SYSTEM-BASED PRECISION AGRICULTURE FOR SUSTAINABLE CROP PRODUCTION

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Abstract.

The major challenge addressed is the systemic mismanagement of nitrogen (N) fertilizer in agricultural fields leading to problems such as leaching of nitrates into groundwater and emission of harmful greenhouse gases. Digital technologies are commercialized in agriculture (available from the early 1990s) but have failed with N fertilization. Despite agriculture is the least digitized sector (as highlighted at the last World Economic Forum) to make a reliable recommendation, researchers need to extract and simplify complex science into practical and relevant information enabling advisors and farmers to use such information to make N recommendations for individual fields.

The study illustrated results of the first two years of this 5-years research project showing spatio-temporal variability of plant N uptake, soil water, soil mineral N, nitrate leaching and nitrous oxide emissions, as well as spatial variability of soil physical, chemical, biological properties. The field was a 5 ha field with 48 points samples.

In addition, the project includes a 300 ha farmer's field which has all the technologies for implementation but never adopted precision management. Therefore, we used a reductionist approach to evaluate how much of our know-how we can apply in real farming conditions.

Keywords.
Nitrogen, leaching, emission, fertilization

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Introduction

Precision Agriculture (PA) is "*a management strategy that takes into account temporal and spatial variability to improve sustainability of agricultural production*" (ISPA, 2026). There are several key elements to consider in such definition: the agronomic component which considers field management, the economic one made by the final product (and/or its quality), and the environmental sustainability of production (represented by losses of reactive nitrogen (N)). Those elements must be optimized with the aim of keeping farming highly productive and profitable with lower environmental impacts. PA distinguishes itself from classical agronomic trials because it attempts to consider the spatial (within a field or between fields) and temporal (during a growing season and/or between growing seasons) variability of the factors affecting nutrient dynamics (e.g., topography, soil organic carbon, soil texture). It thus attempts to analyze the multiple factors at play in farmers' fields rather than a few isolated ones.

Considering (and understanding) the patterns of in-field spatial and temporal crop variability is the first step for designing site-specific agronomic management. In fact, even with little or low spatial variability within a field, the temporal variability (e.g. interannual weather conditions) impacts spatial crop growth so that the purpose of PA does not change.

While research on PA for agronomic management is about 40 years old, the adoption of PA technologies for site-specific management is low. Approximately 26% of Danish farmers use software for planning of N application rate and the same number use satellite and/or Unmanned Aerial Vehicles (UAV) images in their production (Statistics Denmark, 2023). Lowenberg-DeBoer and Erickson (2019) concluded that despite such low level of adoption (about 20%) farmers appreciate the idea of site-specific management but are not convinced of its value. A value that should be both economic and environmental (Cammarano et al., 2019) as noted in the original definition.

Among the various management factors, one of the major challenges of global significance relates to the inefficient application of fertilizer in agricultural fields with a focus on the systemic mismanagement of N fertilizer (Rockström, et al., 2009). While steps have been taken to rationalize its use, a chronic inefficiency of the N fertilization leads to environmental problems such as leaching of nitrates into groundwater, surface water (e.g. Hjarbæk Fjord), greenhouse gas (GHG) emission and in some cases to hypoxic dead zones (e.g. Gulf of Mexico, Baltic Sea) (Carstensen et al., 2014). In fact, as N fertilization there are numerous variables involved in best N form, timing and amount for a given growing season. Spatial variability in soils and temporal variability in weather lead to complex spatio-temporal interactions in the field. Thus, research is far from finding a solution to optimally manage an agronomic input like N fertilization.

Research must gain a better understanding of such complexities. Otherwise, farmers will keep applying N fertilizer in ways that will be harmful to the environment. Nowadays, the use of digital technologies like sensors, models, big data, combined with on-farm experimentation (Lacoste et al., 2021) give us a chance to increase the efficiency of N fertilization. However, while there is a growing interest and high expectation in these technologies, scientists are often skeptical in the way they are used (Colaço and Bramely, 2018; Manning, 2017) because what is missing is a standardized framework to obtain and interpret data, translate such information into practical agronomic practices, and to evaluate the economic and environmental outcomes.

In fact, because of the issue described above, the commercial techniques adopted in PA(available from the early 1990s) have not had much success with N fertilization. Indeed, farmers (and researchers) often complain that they do not know what to do with their data (Bullock et al., 2019).

Denmark (along with other EU countries) has implemented EU directives and national legislation on N losses and GHG emissions and therefore it is important to develop appropriate techniques that are truly game-changing for supporting sustainable site-specific agricultural practices.

