Modelling the decline in protein content in grain from 1990 to 2015

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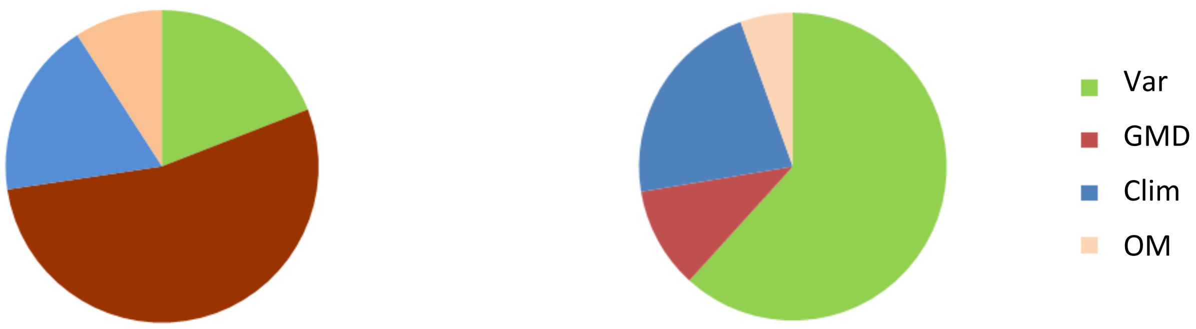
Summary

Main results

The decline in protein content in grain (spring barley and winter wheat) in the period from 1990 to 2015, which has been documented through analyses of samples collected from a range of Danish farms (Poulsen and Sloth, 2016 – Knowledge center for pig production), is caused by a combination of increased dry matter production and less plant available nitrogen. The increased dry matter production is mainly caused by plant breeding and the reduced amount of plant available nitrogen is mainly a result of decreased application via fertilizers/manure. For spring barley, plant breeding is the dominating factor while for winter wheat it is the fertilization level including a decline in deposition of about 6 kg N/ha as well as management changes (Figure 1). In both cases, changes in climate are the third most important factor.

In order to increase the amount of protein in the grain without decreasing the dry matter yield, it is necessary to increase the amount of plant available nitrogen. This can be done by increasing the amount of fertilizer/manure or adding N-fixing crops in the rotation. Other changes are expected to have little effect because the crops already utilize the nitrogen available efficiently, particularly when assessing the full rotation.

The conclusion builds on hundreds of field experiments, thousands of model simulations with different combinations of soil, weather and management, as well as existing literature.



a) Winter wheat, loam

b) Spring barley, loam, mineral fertilizer

Figure 1 Contribution to total change in N % in grain in a) winter wheat (both mineral and organic fertilizer, weighted according to area) and b) spring barley in a rotation receiving mineral fertilizers on a JB7 (sandy loam/loam). The diagrams show how the total change is divided on effects of new varieties (Var), change in fertilization (incl. Management and 6 kg N/ha less deposition (GMD), a slightly higher temperature combined with 10 % mere precipitation (Clim) and little less mineralization due to falling humus content (OM).

The project in general

A considerable amount of the regulation in agriculture and some of the advisory work are based on model analyses. Economic calculations rely on that the model predictions of yield, protein content and leaching are correct. The last 25 years we have seen a decline in protein content in grain which has not adequately been included in such analyses. The overall goal of the project is to improve the understanding and description of such relationships in Daisy to improve the quality of advice given and cost-benefit analyses of measures carried out.

The goals of the project are 1) to investigate whether the decline in protein content observed in Danish grain can be explained on the basis of the existing understanding of processes implemented in the soil-plant-atmosphere-model code ”Daisy” and 2) if that is not the case, investigate the assumptions, process descriptions and parameterization of the model in order to obtain a better description that can be used to evaluate regulative measures. The project builds on existing data on fertilization norms, actual fertilization practices, N-deposition, fertilizer trials in winter wheat and spring barley carried out by SEGES, data from the Danish statistical office (yields, land use), data from the quadrant net as well as information about trends in plant breeding. The period 1990 (1987-1994) was compared to “now”, defined as the growing season 2014-15 (2010-15).

