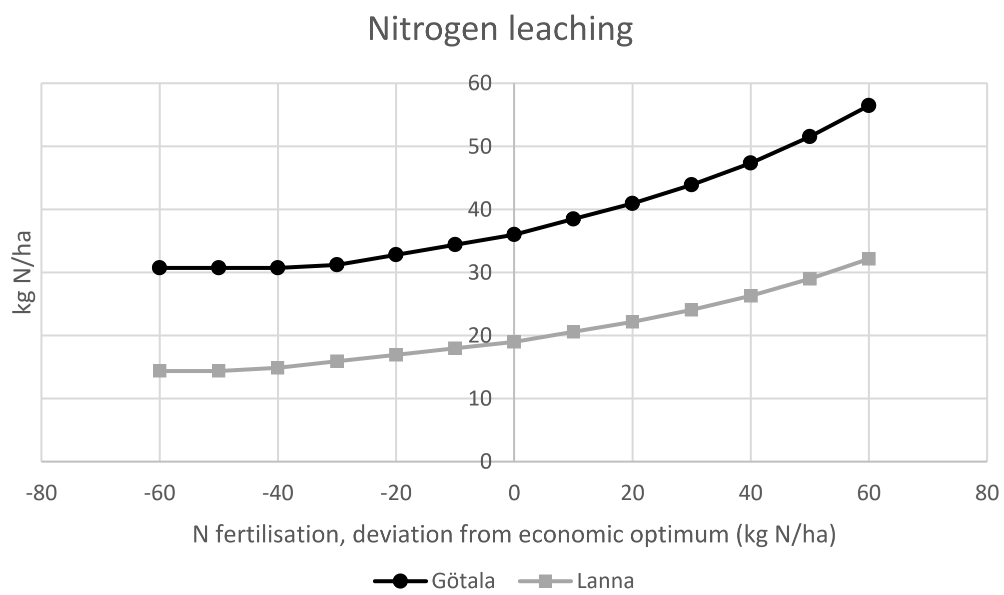

Figure 2. Modelled nitrogen (N) leaching at different fertilisation rates for the Götala and Lanna sites, presented as difference from optimum.

2.2.2. Models for N_2O emissions

Nitrous oxide emissions were estimated using empirical data from Wallman (2021) obtained in different fertilisation treatments in an annual spring-sown crop (spring barley) at Lanna. Data were available for treatments in spring barley without N fertilisation, with the recommended N fertilisation rate (120 kg N/ha) and with fertilisation at 50% above the recommended rate (180 kg N/ha). In order to make calculations for every 10 kg interval of fertiliser deviation from the optimum, a response curve was fitted to the data, with a linear function between zero fertilisation and the optimum and a quadratic function between the optimum and fertilisation above (Figure 3). Further, N_2O emissions at Götala were assumed to show a similar response to fertilisation as at Lanna, but at a higher level due to higher N delivery from the Götala soil. To estimate emissions at Götala, the emissions at Lanna were therefore multiplied by the ratio of N offtake in the unfertilised control at the two sites.

In addition, two models were used to estimate N_2O emissions. One model simply used the Intergovernmental Panel on Climate Change (IPCC) threshold, based on a linear relationship between fertilisation rate and N_2O emissions without regard to N use efficiency. The second model was based on field N balance, where excess N contributes more to emissions, so optimised fertilisation was thus expected to generate lower emissions. These two models are explained in section 2.5.4.

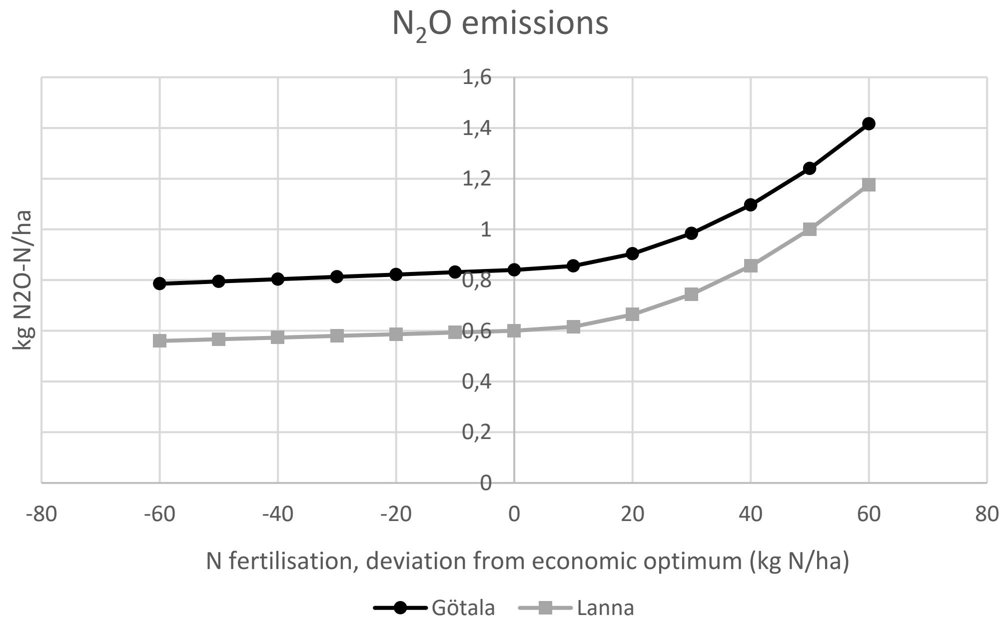

Figure 3. Nitrous oxide (N_2O) emissions at different fertilisation rates for the Götala and Lanna sites, presented as difference from optimum.

2.3. Field-specific nitrogen fertilisation

2.3.1. Between-field variations in nitrogen requirement

The effects of field-specific N fertilisation compared with using an average recommended fertilisation rate was assessed using data from 65 field experiments on winter wheat crops in grain-producing areas throughout southern and central Sweden in 2008-2013. These experiments provided information on the variation in optimum N fertilisation rate between fields. There was also information on how close a general recommendation and a field-specific estimate from zero-N plots at each site were to the optimum N rate (Figure 4). In Figure 4, tall bars are more concentrated to the centre, indicating small error at most sites. Based on these distributions, grain yield, N yield, total N application, N leaching and N_2O emissions were estimated for both scenarios at all 65 sites. Average emissions per hectare and per kg grain produced in both scenarios could thereby be obtained.

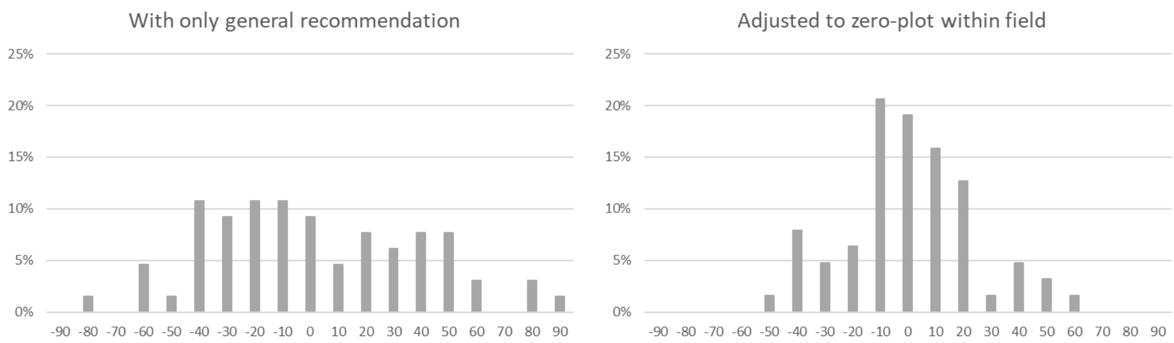

Figure 4. Variation between fields in accuracy of prediction of optimum fertilisation rate based on the general recommendation and using measurements in non-fertilised zero-plots. Data compiled from 65 Swedish field experiments on winter wheat conducted 2013-2020.

2.3.2. Grain (winter wheat) yield

Differences in winter wheat grain yield between field-specific and general recommendation fertilisation were calculated from the fertilisation rates in Figure 4 combined with the response curve presented in Figure 5. This particular experiment was performed at a similar location as Götala, but could be considered to represent most sites since yield response just above and below optimum was very similar between sites.

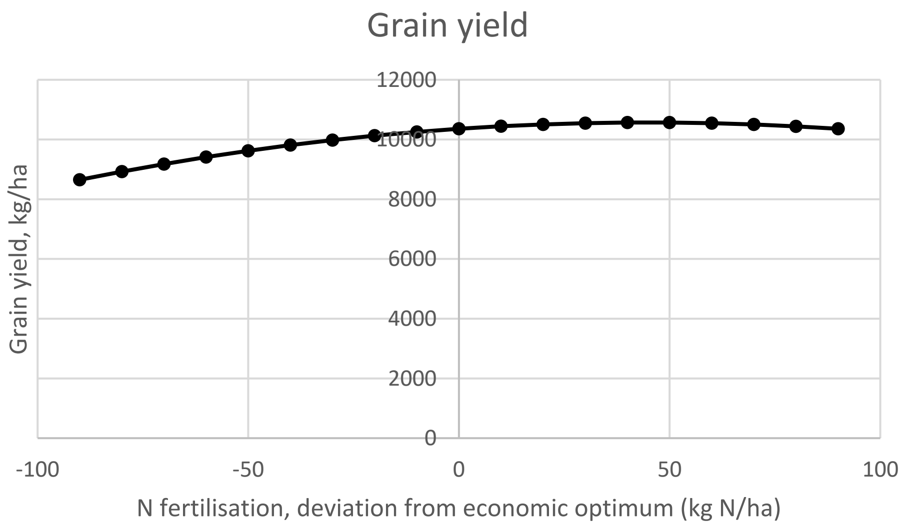

Figure 5. Yield of winter wheat (kg per hectare) at different fertilisation rates for the Götala site, presented as difference from optimum.