If a proper site-specific application that accounts within field variability is not adopted, they will continue making N fertilization decisions that are not environmentally and economically sustainable. In a broader perspective, the adoption of PA technologies can support the green transition because it allows to reduce N inputs in a sustainable way even if agriculture is among the least digitized sectors (World Economic Forum, 2023).

To make a reliable recommendation, researchers need to extract and simplify complex science into practical and relevant information enabling advisors and farmers to use such information to make N recommendations for individual fields. The severe bottlenecks in research, development and application of PA cause key research to be disconnected.

The objectives of the proposed study, which is part of an on-going project was to: a) Evaluate agronomic and environmental data collected on a 5 ha field and on a 50 ha farmer's field collected so far; b) Quantify spatial variability of soil biological properties; c) identify patterns of nitrogen emissions and leaching during the growing season.

Materials and Methods

The 5-ha field (Field#1) is located in Foulumgård (Latitude 56° 29' N, Longitude 9° 34' E, 53 m a.s.l.) in the central part of the Jutland peninsula, Denmark. The climate was defined as cool temperate maritime with moderate air temperatures and consistent summer rainfall and cool winters. The field presents a rolling landscape (Fig. 1a) and was cultivated for both 2024 and 2025 with the same spring barley cultivar (*Hordeum vulgare* L.) which was sown on 10 May in 2024 (late sowing due to heavy spring rain) and harvested 26 Aug 2024. In 2025 it was sown on 27 Mar 2025 (normal sowing window) and harvested the 12 Aug 2025. For both growing seasons uniform N fertilization was given using granular N-P-K (21-4-10) at a rate of 140 kg N ha^{-1}.

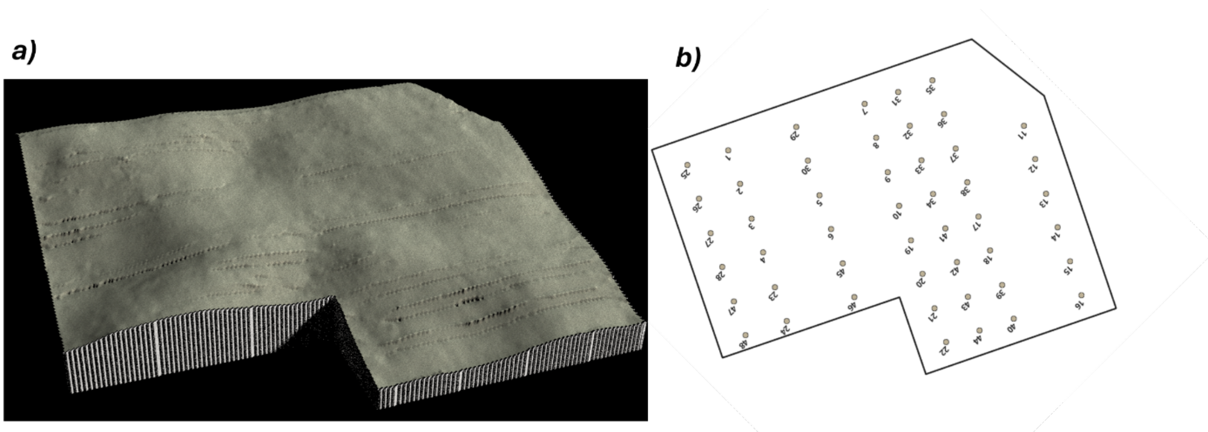

Fig 1. Field#1 located in Foulumgård, Denmark as seen from (a) the Digital Elevation Model, and (b) the 48 grid points used for sampling soil and plant properties, N leaching, and N emissions.

Given that on this field there were multiple projects that complemented each other, a series of measurements involving soil physical, chemical, and biological were made (Table 1), as well measurements of N_2O emissions with the MIRA CO2/N2O portable analyzer (Aeris Technologies, Inc.) coupled with a custom-designed portable circular static chamber (22.7 L prior stem elongation and 52.89 L up to harvest).

Table 1. Soil, plant, sensors measurements on the Field#1 (Foulumgård, Denmark).