The most important trends in the period can be described as a small increase in the area with winter wheat (18 to 25 %), but a marked increase in the frequency of winter wheat after winter wheat (from 25 to 60 %). About 25 % of the fields with winter wheat after winter wheat received animal manure in 1986-90 while it was 55-70 % between 2000 and 2008. The deposition has fallen with in average 6 kg N/ha and the fertilizer amounts have been markedly reduced, particularly on the sandy soils. At the same time, the N-loss at manure application has been reduced. In parallel, the winter wheat varieties have been adapted to the conditions. The potential production of winter wheat is almost the same throughout the period but the production under limited nitrogen conditions is increased. For spring barley both the potential production and the production under limited nutrition has increased.

In order to calibrate old and new varieties, the fertilizer trials by SEGES were analyzed. For winter wheat, the trials with more than 65 kg N harvested in grain in the unfertilized plots (and trials without N-measurements) were removed from the sample, so the compared experiments had similar levels of mineralization. The best 20 % of these in the periods 1987-1994 and 2010-15 were the basis for calibration of Old and New winter wheat variety, as they were expected to be limited by water and N only. For spring barley the same procedure was tried, but the best 20 % of the trials had a strong bias towards beets as pre-crop and a large part of the experimental areas had received manure earlier. Therefore the whole dataset with less than 65 kg N harvested in the unfertilized plots was used as calibration goal.

Scenario calculations were carried out on the rotation: spring barley – winter wheat – winter rape – winter wheat – winter wheat to see the effect of a pre-crop with short roots and a one that leaves more nitrogen. The fertilization scenarios (mineral and organic) were constructed based on data from the quadrant net for ”1990” including the deposition and expected ammonia loss at the time, and for ”2014” based on the norms established by NaturErhvervsstyrelsen for 2014-5. The simulations were done on soils parameterized as JB4 (loamy sand) with free drainage as well as pipe drained JB6 and 7 (sandy loam, loam) on the basis of the Daisy handbook (Styczen et al. 2005), but with a plough sole just below plough depth. The crop rotation was simulated 100 times with a synthetic rainfall series develop to describe the present climate in eastern Denmark. The data set is described in Rasmussen et al. (2017) and has the statistical characteristics found in our present climate. It allows simulation of long time series and improves the evaluation of uncertainty related to weather compared to a simulation with data from the last 10-15 years. Thus, each simulation include 300 years of winter wheat and 100 years of spring barley. The basis scenario consists of three soil types * two fertilization levels * two fertilization types * [Old and New variety for each of the two crops].

During the calibration phase the description of denitrification was modified. The earlier parameterization was based on measurements but with a different description of the soil profiles (without plough sole). With the present descriptions the denitrification levels became unrealistically high.

The calibration of Old winter wheat variety is based on the earlier winter wheat parameterization in Daisy, which is well tested. However, the root length and root growth rate were adjusted to fit recent research results. The same goes for the N-concentrations in the straw. Furthermore, the development rate in the reproductive phase was reduced. Three organ-specific N-concentrations govern the N-content in the storage organ and other plant parts: C_{nonf}, below which the organ cannot function, C_{crit}, which is the concentration adequate to obtain maximum production and C_{pot}, which is the maximum concentration governing plant uptake. We had expected to be able to read these concentrations for the grain directly from the plots of data from the experiments for the investigated periods, but the values could not be used directly. Loss of dry matter (respiration and loss of leaves) can result in an increase in the concentration of N in the plant material to values greater than the one governing N-uptake ($C_{pot)}$. C_{nonf} turns out to be a concentration that the crop in practice will not reach, because the dry matter production will be limited by N-stress. This means that C_{pot} must be lower than the highest values measured and C_{nonf} must be lower than the lowest measured values.