2.3.3. Nitrogen yield

Similarly to grain yield, N yield was calculated using the response in N offtake from the same experiment (Figure 6).

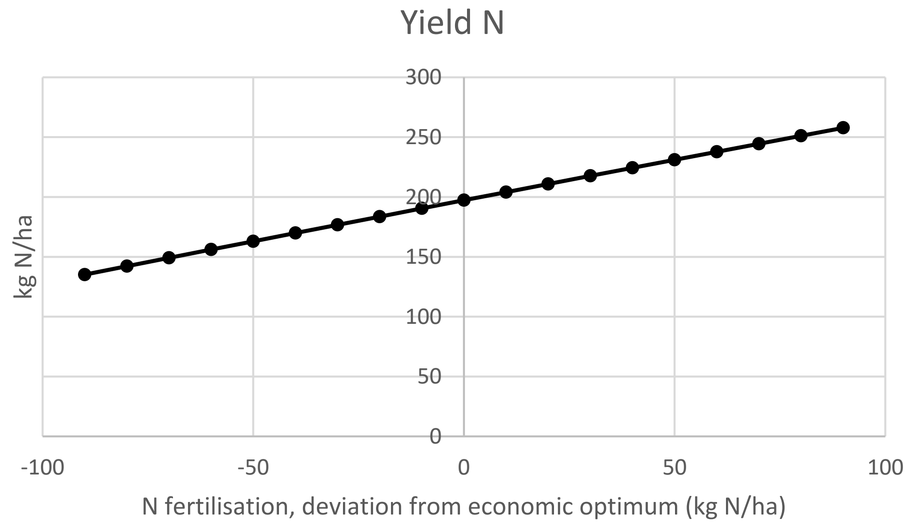

Figure 6. Nitrogen (N) yield of winter wheat (kg per hectare) at different fertilisation rates for the Götala site, presented as difference from optimum.

2.4. Variable-rate nitrogen application

2.4.1. Within-field variations in nitrogen requirement

The effect of VRNA will depend on the degree of within-field variation, which varies between fields. To get an idea of the effect, calculations were made for seven different within-field N requirement distributions based on literature reports. Some of the reported values were from N sensor measurements (Nissen *et al.*, 2010A, 2010B; Söderström) and others from multiple zero-N plot measurements within fields (Delin *et al*., 2015), or simply statistical distributions based on the same standard deviation as measured in field experiments. The distributions are presented in Figure 7. In addition, an *imaginary* distribution was added, where N requirements above and below recommended levels did not mirror each other (as in the case of the symmetric, normal and binomial distributions) and where a relatively large part of the field had an N requirement lower than the recommendation (-30 kg/ha in this case). Optimum N fertilisation was assumed to be 110 kg N per ha at Götala and 150 kg per ha at Lanna, according to experimental data for oat crops at these sites in 2021 (Delin & Engström, manuscript).

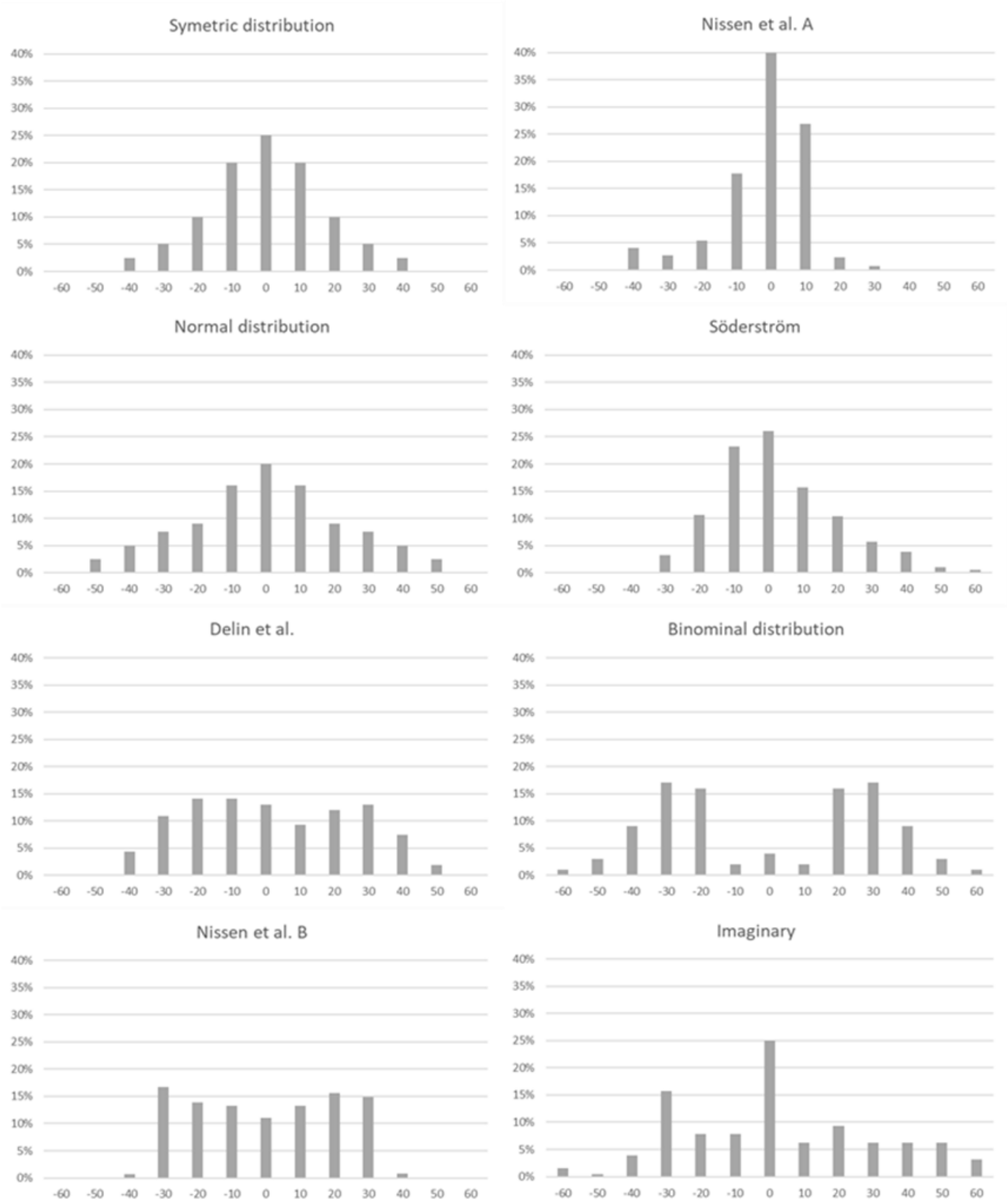

Figure 7. Within-field variations in nitrogen (N) fertiliser requirements, presented as difference from the recommended N rate. Examples taken from documented N sensor readings (Söderström, Nissen *et al*. A and B), experimental data (Delin *et al*., 2015), normal and binomial distribution with similar standard devistion as in experimental data, and a made-up distribution.

2.4.2. Grain (oats) yield

Grain yield at Götala and Lanna was estimated from yield response curves derived from experiments on oats involving leaching measurements conducted at Götala in 2007-2009 (Delin and Stenberg 2014) and at Lanna in 2009-2011 (Delin *et al.*, 2015) (Figure 8).

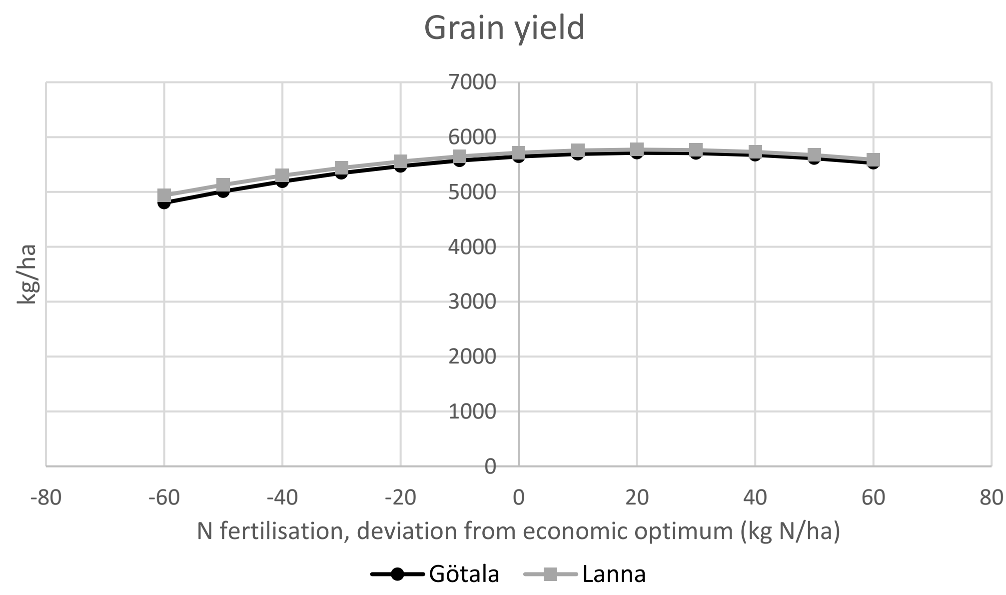

Figure 8. Yield (per hectare) at different fertilisation rates for the Götala and Lanna sites, presented as difference from optimum. Experimental data used for calculation of yield effects of variable-rate nitrogen (N) fertilisation at the two sites.

2.4.3. Nitrogen yield

Nitrogen yield with the harvested grain was estimated based on grain N content at different fertilisation rates and the above-mentioned yield data (Delin *et al.*, 2015; Delin & Stenberg, 2014) (Figure 9).