Property	Depth (cm)	#Points	Sampling Frequency
Texture	0-30; 30-60; 60-90	100	Feb 2023
Bulk Density	0-15; 15-30; 30-40; 40-50	48 (3 reps by depth by point)	Mar 2026
Soil Hydraulic limits	0-15; 15-30; 30-40; 40-50	48 (3 reps by depth by point)	Mar 2026
Soil Water	15; 40	48	15-min (during Growing Season - GS)
Organic Matter	0-30; 30-60; 60-90	100	Feb 2023
Pot Nitrification	0-15	80	Feb 2023
Denitrifying Enzymatic Activity	0-15	80	Feb 2023
Pot. Mineralization	0-15	48	Apr 2024; Nov 2025
Field Mineralization	0-15	24	Teabags in frames under soil
N-related bacteria	0-15	48	DNA extraction, PCR, and qPCR
Soil pH	0-15	48	Apr 2024
Soil total N (NO3+NH4)	0-30	48	7/9 times during GS
N2O emissions	Aeris Mira GHG analyzer	48	9 to 20 times during GS
Nitrate Leaching	150	48 (72 from 2026)	Foumgård protocols
Plant N + biomass	-	48	4 times during GS
Root density / depth	150	48	Minirhizotron
Apogee CHL + LAI + height	-	48	6/10 times during GS
Yield	-	-	48 manual + yield monitor
Biomass at harvest plus N%	-	48	Harvest
Proximal sensors	VERIS, EMI, Gamma Ray, Ground Penetration Radar	-	2023, 2024, 2025
Remote Sensing	DJI Multispectral + Thermal	-	8/10 times during GS

Nitrate leaching was measured every 2 weeks, but the sampling frequency was adjusted during period of heavy rainfall. The concentration of nitrates (mg L^{-1}) was determined with an auto-analyzer following Best et al. (1976) protocols. The nitrate content (kg N ha^{-1}) was obtained by simulating drainage using EVACROP model (Olesen and Heidmann, 1990) as this model has been developed, applied and evaluated extensively in Foulumgård making it suitable for capturing leaching content on those fields.

In both growing seasons the soil was sampled prior sowing and after harvest to determine the amount of soil mineral N and analyzed privately at Eurofins Labs by automated colorimetric analysis. For soil water content the TOMST (Wild et al., 2019) sensors were used and installed on the 48 points at 15 and at 40 cm below the surface. Those sensors record soil moisture, soil temperature 15 cm above the surface, on the surface and 8 cm below the surface.

Aboveground biomass was determined in correspondence to the dates of N_2O sampling but also to the growth stages of tillering, booting, flowering, and harvest for both growing seasons.

Point data were interpolated using kriging with external drift where the Topographic Wetness Index (TWI) was calculated as such. The maps were generated either with Surfer or with R.

Another field (Fied#2) is a 50-ha private farm field, part of a 300-ha farm that is currently being mapped (Figure 2) and located in Værum (Denmark). The farm started participation in 2025, and the crop planted was spring barley, for the 2026 it was pea. Here the first approach was to discuss with the farmer the main agronomic issue affecting his productivity. From the discussion, the farmer was interested in optimizing mostly seeding density of his rotations. And, in spring barley also the amount of total N fertilization to avoid excessive N leaching. Therefore, for the 2025 growing season six strips within the field was selected, representing two planting densities as a main factor (***D1***: 138 kg seeds ha^{-1} and ***D2***: 204 kg seeds ha^{-1}); in each strip a different amount of total N fertilization was also applied as subplot treatment (***N1*: ** 119 kg N ha^{-1}; ***N2***: 140 kg N ha^{-1}). Sampling of soil N (before planting, during the growing season and at harvest), texture, organic matter, and N leaching were made on the sampling points (Fig 2b, c). As well as non-destructive measurements of LAI (LICOR 2200C), Chlorophyll content (Apogee meter), and drone flight. N leaching was measured by placing silica-disks gel below 70 cm (3 per points) using the approach described in Wangari et al. (2024). The 2025 data, in the way of the different treatments replicated randomly in the field (Fig 2b) were analyzed using an analysis of covariance (ANCOVA) by using the coordinates of each point as covariates to account for spatial variation. Treatments were included as a fixed factor, with GPS coordinates of each point (longitude, X; latitude, Y) entered as continuous covariates to capture any underlying spatial gradients in soil or environmental conditions. Type II sums of squares were used to ensure that covariate effects were estimated independently of treatment and each other. Post-hoc pairwise comparisons were conducted using Fisher's Least Significant Difference (LSD) test, with treatment least-squares means (LS-means) adjusted for the spatial covariates. All statistical analyses were performed in R (version 4.3.3) using the *car* package for Type II ANOVA and the *emmeans* package for LS-means estimation and pairwise contrasts.