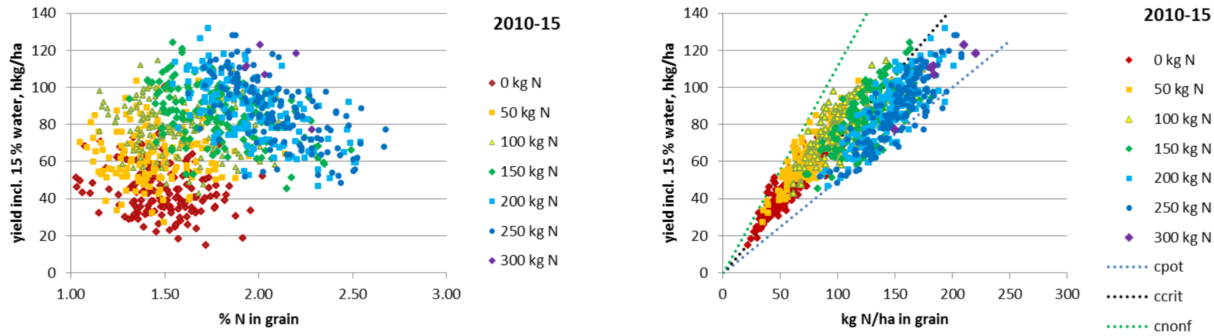


Figure 2. Results from SEGES' fertilizer trials in winter wheat from the period 2010-15. Yields plotted as a function of % N in grain and kg N in grain. The potential, critical and non-functional N-concentration in the figure was estimated based on observations, but could not be used for simulation.

In New winter wheat variety, the harvest index was increased to match research data. This had a marked effect on the amount of harvested N and it was not possible to describe the differences between old and new trials without changing this parameter. As the fertilizer trials by SEGES only include data on yield and N-content in grain at harvest we cannot be sure that the New variety also has a well described biomass production all through the growing season. The harvest index was calibrated by changing the allocation of assimilate to different organs, but it could also have been done by e.g. increasing the loss of leaves during the growing season.

The spring barley model was from the beginning poorer calibrated than the winter wheat model and both Old and New spring barley variety were re-calibrated. The New spring barley variety was calibrated using RVI-data from a 7-year experiment at Højbakkegård as the main source and adjusted to fit the SEGES trials. Old spring barley variety is based on the New variety and was adjusted based on SEGES trials and other sources. The root/shoot-development in the early phase, the development rate in the vegetative and reproductive phases, the description of photosynthetic capacity and the rate of leaf death were changed. The yield and harvest index were adjusted. The nitrate concentrations in leaves and stems were based on earlier Danish parameterizations.

The N-uptake at high N-availability was too high in the simulations and different ways of reducing this uptake were investigated. A reduction of C_{pot} improved results. In addition, a new model for N-uptake through the roots was developed. In both the old and the new root model there are physical limitations on the N-uptake and the ability of the soil to transport N from the soil matrix to the root surface. This transport is largest when the N-concentration at the root surface is 0. In the new model, an plant physiological limitation in the ability of the root to take up N through the surface has been added. This uptake is most efficient when the concentration at the root surface is low. The new model will find the concentration where the transport to the root surface and the uptake through the surface are equal. The implemented equations are documented in the report and published on Daisy's home page. We have limited experience with this new model and it affects the spring barley simulations more than the winter wheat simulations.

The new parameterizations of winter wheat and spring barley reproduce yields, the total N-uptake in grain and the N-% in grain together with most of the variation found in the experimental data.

In addition to the basic scenarios, we have looked at the sensitivity of the changed root parameters and the choice of drainage conditions. Furthermore, the effect of adjusting the rainfall to "Foulum-conditions" (central Jutland) by scaling the monthly rainfall was looked into as well as an increase in temperature of 0.5°C and in rainfall of 10% (based on an analysis of time series from the Danish Meteorological Service for the period 1990-2015). Finally, the effect of a reduction in organic matter in the JB7 (loam)- soils of 20 % and of JB6 (sandy loam)-soils of 10 % with "slow" turnover of the remaining organic matter was investigated.

According to the "Knowledge center for Pig production" (SEGES), the content of raw protein in grain (incl. 15 % water) has dropped by 2-2.5 % in the period 1990-2015. The interval is equal to 2.4-2.9 % raw protein in dry matter. Based on the scenario calculations for the three soil types and the changes in growing conditions for winter wheat it was estimated how much of the reduction in protein content can be explained due to change in variety, change in fertilization and management, change in weather and change in background mineralization. The total effects on JB4, JB6 and JB7 sum up to reductions of 0.40, 0.34 and 0.33 % N in dry matter, respectively or 2.5, 2.1 and 2.1 % raw protein in dry matter (factor 6.25) from Old Variety under 1990-conditions to New Variety under 2014-conditions. The effect of the variety makes up 14-19 %, the difference in fertilization, management and deposition makes up 53-70 %, the difference in weather accounts for approximately 14-18 % and the difference in background mineralization on JB7 accounts for approximately 9 %. It is not clear to which extent the winter wheat has been pushed towards more sandy soils, but there is also a negative effect on the protein content of changing soil type from JB6 to JB4 (0.036 % N or 0.2 % raw protein), and simulations with "Foulum weather" gave an additional negative correction (0.07 % N or 0.4 % raw protein) because the higher precipitation during winter led to higher leaching and denitrification. Thus, most of the observed decline in N % in grain for winter wheat could be explained by the calculations. The change in background mineralization may, however, be underestimated by the simple crop rotation used in the comparison.