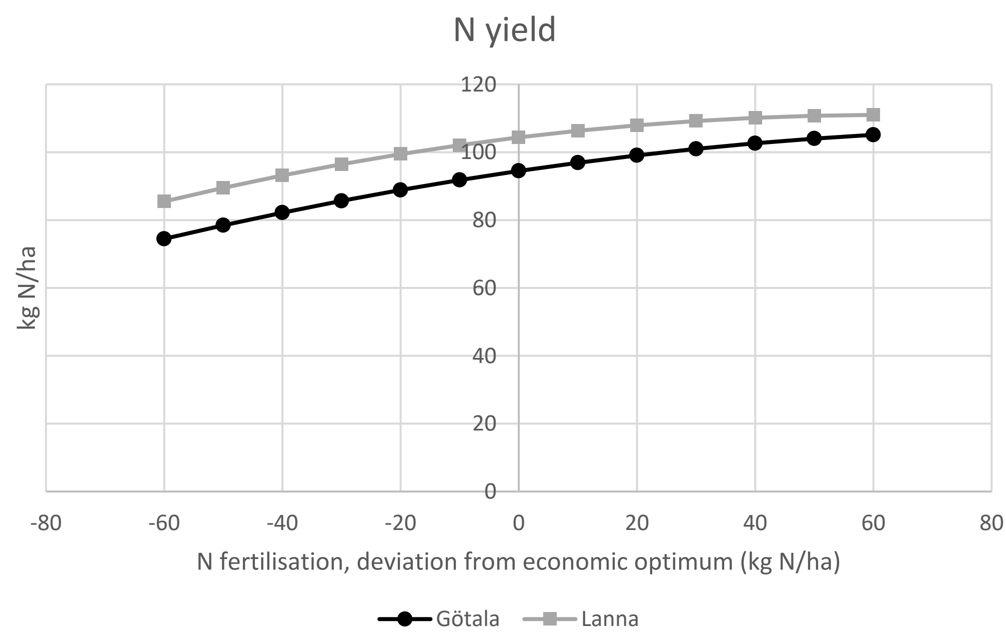

Figure 9. Nitrogen (N) yield (kg per hectare) at different fertilisation rates for the Götala and Lanna sites, presented as difference from optimum.

2.5. Climate impact calculations

2.5.1. System boundaries and functional unit

The climate impact calculations included the impact from N fertiliser (ammonium nitrate) production (Biograce, 2015) and field N_2O emissions. Indirect N_2O emissions in accordance with IPCC estimates (IPCC, 2019) were included for the scenarios showing *total climate impact*. The climate impact was calculated for the functional units 1 hectare and 1 kg harvested grain.

2.5.2. Scenarios

Scenarios for field-specific N fertilisation calculations

Comparison of effects from field-specific fertilisation according to zero-N plots and general recommendations was made for scenarios assuming that the average fertilisation rate over all fields was the same for both field-specific and general recommendation fertilisation. Use of field-specific rates based on zero-N plots to estimate N delivery from the soil should be fairly accurate, while using general recommendations that are adjusted for yield, but not between-field and within-field differences, will lead to both over- and under-estimation.

Scenarios for VRNA calculations

For each of the two sites in south-west Sweden (Götala and Lanna), crop yield, N yield, field N_2O emissions and N leaching were estimated for all eight distributions, for uniform N application (Reference) and site-specific VRNA. In one scenario the same average fertilisation rate was assumed for Reference and VRNA (although differently distributed over the field). In another scenario, the effect of a higher fertilisation rate in Reference was analysed. For this, a 10 kg higher rate than in the VRNA case was assumed, since the average field fertilisation requirement is often over-estimated when only a small part of the field is used for estimation compared with when all parts of the field are measured (Stenberg *et al.*, 2005).

2.5.3. Nitrogen fertiliser rates

Field-specific N rate

The field-specific calculations were based on data from winter wheat experiments. The average optimal rate in those experiments was around 200 kg N per hectare, which was taken as the average rate in the calculations.

VRNA

Nitrogen fertiliser application rates were estimated for each within-field distribution in Figure 7. For yield around the economic optimum, the average rate was 110 kg N per hectare for Götala and 150 kg N per hectare for Lanna (Figure 8). As mentioned above, one scenario assumed the same fertilisation rate in Reference and VRNA, and one scenario assumed 10 kg higher N rate in Reference fertilisation.

2.5.4. Modelling field N_2O emissions

Field N_2O emissions at different fertilisation rates were estimated from Wallman (2021) as described in section 2.1.2. For comparison, two other methods for estimating field N_2O emissions were applied: The IPCC model and the partial N balance model (Eagle *et al.*, 2020). Both models are further explained below.

The IPCC provides models for estimating emissions of GHG from *e.g.* managed soils. The models are used in national GHG accounting (Hergoualc'h *et al.*, 2019), but are also commonly used in life cycle assessment studies to estimate N_2O emissions from cropping systems. Emissions of N_2O from managed soils are grouped into *direct emissions* and *indirect emissions.* Direct emissions are estimated based on a linear model where N amount added as fertiliser is multiplied by an emission factor (EF). In this study, an EF value of 1.6% was applied, which is for synthetic fertiliser use in wet climates. Further direct N_2O emissions arise from N in crop residues, which are calculated by multiplying the estimated N content by an EF value, in this study 0.6%, which is for other N inputs (*i.e.* other than mineral fertilisers) in wet climates (Hergoualc'h *et al.*, 2019). Nitrogen content in crop residues was estimated using the method in Hergoualc'h *et al.* (2019). Indirect N_2O emissions arise from volatilisation of ammonia (NH_3) in the field and N leaching from the field. Indirect emissions were not included when estimating field N_2O emissions with the IPCC model, but indirect N_2O emissions were included for all scenarios when estimating total climate impact. Assumptions used in the calculations are presented in section 2.5.5.

In the partial N balance (PBN) model suggested by Eagle *et al.* (2020), PNB is calculated as *N applied – N harvested.* Use of N balance as a basis for predicting N_2O emissions is based on the finding that there is a risk of higher N_2O emissions with higher N availability in the soil (Eagle *et al.*, 2020), *i.e.* when crops are fertilised above optimum. The following equation was used (Eagle *et al.*, 2020):

$$N_2O\text{-}N = \exp(0.339+0.0047*PNB)$$

where N_2O-N is accumulated annual N_2O emissions in kg per hectare and PNB is the partial N balance in kg N per hectare.

2.5.5. Indirect N_2O emissions

Indirect N_2O emissions were included for all scenarios when calculating *total climate impact.* Indirect N_2O emissions were based on Hergoualc'h *et al.* (2019), meaning the IPCC model for indirect N_2O emissions. The emission factors used here for indirect N_2O emissions were 1.1% for leached nitrogen and 1.6% for volatilised nitrogen. Ammonia volatilisation was estimated to be 5% of total nitrogen applied as ammonium nitrate fertiliser (Hergoualc'h *et al.*, 2019).

3. Results

3.1. Results for field-specific N fertilisation

3.1.1. Yield effects of using field-specific nitrogen rate

Applying a field-specific N rate increases yield in those fields where the general recommendation would have meant underestimation of the fertiliser requirement. In other fields, the yield may be unaffected or slightly reduced. Here, the calculated average yield increase was 1% (around 100 kg per hectare), when using field-specific N rate for each field compared with general recommendation. This was when the average N rate was assumed not to be affected.

3.1.2. Results based on measured field N_2O emissions

The combined climate impact per hectare from direct N_2O emissions and indirect emissions from leaching (when applying IPCC factors) clearly increased at fertilisation rates above the optimum (Figure 10).

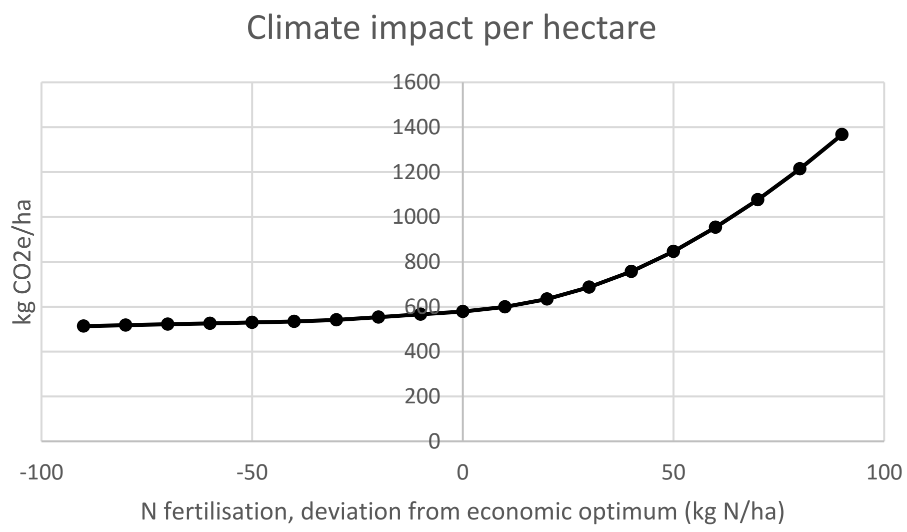

Figure 10. Climate impact per hectare from field nitrous oxide (N_2O) emissions and indirect N_2O emissions from winter wheat cultivation at different fertilisation rates at the Götala site, presented as difference from optimum.

Climate impact per kilogram harvested wheat was lowest for fertilisation around or below the optimum (Figure 11). However, fertilisation rate well above (+20kg N/ha) the optimum had a strong effect on climate impact (Figure 11).