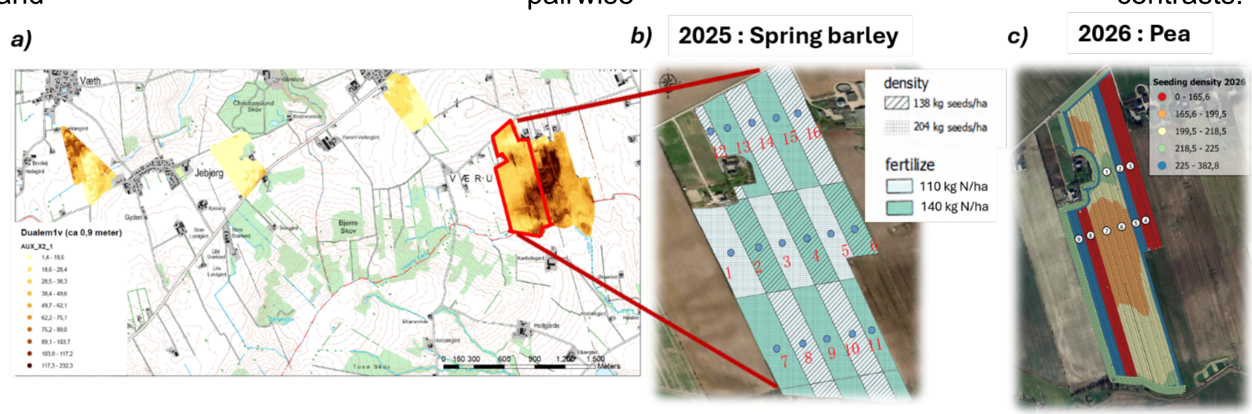

Fig 2. Field#2 located in Væreum, Denmark as seen from (a) the EMI mapping of part of the farm (ongoing), and (b) the way seeding and fertilizer was applied in 2025 on spring barley, and (c) the seeding density applied on pea in 2026. The blue points in (b) and the white points in (c) are the sampling points.

Results and Discussion

Field 1

The soil of Field#1 did not present much variability in terms of texture up to 90 cm (Table 2) having more than 70% sand in each layer. However, biological properties, such as the Denitrifying Enzymatic Activity (DEA) showed an interesting spatial structure (Fig 3a). A 16-fold difference between the lowest and highest DEA values was large (Fig 3a) but typical of what has bee reported in the literature for agricultural fields (Simek et al., 2000; Hofstra and Bouwman, 2005). In fact, DEA is known to be among the most spatially variable soil biological properties. Soil organic matter (Fig 3d) and carbon availability would probably be the dominant driver of the DEA variability as DEA closely tracks labile carbon supply. Hotspots of 80 µg N_2O g^{-1} h^{-1} correspond to areas of the fields with higher organic carbon. Soil texture and water retention modulate anaerobic microsites where denitrification occurs. Even in a seemingly uniform field, like this field, subtle textural differences create pockets of higher water-filled pore space that favor denitrifier activity.

The nitrification potential showed a distinct spatial pattern with higher values in the top part of the field and lower at the bottom (Fig 3b). Nitrification processes naturally could potentially lead to an accumulation of nitrates in the soil, and under poorly drained or oxygen-depleted conditions (water-logged soils), other soil microbes could use these nitrates for denitrification processes, resulting in additional N_2O emissions. However, the results of this study showed that for the 2024, 2025 (and the previous 2023) growing season there was an opposite pattern of nitrate leaching and N_2O emissions (Fig 4).

Table 2. Mean values of soil texture at three depts for the Field#1. Values are the average of 100 sampling points at each depth, and the numbers in parentheses represent the standard devitation.

Property*	0-30 cm *(%)*	30-60 cm *(%)*	60-90 cm *(%)*
Clay	9.38 (1.05)	10.53 (2.13)	12.34 (2.84)
Sand	79.27 (3.41)	79.09 (5.62)	77.20 (5.83)
Silt	11.35 (1.51)	10.38 (2.13)	12.34 (2.84)