The calculations for spring barley only contain one pre-crop and the soil types do not cover the range of conditions of relevance for spring barley. Therefore we cannot make a consolidated estimate as was done for winter wheat. If we only analyze the differences between Old variety with 1990-fertilizer and management and New variety with 2014-fertilizer and management (mineral vs. mineral and organic vs. organic), the decline in raw protein in dry matter is 1.9-2.1 on JB4, 1.9-2.6 on JB6 and 1.7-2.4 on JB7, incl. the correction for less mineralization. A correction for warmer and wetter weather of 0.5 % can be added to these values, resulting in the final intervals for the decline in raw protein of 2.2-3.1 %. Thus, the observed decline in raw protein can be explained by the simulations. For barley, the change in variety makes up 39-62 % of the decline, highest on JB7 and lowest on JB4. The change in fertilization and management (and deposition) only makes up 11 % of the change on JB7-soils receiving mineral fertilizer and from 23-42 % of the change in the other combinations. The change to warmer and wetter weather makes up 21-22 % of the effect in scenarios receiving mineral fertilizer and 16-19 % in scenarios with organic fertilizer. The decline in background mineralization can explain 4 % of the change on the JB7-soil.

Finally, scenario calculations were carried out in order to investigate whether simple changes in management could increase the N-% in grain. The use of (unfertilized) peas instead of spring barley gave a positive effect on the following winter wheat in most combinations, but not necessarily on JB7, which has the highest N-fertilizer norm for spring barley. The higher pre-crop effect which must be deducted from the norm will, however, remove most of this positive effect. Introduction of a stronger (non-N-fixating) catch crop had in some cases a small positive effect on the N-uptake in the spring barley after the catch crop, but it did not affect the wheat in the crop rotation. Early sowing of winter wheat resulted in higher yields and N-uptake, but at the rather low fertilization level in 2014, the end result was a marked reduction in the N-% in grain. The leaching fell by 30-40 kg N over the 5 year rotation (6-8 kg N/year). Use of pure ammonia fertilizer also resulted in slightly larger yields and in most scenarios also in slightly larger N-uptake. The concentration of N in grain was positive in one and negative in two of the occurrences of wheat in the rotation as well as for the spring barley, and the variation in the results within each scenario increased. A scenario with cattle manure instead of pig manure did not give a positive result either. However, it should be noted that the calculations are made so there is no long-term increase in the organic pools in the soil, which could change the picture in the long term. The effect of high organic matter content is clear in a scenario where the content of humus has been increased to match the 95-percentile humus content for each soil type. That resulted in higher yields, considerably higher N-uptake and an increase in N-% of 0.2-0.3 (1.3-1.9 % raw protein in dry matter), but also higher leaching. The conclusion is that with these very strict fertilizer norms, it is only increased N-addition in the form of fertilizer, N-fixation or increased mineralization that can increase the N-concentration in grain.

In addition, a scenario was run where 40 kg N of the N-quota for winter wheat was added on 15th of May. Experience shows that it is possible to increase the N-% in grain by late application, but this was not the case in the simulation. This is expected to be an artefact of the limitations implemented on the N-uptake of "New variety". The slower uptake means that the late application does not benefit the plant in the simulation. With this parameterization, the model is, thus, not able to simulate the effect of late N-fertilization realistically. There are two possibilities of improving this in the future. A detailed calibration of the N-uptake over time on the basis of detailed measurements of the N-content in the different parts of the plant should be made, and in addition there is a need to investigate whether the description of the N-demand in the reproductive phase can be improved. At the moment, the N-uptake is primarily regulated via the root processes and the general growth of the plant and that may not be detailed enough.

For the other measures investigated, we judge the calculations to provide a correct picture. We conclude that the project has succeeded in reproducing the observed changes in protein content and pointing out their courses, as well as in identifying areas of the model parameterization and descriptions that modelers must be aware of when using the Daisy model for environmental assessments in the future.