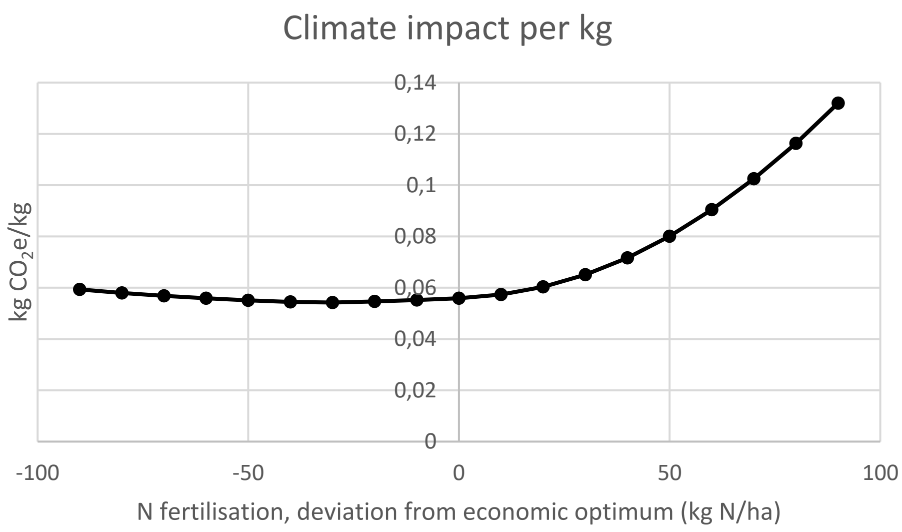

Figure 11. Climate impact per kg harvested wheat through field nitrous oxide (N_2O) emissions and indirect N_2O emissions from winter wheat cultivation at different fertilisation rates at the Götala site, presented as difference from optimum.

3.1.3. Comparison of field-specific N rate with the general recommendation

Field-specific N fertilisation reduced hectare-based climate impact by approximately 6% for field N_2O which corresponds to a decrease by 2% for total climate impact, compared with the general recommendation (Reference), when average fertilisation rate was the same in both cases (Table 1). The reduction in climate impact per kg harvested wheat was somewhat higher, due to the higher yield in field-specific N fertilisation (Table 1).

Table 1. *Climate impact per hectare and per kg harvested grain from field nitrous oxide (N_2O) emissions only and total climate impact (including production of mineral fertilisers and indirect N_2O emissions) for an average fertilisation rate of 200 kg N/ha in Reference and field-specific N fertilisation*

	Field N_2O (kg CO_2e)		Total climate impact (kg CO_2e)	
	per ha	per kg	per ha	per kg
Reference	432	0.042	1387	0.136
Field-specific N rate	409	0.040	1356	0.132

3.1.4. Comparison of results from the IPCC and nitrogen balance-based models for estimating field N_2O emissions

The IPCC model predicted that N_2O emissions (per hectare) would increase slightly with field-specific N fertilisation, primarily due to the higher yield (and presumably more crop residues). The PNB model for predicting field emissions gave a small decrease in N_2O emissions, due to higher yield (affecting the N balance), but the decrease was not as high as that predicted from field measurements (Wallman, 2021).

Table 2. *Percentage change in yield, field nitrous oxide (N_2O) emissions and total climate impact for field-specific nitrogen (N) fertilisation compared with Reference fertilisation*

	Base case (N2O based on site specific data)					IPCC model for N2O				PNB model for N2O			
	Yield	Field N2O em.		Tot. climate impact		Field N2O em.		Tot. climate impact		Field N2O em.		Tot. climate impact	
		ha-1	kg-1	ha-1	kg-1	ha-1	kg-1	ha-1	kg-1	ha-1	kg-1	ha-1	kg-1
Field specific N rate	1.0%	-5.5%	-6.4%	-2.2%	-3.2%	0.2%	-0.8%	-0.1%	-1.2%	0%	-1%	-1%	-2%

3.2. Results for variable-rate nitrogen application

3.2.1. Yield with different within-field fertiliser distribution

With VRNA, yield increased by 0.6-2.3% (approximately 10-130 kg per hectare) compared with the Reference with the same average fertilisation rate applied throughout the field. However, at a 10 kg higher N rate in the Reference case, the yield difference between Reference and VRNA was smaller and occasionally reversed (Table 3).

3.2.2. Emissions based on measured field N_2O

Climate impact per hectare, including both direct N_2O emissions and indirect N_2O emissions from leaching but not from N fertiliser production, increased much faster with fertilisation at rates above the optimum (Figure 12). In this case direct emissions were based on Swedish field measurements (Wallman, 2021) and indirect emissions from leaching were calculated using the IPCC factor (EF = 1.6%).

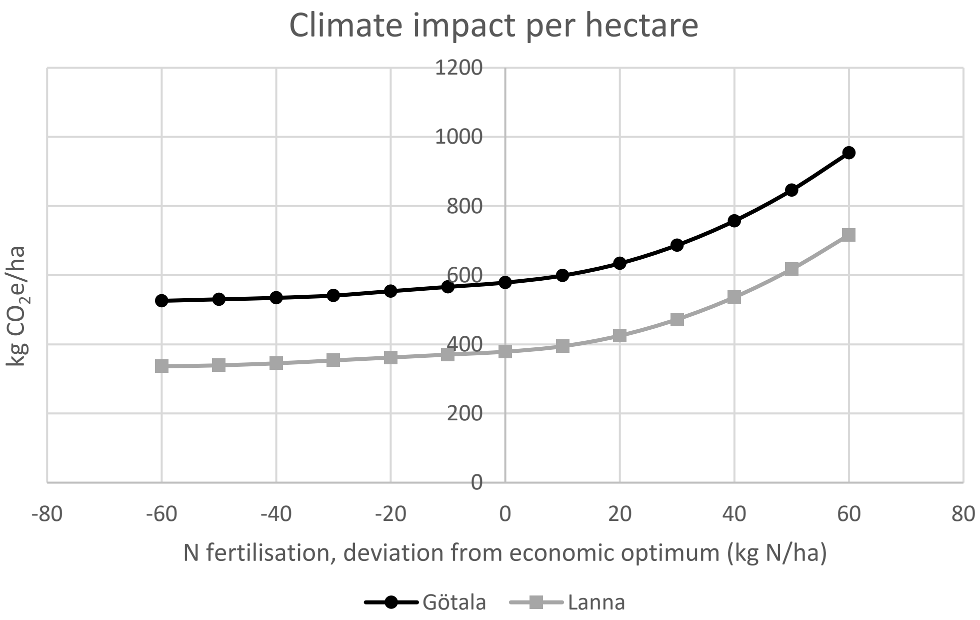

Figure 12. Climate impact per hectare from field nitrous oxide (N_2O) emissions and indirect N_2O emissions from oat production at different fertilisation rates at the Lanna and Götala sites, presented as difference from optimum.

However, when calculated per kg, the climate impact from direct and indirect N_2O emissions appeared to be lowest around the optimum rate (Figure 13). This is because fertilisation below the economic optimum by definition gives lower yields, and emissions per kg of harvested crop are therefore higher.

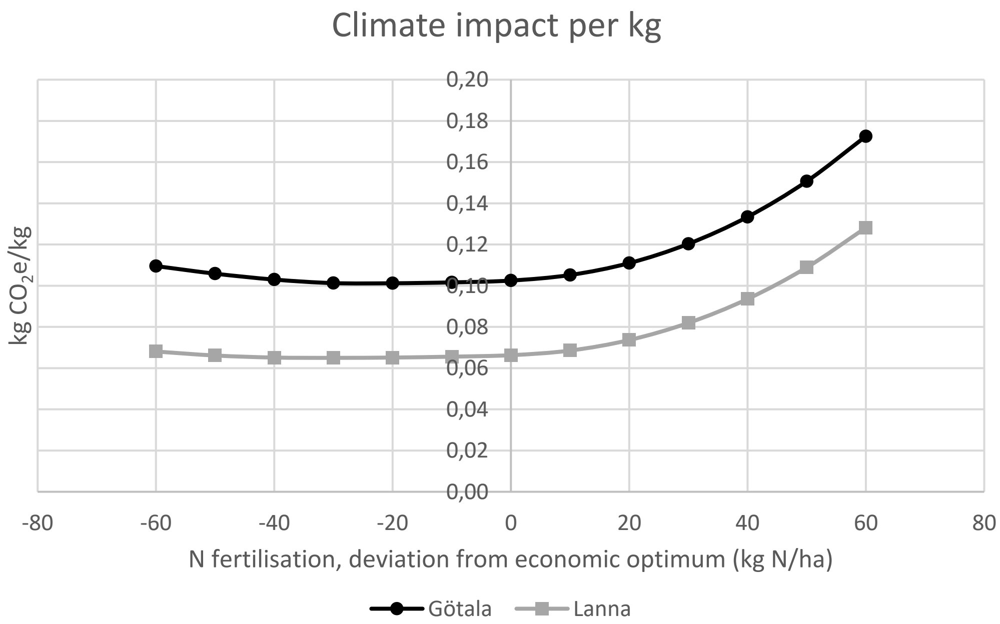

Figure 13. Climate impact per kg from field nitrous oxide (N_2O) emissions and indirect N_2O emissions at different fertilisation rates at the Lanna and Götala sites, presented as difference from optimum

3.2.3. Comparison of variable-rate nitrogen application with uniform fertiliser application at the same rate

Climate impact from field N_2O emissions

Reference fertilisation (uniform N application) gave 1-10% higher field N_2O emissions than VRNA (Figure 14). The emissions reduction with VRNA varied depending on within-field variation and was highest for the binomial distribution (Figure 14). As can be seen in Figure 14, it was assumed that N_2O emissions at Götala and Lanna followed the same pattern, although somewhat higher at Götala due to higher N delivery from that soil. The method used for estimating field N_2O emissions based on field measurements at Lanna is described in section 2.2.2.