**n=100*

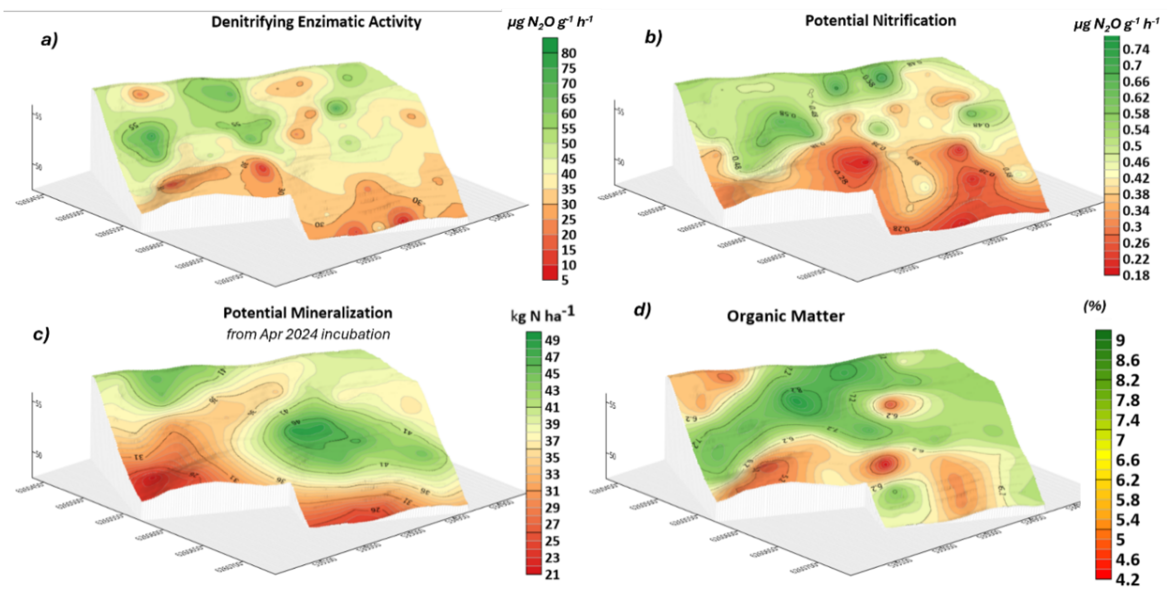

Fig 3. Field#1 maps for (a) Denitrifying Enzimatic Activity (n=80), (b) Potential nitrification (n=80), (c) potential mineralization (n=48) and (d) organic matter (n=100).

During the 2024 growing season the cumulative nitrate leaching varied between 27.5 and 42 kg N ha^{-1} with higher leaching measured in the top sides of the field and the lower leaching in the bottom part of the field (Fig 4a). On the other hand, the cumulative N_2O emissions ranged between 2 and 9 kg N_2O-N ha^{-1} with a spatial pattern opposite to the one observed for leaching but concentrated in areas where higher denitrification and nitrification was observed. Such high emissions values for the 2024 growing season were obtained on a sandy loam following warm spring temperatures and several weeks of rainfall (data not shown). However, in the same area others have reported similar high N_2O emissions (Petersen et al., 2023). On a previous study in the same field, it was found that the patterns of N_2O emissions had a similar spatial structure (e.g. points that were higher emitters in 2023 were also higher emitters in 2024) and attempted to use the concept of yield stability maps to draw N_2O stability zones (Yin et al., 2025); however this on-going project would allow for additional growing seasons to be included and a better understanding of this spatio-temporal variability of N losses will be gained. Among the factors impacting those losses were field topography, N uptake and weather patterns during the growing season (Yin et al., 2025). In the field under study the areas of high nitrification potential also show the highest leaching and lower emissions, suggesting that such process drives most of the N losses by leaching and so even if there is high denitrification, seldom the conditions allow the soil to be oxygen depleted. In the low-lying areas, on the other hand, intense rain could cause such conditions favoring emissions (Fig 4).

The harvested yield of spring barley (same cultivar and management for both years) showed similar spatial patterns for the 2024 and 2025 growing season. In 2024 due to late planting the yield ranged between 1,600 to maximum 4,000 kg DM ha^{-1} while in 2025 it reached 6,000 kg DM ha^{-1} (Fig 4c,d). However, the high yielding areas seemed to be consistent in both growing seasons, and those areas were also the ones that correspond to low leaching and higher emissions. Also, data from minirhizotron confirmed that areas of high yield and low leaching had also higher rooting depth (data not shown).

An implication of this variability is that the areas of the field with higher leaching are also low yielding areas. In this case, a sensor-based approach for adjusting fertilization might actually exacerbate the problem of N losses causing more environmental damage than any real increase in productivity.

Therefore, for the 2026 growing season it was decided to divide the field into eight strips (25m wide) in which uniform vs. prescription of fertilization based on a commercial approach (Danish Agro, with 475 kg ha^{-1} NPK 21-3-10) will be compared (Fig 5). In each strip the same in-season measurements shown in Table 1 will be made so that it will be possible to have an environmental and agronomic trade-offs of yield vs. N losses for both uniform and site-specific approach.