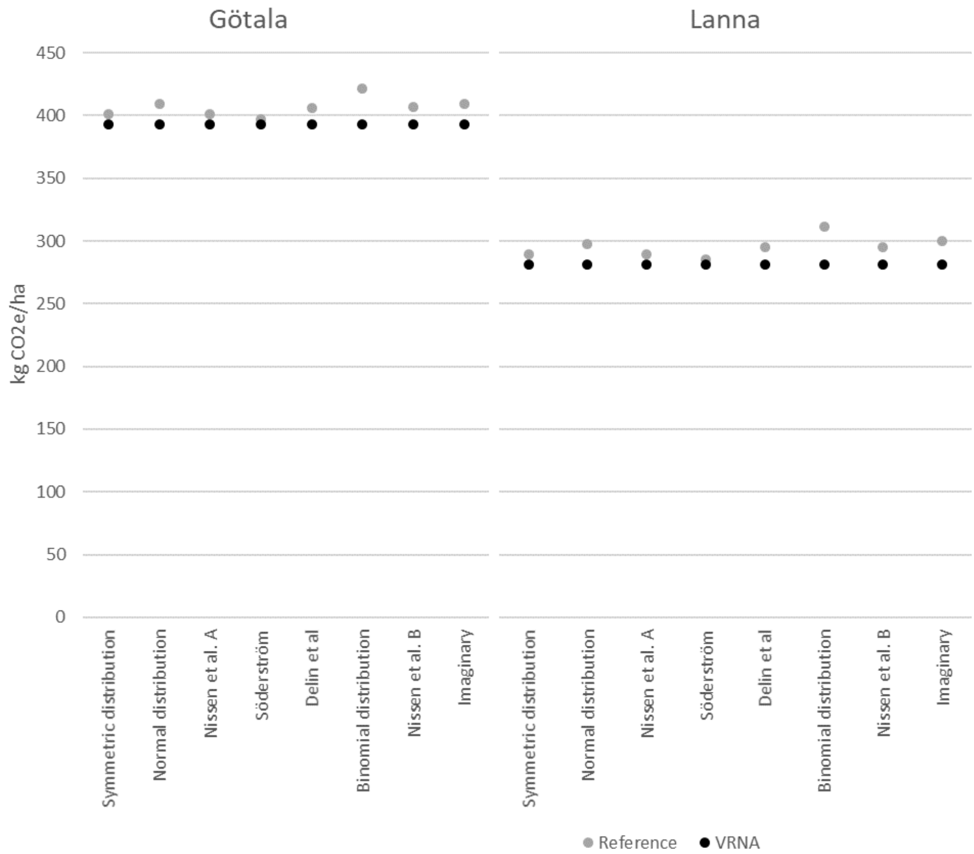

Figure 14. Climate impact (kg CO_2e per hectare) from field nitrous oxide (N_2O) emissions for the different distributions of within-field variation (*cf*. Figure 7) at the Lanna and Götala sites. Reference = uniform nitrogen application, VRNA = variable-rate nitrogen application.

When using the functional unit 1 kg oats, the difference between Reference fertilisation and VRNA increased due to the higher yield when using VRNA. Climate impact per kg oats was reduced by 2-12% with VRNA (Table 3).

Total climate impact

When the impact from ammonium nitrate production and indirect N_2O emissions was included, the percentage difference between Reference and VRNA was smaller than when only considering field N_2O emissions (Figure 15). This is because in this case it was assumed that VRNA did not affect total N use, but rather gave a better distribution of fertiliser within the field.

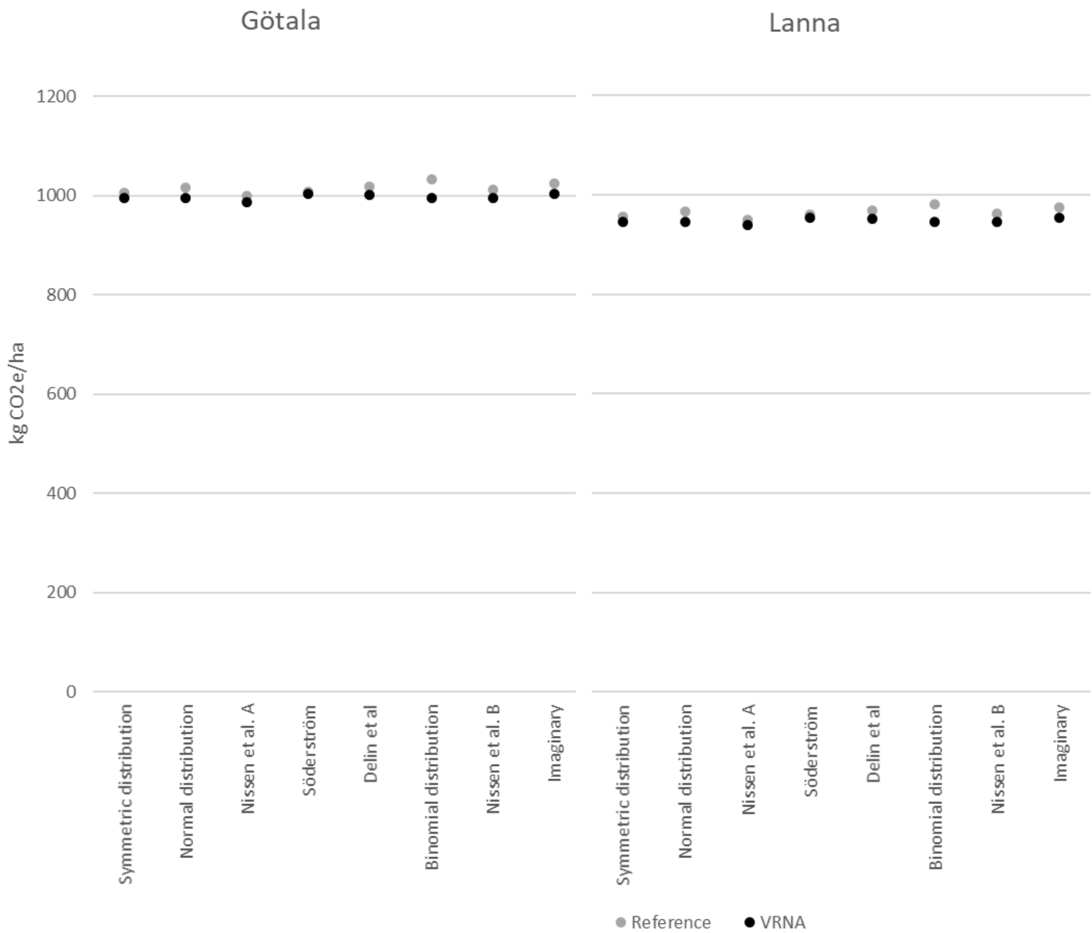

Figure 15. Total climate impact (kg CO_2e per hectare) for the different in-field distributions and sites. Reference = uniform nitrogen application. VRNA = variable-rate nitrogen application.

3.2.4. Comparison of different in-field distributions with uniform fertiliser application at a higher rate

Climate impact from field N_2O emissions

When we assumed that VRNA in addition to site specificity also remediated an over-optimal N-rate in the Reference higher field N_2O emissions were further reduced (Figure 16). Thus the N_2O emissions reduction potential from using VRNA was higher when the N fertiliser rate used was kept lower than the uniform recommended fertilisation rate. Interestingly, although the yield increase for VRNA compared with Reference fertilisation decreased when Reference had 10 kg higher fertilisation rate, for many within-field distributions yield was similar or even slightly higher for VRNA. The results indicated that VRNA has the potential for decreasing field N_2O emissions by around 2-17% (depending on within-field distribution) while reducing the N fertilisation rate and maintaining the yield level.

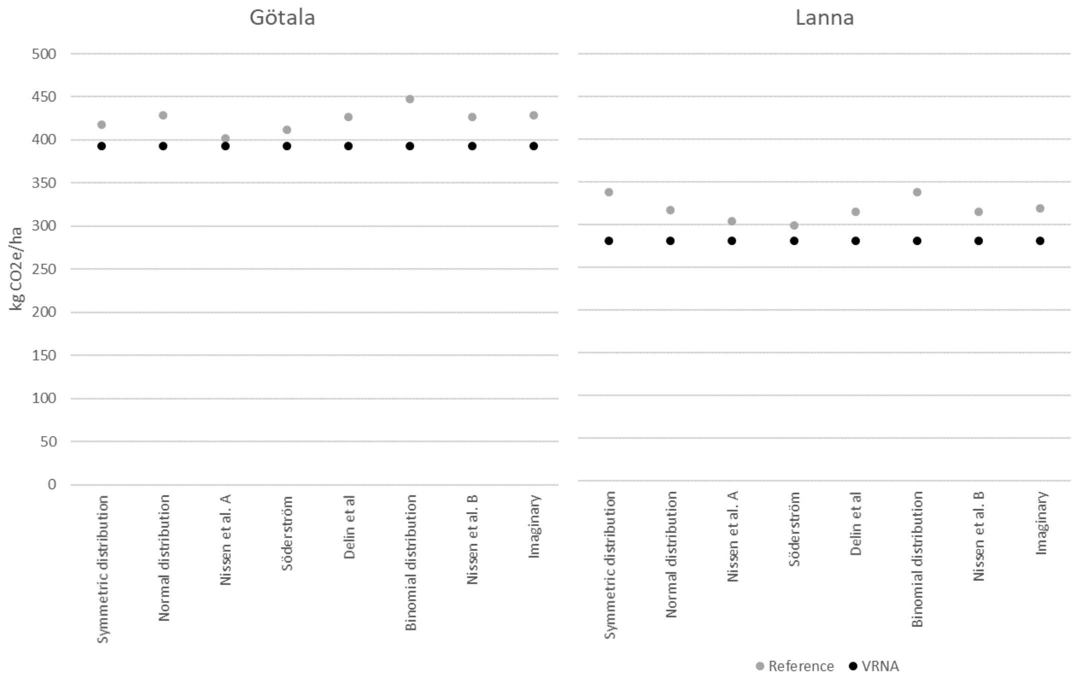

Figure 16. Climate impact (kg CO_2e per hectare) from field nitrous oxide (N_2O) emissions for the different in-field distributions at the two sites. Reference = uniform nitrogen application with 10 kg per hectare higher fertilisation rate, VRNA = variable-rate nitrogen application.

Total climate impact

The results for total climate impact per hectare showed a clear advantage of VRNA for all within-field distributions, due to the lower N application rate compared with Reference fertilisation (Figure 17). The difference in fertilisation rate also affected N leaching, which in turn affected indirect N_2O emissions. The total climate impact was assessed to be approximately 6-10% lower per hectare for VRNA compared with Reference fertilisation. When using the functional unit 1 kg oats, approximately the same reduction in total climate impact was achieved (4-12%), due to the similarities in yield between VRNA and Reference.

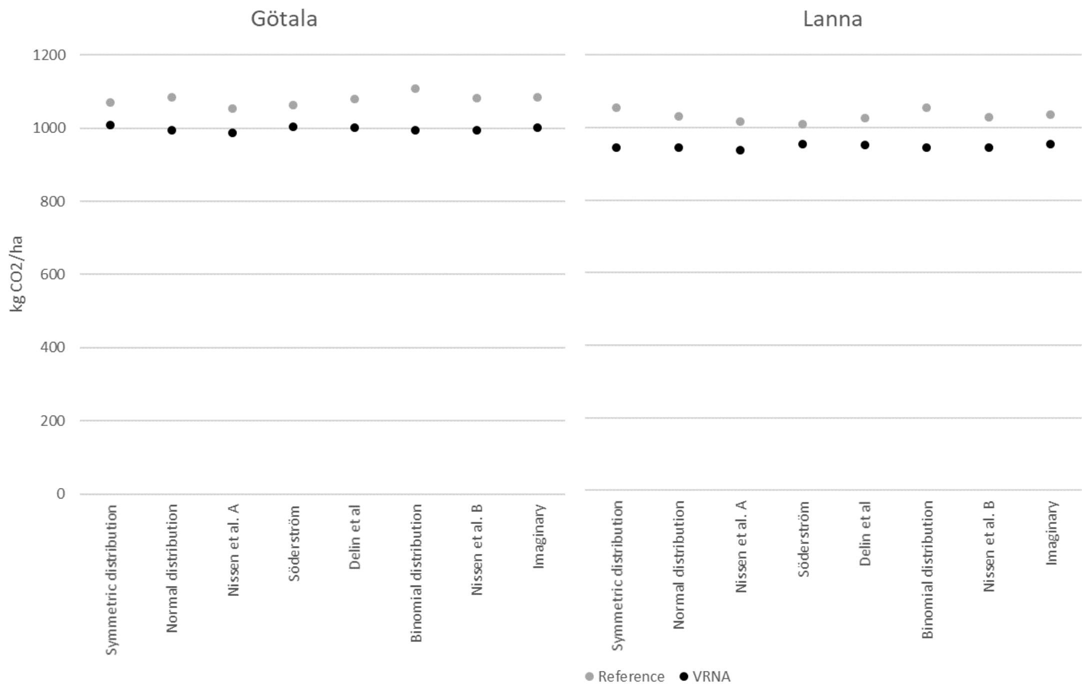

Figure 17. Total climate impact (kg CO_2e per hectare) for the different in-field distributions and sites. Reference = uniform nitrogen application with 10 kg per hectare higher fertilisation rate, VRNA = variable-rate nitrogen application.

3.3. Comparison of field N_2O emissions estimates produced by the IPCC model and nitrogen balance-based model

The N_2O emissions estimates based on field measurements at Lanna and those produced by the IPCC model and the PNB model are shown in Table 3. The results are presented as difference from Reference fertilisation, *i.e.* a negative value indicates a decrease in climate impact or yield, while a positive value indicates an increase.

As expected, the estimates from the PNB model were more similar to values based on field measurements than to estimates made using the IPCC factor. However, the PNB model predicted much more moderate reductions in N_2O emissions than those calculated from field measurements. Nevertheless, the PNB model consistently predicted a decrease in N_2O emissions, whereas the IPCC model sometimes predicted an increase (Table 3). The higher emissions for VRNA when using IPCC were primarily due to higher N_2O emissions from crop residues due to the higher yield. However, the reduction in N_2O emissions for VRNA compared with Reference fertilisation was clearly higher when based on the field measurements at Lanna than for any of the other models assessed (Table 3).

When fields were fertilised at the same rate but with better distribution (as in VRNA), the IPCC model did not give any great difference in the per hectare results, since that model does not consider fertiliser N use efficiency at all. However, in the scenario where Reference had a higher fertilisation rate (+10 kg N per hectare), the IPCC model often (for many within-field distributions) gave a higher reduction for VRNA compared with Reference fertilisation (Table 3). At the higher fertilisation rate, the change in field N_2O emissions for many within-field distributions assessed with the IPCC model was higher than with N_2O estimates calculated from field measurements (base case).

Table 3. *Percentage change in yield, field nitrous oxide (N_2O emissions) and total climate impact for variable-rate nitrogen application compared with Reference fertilisation. Different shades of green indicate no change or small increase, while yellow to red shades indicate different degrees of emissions reduction compared with Reference fertilisation*

	Base case (N2O based on site specific data)					IPCC model for N2O				PNB model for N2O			
Distribution	Yield	Field N2O em.		Tot. climate impact		Field N2O em.		Tot. climate impact		Field N2O em.		Tot. climate impact	
		ha-1	kg-1	ha-1	kg-1	ha-1	kg-1	ha-1	kg-1	ha-1	kg-1	ha-1	kg-1
GÖTALA	Same fertilisation rate												
Symmetric distribution	0.7%	-2.0%	-2.7%	-1.1%	-1.8%	0.1%	-0.5%	-0.1%	-0.8%	-0.2%	-0.9%	-0.4%	-1.0%
Normal distribution	1.3%	-3.9%	-5.1%	-2.1%	-3.3%	0.3%	-1.0%	-0.2%	-1.4%	-0.3%	-1.6%	-0.6%	-1.8%
Nissen et al. A	0.2%	-2.1%	-2.3%	-1.3%	-1.5%	0.0%	-0.2%	-0.2%	-0.4%	0.1%	-0.1%	-0.3%	-0.5%
Söderström	1.0%	-1.0%	-1.9%	-0.5%	-1.4%	0.2%	-0.8%	0.1%	-0.9%	-0.5%	-1.4%	-0.3%	-1.3%
Delin et al	1.6%	-3.2%	-4.7%	-1.7%	-3.2%	0.3%	-1.2%	0.0%	-1.6%	-0.6%	-2.1%	-0.6%	-2.2%
Binomial distribution	2.3%	-6.6%	-8.7%	-3.6%	-5.8%	0.5%	-1.8%	-0.3%	-2.5%	-0.6%	-2.8%	-1.0%	-3.2%
Nissen et al. B	1.1%	-3.3%	-4.3%	-1.8%	-2.8%	0.2%	-0.8%	-0.2%	-1.2%	-0.3%	-1.3%	-0.5%	-1.6%
Imaginary	2.1%	-3.9%	-5.9%	-2.1%	-4.1%	0.4%	-1.6%	-0.1%	-2.1%	0.0%	0.0%	0.0%	0.0%
LANNA													
Symmetric distribution	0.6%	-3.0%	-3.0%	-1.1%	-1.8%	0.1%	0.1%	0.0%	-0.7%	-0.2%	-0.2%	-0.3%	-1.0%
Normal distribution	1.2%	-5.7%	-6.7%	-2.1%	-3.2%	0.2%	-1.0%	0.0%	-1.2%	-0.4%	-1.6%	-0.4%	-1.6%
Nissen et al. A	0.2%	-3.0%	-3.2%	-1.2%	-1.4%	0.0%	-0.2%	-0.1%	-0.3%	0.1%	-0.1%	-0.2%	-0.4%
Söderström	0.9%	-1.6%	-2.5%	-0.5%	-1.4%	0.1%	-0.7%	0.1%	-0.8%	-0.5%	-1.3%	-0.3%	-1.2%
Delin et al	1.5%	-4.9%	-6.2%	-1.7%	-3.1%	0.2%	-1.2%	0.1%	-1.4%	-0.6%	-2.1%	-0.5%	-1.9%
Binomial distribution	2.1%	-9.9%	-11.7%	-3.7%	-5.7%	0.3%	-1.7%	0.0%	-2.1%	-0.8%	-2.8%	-0.8%	-2.8%
Nissen et al. B	1.0%	-4.9%	-5.8%	-1.8%	-2.8%	0.2%	-0.8%	0.0%	-1.0%	-0.3%	-1.3%	-0.4%	-1.4%
Imaginary	1.9%	-6.4%	-8.1%	-2.3%	-4.1%	0.3%	-1.6%	0.1%	-1.8%	-0.8%	-2.7%	-0.6%	-2.5%
GÖTALA	Higher fertilisation rate in reference												
Symmetric distribution	-0.1%	-5.8%	-6.4%	-5.8%	-6.4%	-6.7%	-7.4%	-6.4%	-7.0%	-3.7%	-4.3%	-4.7%	-5.3%
Normal distribution	0.4%	-8.3%	-8.6%	-8.3%	-8.7%	-6.6%	-7.0%	-7.3%	-7.7%	-3.8%	-3.8%	-6.0%	-6.0%
Nissen et al. A	-0.5%	-2.1%	-1.5%	-6.2%	-5.7%	-7.9%	-7.4%	-8.2%	-7.7%	-4.3%	-4.3%	-6.4%	-6.4%
Söderström	0.0%	-4.4%	-4.4%	-5.6%	-3.5%	-5.2%	-5.2%	-5.6%	-4.4%	-2.9%	-2.9%	-4.5%	-2.9%
Delin et al	0.6%	-7.8%	-8.3%	-7.3%	-7.9%	-5.3%	-6.0%	-6.0%	-6.6%	-3.2%	-3.2%	-5.0%	-5.0%
Binomial distribution	1.4%	-12.2%	-13.4%	-10.3%	-11.6%	-6.5%	-7.8%	-7.4%	-8.7%	-4.1%	-4.1%	-6.4%	-6.4%
Nissen et al. B	0.2%	-7.8%	-8.0%	-8.2%	-8.4%	-6.8%	-7.0%	-7.4%	-7.6%	-3.8%	-3.8%	-6.0%	-6.0%
Imaginary	1.1%	-8.3%	-9.3%	-7.6%	-8.7%	-5.1%	-6.2%	-5.9%	-7.0%	-3.2%	-3.2%	-5.1%	-5.1%
LANNA													
Symmetric distribution	-0.1%	-16.8%	-16.8%	-10.4%	-11.0%	-5.3%	-5.3%	-6.0%	-6.6%	-3.9%	-3.9%	-5.5%	-6.2%
Normal distribution	0.4%	-11.3%	-11.7%	-8.2%	-8.6%	-5.2%	-5.6%	-5.8%	-6.2%	-4.1%	-4.1%	-5.4%	-5.4%
Nissen et al. A	-0.4%	-7.5%	-7.1%	-7.7%	-7.3%	-6.4%	-5.9%	-6.8%	-6.4%	-4.6%	-4.6%	-6.0%	-6.0%
Söderström	0.1%	-6.2%	-6.3%	-5.5%	-3.4%	-4.1%	-4.1%	-4.5%	-3.5%	-3.1%	-3.1%	-4.1%	-2.6%
Delin et al	0.6%	-10.7%	-11.3%	-7.2%	-7.8%	-4.4%	-5.0%	-4.9%	-5.5%	-3.5%	-3.5%	-4.5%	-4.5%
Binomial distribution	1.3%	-16.8%	-17.9%	-10.4%	-11.6%	-5.1%	-6.3%	-5.9%	-7.1%	-4.6%	-4.6%	-5.8%	-5.8%
Nissen et al. B	0.3%	-10.8%	-11.0%	-8.1%	-8.3%	-5.3%	-5.6%	-5.9%	-6.1%	-4.1%	-4.1%	-5.4%	-5.4%
Imaginary	1.0%	-11.9%	-12.9%	-7.8%	-8.8%	-4.0%	-5.0%	-4.7%	-5.7%	-3.7%	-3.7%	-4.8%	-4.8%