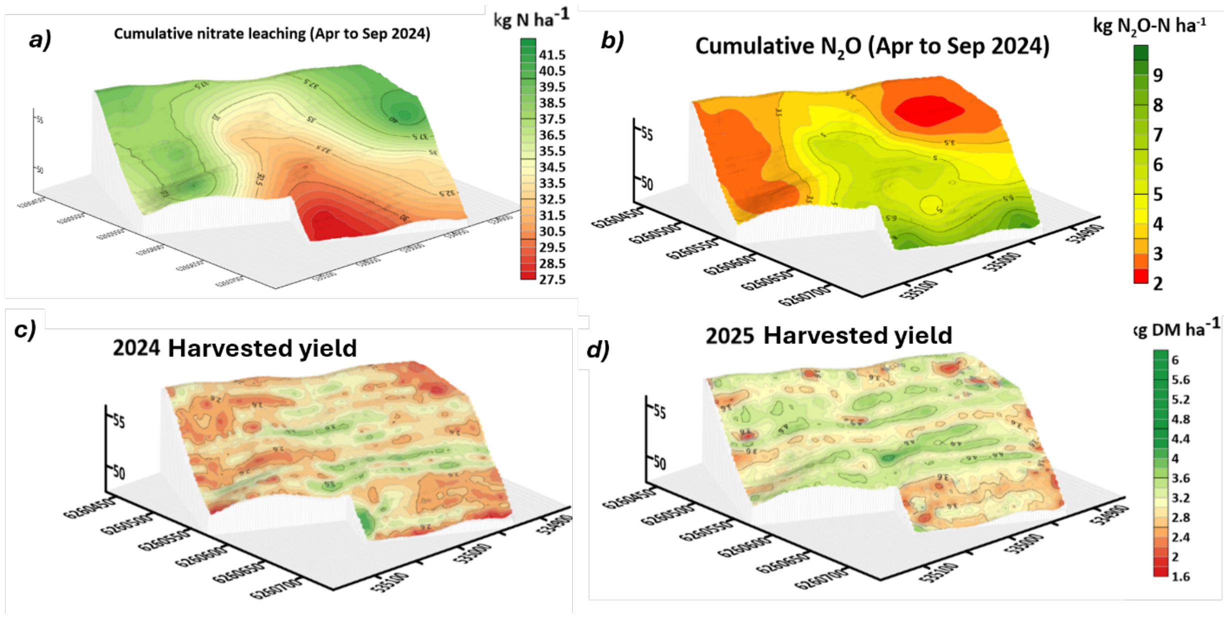

Fig 4. Field#1 maps for (a) Cumulative nitrate leaching for the 2024 growing season, (b) cumulative N2O emissions, and grain yield for (c) the 2024 growing season and (d) 2025 growing season.

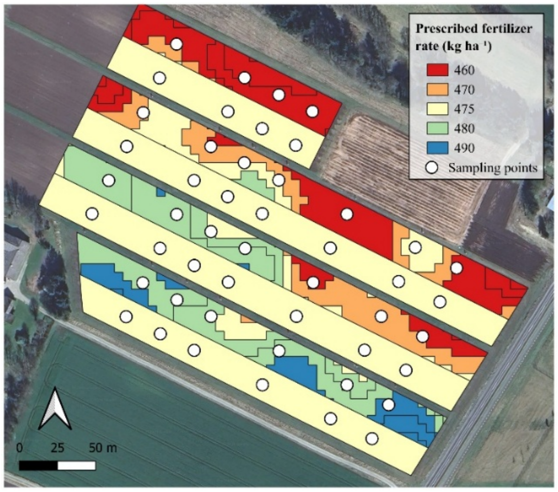

Fig 5. Field#1 maps for the application of fertilization during the 2026 growing season with uniform (yellow strips) fertilization and applied following a commercial approach. The rates refer to the fertilizer which is NPK 21-3-10. The white dots represent the sampling points.

Field 2

In field#2 there was a strong soil variability as highlighted by the EMI survey (Fig 2), and additional lab analysis is undergoing for evaluating texture and organic matter over 100 points selected after the EMI survey. An analysis of the different treatments overlayed on the field showed that at beginning of stem elongation (28 May) the LAI ($p = 0.035$) and chlorophyll content ($p = 0.015$) were significant at 5% (Fig 6). There was a statistically significant covariate for eight variables mostly Chlorophyll, LAI and Stem-N at tillering and flowering.

However, results of this analysis need to be interpreted cautiously because disentangling it from the treatment effect is not straightforward with only 16 plots. This might indicate the presence of a gradient as also noticed in the EMI map and the yield map (Fig 8).

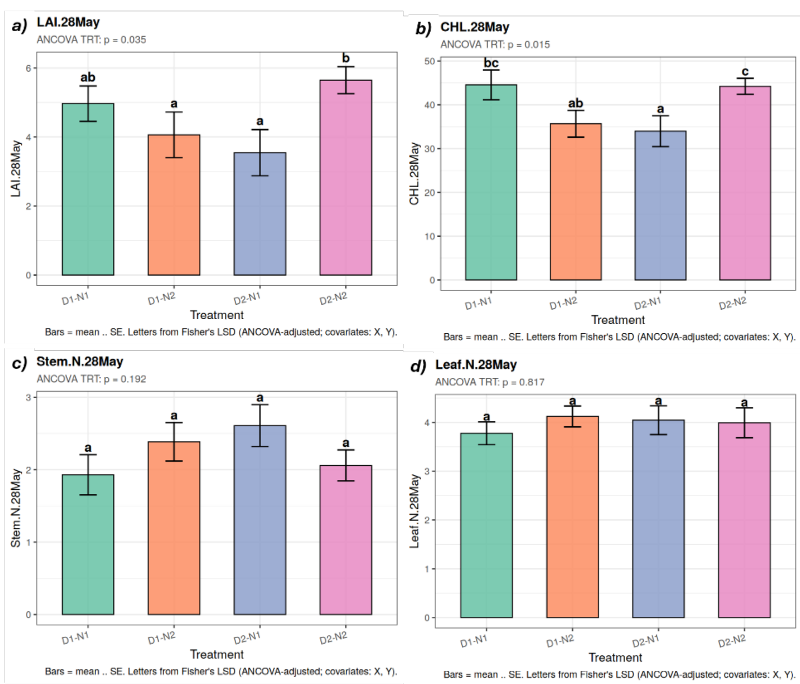

Fig 6. Field#2 analysis of covariance (ANCOVA) for the four different treatments (*D1-N1*: 138 kg seeds ha^{-1} and 110 kg N ha^{-1}; *D1-N2*: 138 kg seeds ha^{-1} and 140 kg N ha^{-1}; *D2-N1*: 204 kg seeds ha^{-1} and 110 kg N ha^{-1}; *D2-N2*: 204 kg seeds ha^{-1} and 140 kg N ha^{-1}) at tillering for (a) LAI, (b) Chlorophyll content from the apogee meter, (c) stem N (d), and leaf N. This result should be interpreted with caution, as the ANCOVA model did not explicitly account for residual spatial variability.

The cumulated N_2O emissions ranged between 1 and 6 kg N-N_2O ha^{-1} during the growing season (Fig 7). There was a spatial pattern of those emissions with the central part of the field showing higher emissions (which is also the area with the low EMI values), and it is interesting to notice that also in the farmer's field the cumulative N_2O emissions were higher as reported in Field#1 and in Petersen et al. (2023).