Thus when the fertilisation rate was assumed to be increased, the IPCC model showed a greater reduction in emissions than the other methods. This is because IPCC assumes a direct relationship between emissions and N application rate, without any consideration of crop uptake, which means that a higher application rate will have a direct effect on modelled N_2O emissions. The N_2O emissions for different fertilisation levels above and below the optimum, estimated from the different methods, are plotted in Figure 18. According to the model based on field measurements, the increase in N_2O emissions above the optimum was rather moderate as long as the optimum was exceeded by less than 40 kg N/ha (‘Field measurements Lanna’ in Figure 18). As most within-field distributions had a variation in nitrogen fertiliser requirement within this range (*cf*. Figure 7), the effect of uniform fertilisation was not excessive.

In contrast, the IPCC model predicted that field N_2O emissions would increase almost linearly, although not completely linearly because of the different yield levels at different fertilisation rates and associated differences in N_2O emissions from crop residues. The slope of this linear relationship was higher around the optimum, giving greater differences between VRNA and Reference fertilisation with the IPCC site-specific model.

The PNB-based model showed a similar pattern to the model based on field measurements in terms of field N_2O emissions in response to N fertilisation rates around the optimum (Figure 19). However, for fertilisation rates well above the optimum, the curve for the PNB model did not predict as high an increase as the model based on field measurements. The PNB model curve was more similar to the site-specific data in terms of emissions amounts.

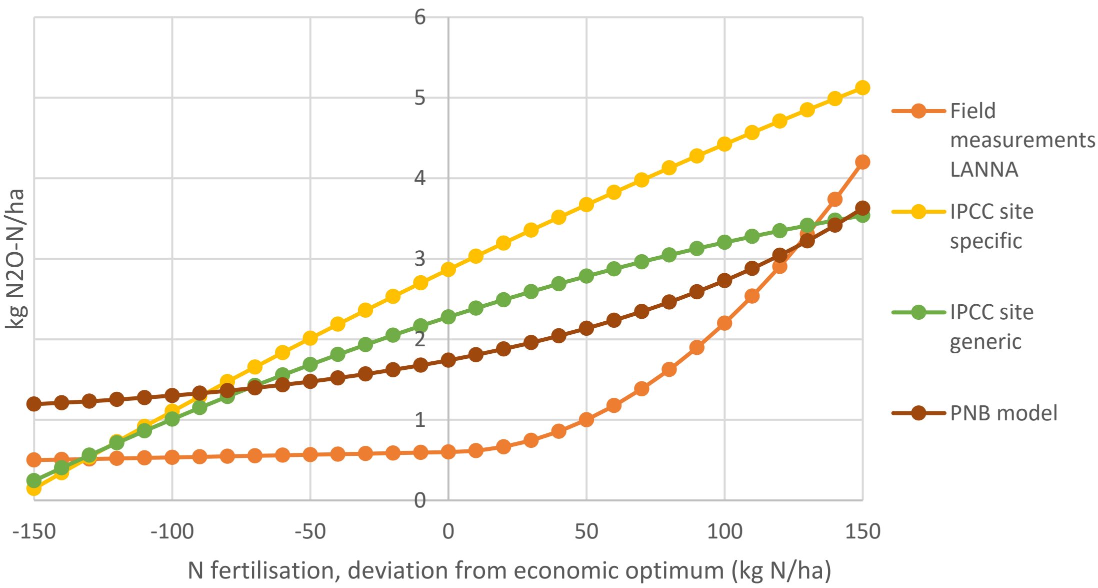

Figure 18. Nitrous oxide emissions (kg N_2O-N per hectare) at different fertilisation levels above and below the economic optimum, calculated from field measurements (LANNA), with two different IPCC factors (site-specific, site-generic) and with the partial nitrogen balance (PNB) model.

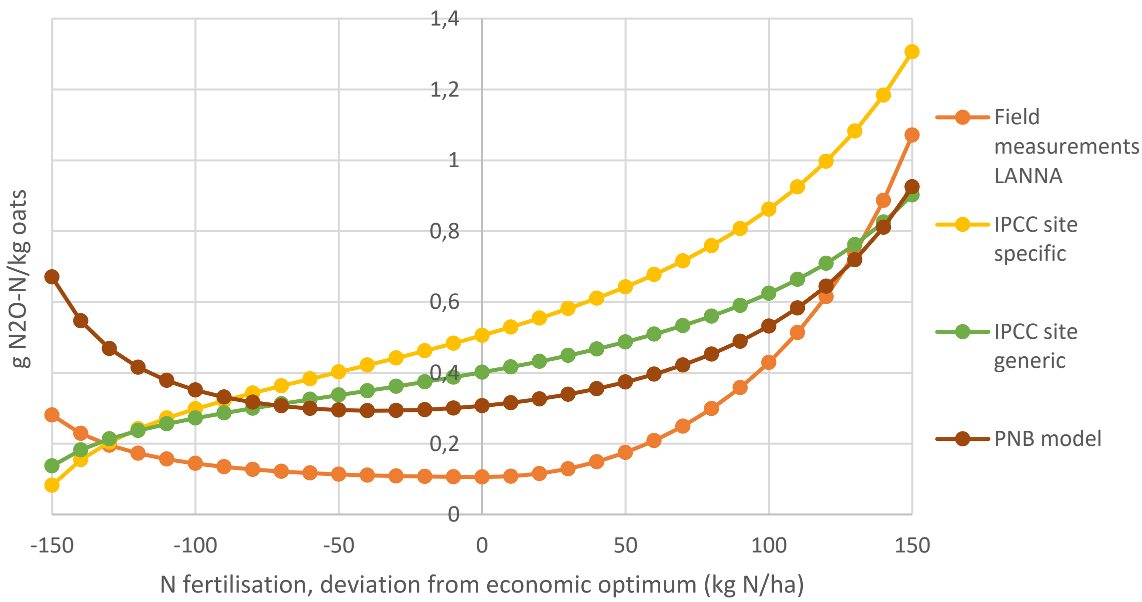

Figure 19. Estimated nitrous oxide emissions (g N_2O-N per kg oats) at different fertilisation levels (and yield levels), presented as difference from optimum.

The calculated total climate impact for all within-field distributions is shown in Figure 20. The PNB-predicted N_2O emissions resulted in a climate impact close to midway between that predicted by the IPCC model (higher values) and that estimated from field measurements (lower values).

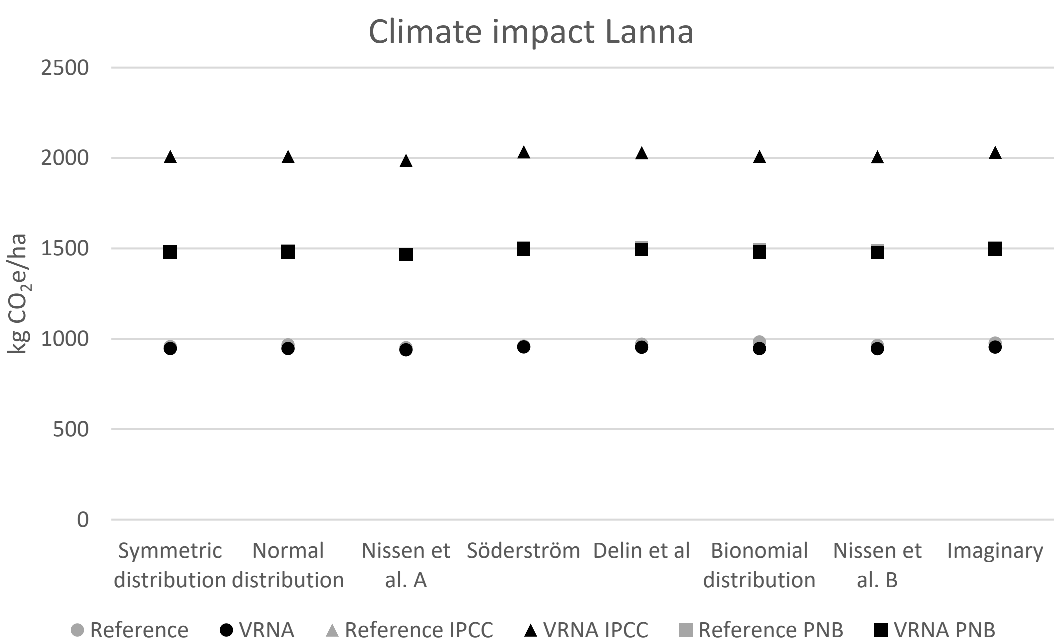

Figure 20. Total climate impact for all in-field distributions assessed and for Lanna based on field data for Reference fertilisation.

Figure 21 shows the total climate impact with higher fertilisation rate in Reference. The results were strongly influenced by the higher fertilisation rate and associated upstream emissions due to fertiliser production. This resulted in all within-field distributions having a lower total climate impact when VRNA was used, due to the lower N rate.

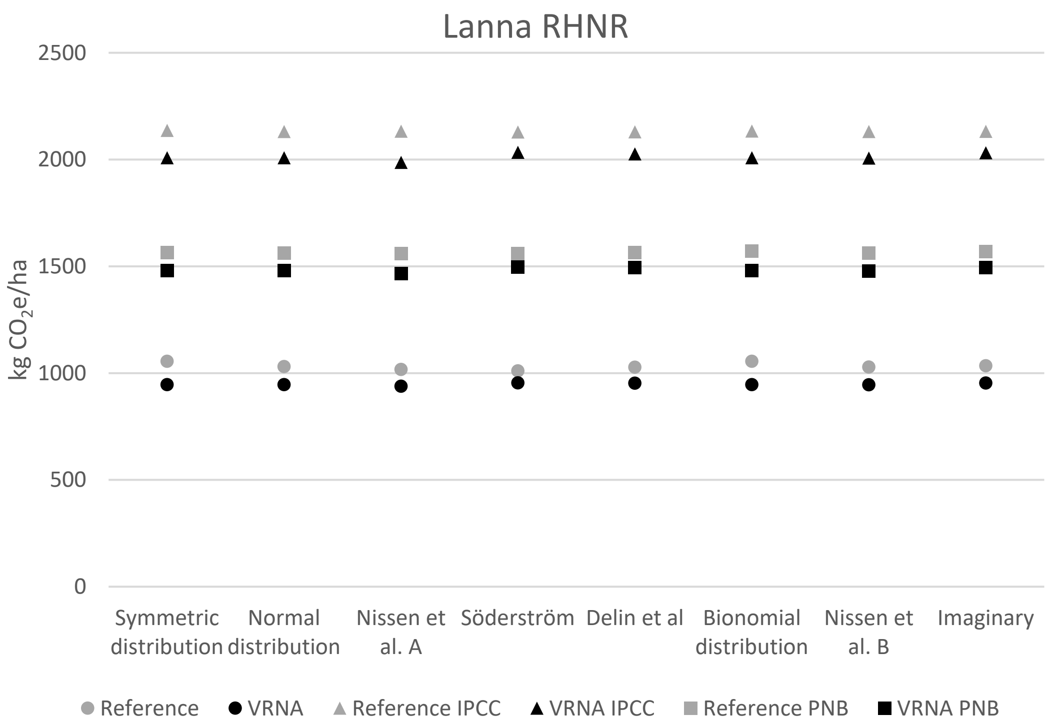

Figure 21. Total climate impact for all in-field distributions assessed, and for Lanna based on field data for Reference higher nitrogen rate (RHNR).

4. Discussion

4.1. More efficient nitrogen fertilisation at national level

Field-specific N fertilisation recommendations from zero-plots and VRNA are both now commonly applied in winter wheat and malting barley production, and work is underway to extend the recommendations to other crops, such as potatoes, forage leys and spring oats. For implementation of VRNA based on crop measurements, split application of N fertiliser and machinery equipped with new technology are required. Both these are becoming standard on large Swedish farms, while farms that are not large enough to buy such equipment can usually purchase precision fertilisation services from contactors. Nitrogen is also applied as organic fertiliser recycled from manure or other organic wastes and these are more difficult to apply with high precision, since there are challenges associated with N content, N availability, ammonia losses, large volumes and application technology. More research and development is needed to enable precision application of organic fertilisers. Apart from technological development, education and training of farmers in precision fertilisation is required, although Swedish farmers are already proficient partly thanks to the national advisory project GREPPA. To increase uptake of N fertiliser optimisation approaches (field-specific and VRNA) in practice, there will need to be an economic incentive for farmers, such as high fertiliser costs and high prices for grain, to encourage them not to apply more fertiliser than is justified by the expected yield return.

4.2. Time perspective on implementation

Technology is already available on the Swedish market and consultants such as Hushållningssällskapet can provide on-field measurements for more accurate N fertilisation. Future improvements could include improved sensors and models to interpret sensor readings and improved use of satellite images. The current trend of rocketing fertiliser prices can lead to more rapid development of technologies for optimised N fertilisation rates, as the economic gain with fertilisation rates closer to the economic optimum increases when fertiliser prices are higher.

4.3. Impacts on other sustainability parameters

4.3.1. Environmental impacts

Apart from reducing climate impacts, measures to improve N use efficiency are likely to decrease eutrophication potential, due to lower leaching losses (Delin *et al.*, 2015). It is estimated that leaching could be reduced by 2 kg N/ha for optimum N fertilisation compared with exceeding the optimum level by around 30 kg N/ha (Delin & Stenberg, 2014). Other impacts associated with mineral N production, including GHG emissions and (fossil) energy use, will also decrease when the N Use efficiency is increased.

Higher yield can also mean higher crop residue production. A greater volume of root biomass and larger quantities of straw returned to the soil could increase soil organic carbon content. Higher soil organic carbon content is beneficial for soil health (Lal, 2014) and has also been suggested as a climate mitigation strategy, as storing more carbon in soil can decrease the amount of CO_2 in the atmosphere (Shukla *et al.*, 2019). The yield increase found in the present study for field-specific N rate and VRNA was around 1-2% in both cases.

4.3.2. Economic impacts

Farm finances are likely to be improved by implementing measures to promote better N use efficiency and this is likely to be the main implementation driver from farmers' perspective.

Other indirect effects of more accurate N fertilisation rates can also affect farm finances, *e.g.* less grain crop lodging in the field would lower the energy demand for drying the grain, lower the cost of harvesting and increase yield (lower losses due to lodging). The effects of lodging was not included in this study. Fertilisation at close to the optimum rate can also result in more uniform protein content in the grain, which is advantageous for some high-value applications such as bread making.

4.3.3. Social impacts

Technologies such as VRNA are quite advanced, requiring specialist knowledge, and can be costly (at least in terms of initial investment). This could lead to more VRNA work being done by entrepreneurs and specialists, especially on smaller farms. Introduction of the technology may thus lead to greater specialisation and fewer agents performing the work. However, it can also inspire the farmers to improve their production, as they will get more information about their fields and crops.

4.4. Models for estimating field N_2O emissions

The IPCC model and the PNB model (Eagle *et al.*, 2020) both predicted higher absolute field N_2O emissions than calculated from field measurements (Wallman, 2021). The field measurements at Lanna were lower than expected from IPCC (Wallman, 2022) and probably low compared with many sites in Sweden. The important aspect was the difference in response above and below optimal N, as also shown in other studies (Shcherbak *et al.*, 2014). Some studies have found a linear correlation, supporting the IPCC model (Hergoualc'h *et al.*, 2021), but these studies have often only included N rates above the optimum or have had insufficient measurements after harvest to estimate the effects of differences in residual N.

One challenge with using a model based simply on partial N balance (N in fertiliser minus N in yield), such as the PNB model (Eagle *et al.*, 2020) in this study, is that the optimum N rate is not known. Field estimates indicate that N_2O emissions can increase quite rapidly if the crop is fertilised at above the optimum rate (Wallman, 2021). A simple N balance does not give much information about whether a crop has been fertilised close to optimum or not, which depends on local factors such as N delivery from the soil and the crop grown in the previous year. This is why the N balance indicator used in this study only predicted small changes in N_2O emissions when using more accurate N fertilisation methods. The methods assessed (field-specific N fertilisation, VRNA) appeared to increase N use efficiency but the changes in yield were small, resulting in only small changes in the N balance. However, the PNB model predicted a decrease in field N_2O emissions when the same amount of N was better distributed over the field than when applied uniformly. This was a clear advantage compared with the IPCC model in predicting field N_2O emissions of measures that do not affect N application rate, but do affect yield.

5. Conclusions

Field-specific N fertilisation was estimated to reduce the climate impact from N_2O emissions by around 5%. Variable-rate nitrogen application was estimated to decrease field N_2O emissions further, by 1-10% (depending on within-field variation). Climate impact per kg harvested grain showed a somewhat higher percentage reduction with both field-specific N fertilisation and VRNA compared with the recommended N fertiliser rate (Reference), owing to small yield increases at the same fertilisation rate.

Fertilisation rate was very important for the overall climate impact. Calculations of N_2O emissions based on models that included the effect of high N use efficiency on emissions showed that it is preferable in a climate impact perspective not to fertilise above the optimum.

The IPCC method for predicting N_2O emissions failed to predict a reduction in N_2O emissions due to better N use efficiency achieved by fertilising closer to the optimum rate. Better distribution of N fertilisation between fields (field-specific N rate) and within fields (VRNA) resulted in higher yields at a given fertilisation rate. Instead of predicting lower N_2O emissions with better N use efficiency, as less leftover N is available to cause emissions, the IPCC model assumed that higher yield would result in a larger amount of crop residues and associated N_2O emissions, and thus gave higher predicted emissions. When the N fertilisation rate was reduced, the IPCC method often predicted greater reductions in field N_2O emissions than expected from field measurements. The nitrogen balance-based method for predicting field N_2O emissions (PNB model) better matched the field measurements in this study, but the rate of decrease in estimated emissions was not nearly as high as expected based on field measurements.

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