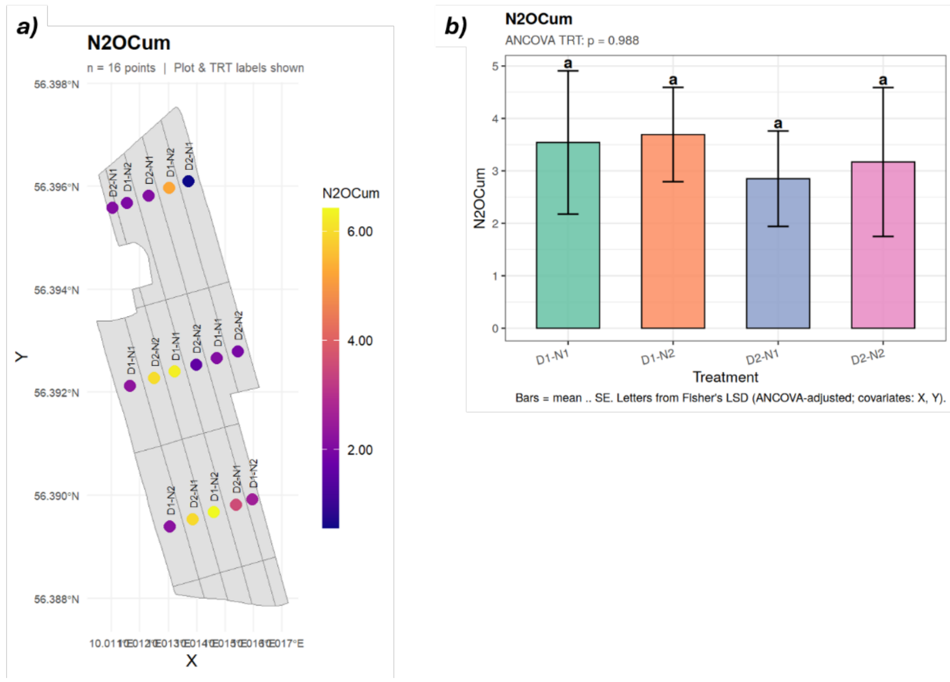

Fig 7. Field#2 maps for (a) cumulative N2O emissions measured from sowing to harvest; and (b) analysis of covariance of the 4 different treatments (*D1-N1*: 138 kg seeds ha^{-1} and 110 kg N ha^{-1}; *D1-N2*: 138 kg seeds ha^{-1} and 140 kg N ha^{-1}; *D2-N1*: 204 kg seeds ha^{-1} and 110 kg N ha^{-1}; *D2-N2*: 204 kg seeds ha^{-1} and 140 kg N ha^{-1}). The boxplot results should be interpreted with caution, as the ANCOVA model did not explicitly account for residual spatial variability

At harvest, the grain yield ranged between 6,000 to 8,000 kg DM ha^{-1} with lower values at the bottom and the top of the field and higher values in the center. From the yield map it is not evident any effect of seeding density and N fertilization. Regarding the fertilization, this was expected because the difference in N application was not so much, as for the plant density, the tillering would have compensated for such difference. Probably, a better effects of the different sowing density on yield would have been possible if different sowing dates were implemented. Data of N leaching from the farmer's field are still not available as the silica disks are being currently analyzed.

Finally, it should be noted that in this particular case, the farmer will not grow spring barley over spring barley but rotations tend to be more complex as before barley the farmer grew winter wheat, canola, winter wheat, barley, and for the 2026 it is pea. Therefore, the results showed here are a preliminary attempt to collaborate and install OFE experiments over the whole 300 ha.

Conclusion

The spatial variability of nitrous oxide emissions and nitrate leaching showed opposite spatial patterns, which means that in order to offset the negative impact of N losses different agronomic actions should be taken within a field. The assumption that controlling N fertilization rate to reduce losses might oversimplify the fact that emissions and leaching might happen at different rates and at different places within an agricultural field. At the same time, the study is highlighting and demonstrating the importance of an establishment of an OFE research, where N losses are also measured within a commercial farm.

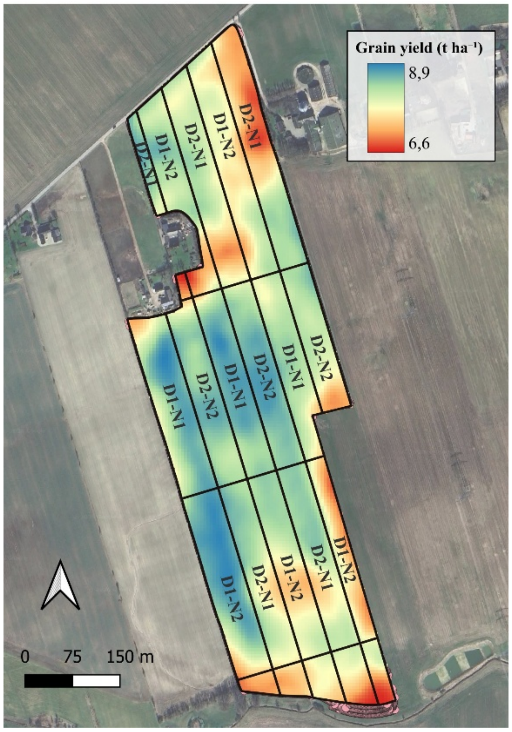

Fig 8. Field#2 Yield map (wet mass) of the 2025 growing season (spring barley); the different treatments are identified by the different rectangles (*D1-N1*: 138 kg seeds ha^{-1} and 110 kg N ha^{-1}; *D1-N2*: 138 kg seeds ha^{-1} and 140 kg N ha^{-1}; *D2-N1*: 204 kg seeds ha^{-1} and 110 kg N ha^{-1}; *D2-N2*: 204 kg seeds ha^{-1} and 140 kg N ha^{-1}).

The study is still ongoing but in the end it aims to: i) a comprehensive and system-based approach to site-specific crop N management to reduce N losses while maintaining harvested yield and crop quality; ii) more frequent and efficient interactions with key stakeholders; iii) better documentation of environmental footprints; iv) enhance interdisciplinary collaboration within and beyond Denmark. The outcomes will achieve a desired change that in the long-term vision (beyond the life of the proposed project) enables farmers and policymakers to use data and modelling tools to support the implementation of farming practices that improve crop production and quality, while reducing environmental and climate impacts.

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