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# Nitrogen management in crop rotations after the break-up of grassland: Insights from modelling

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ABSTRACT

Currently there is a shift from grassland based forage production towards maize systems in the Low Countries of north-west Europe. Breaking-up grassland and turning it into arable fields is associated with high nitrate leaching. Crop models can help to identify cropping strategies to reduce nitrate leaching by performing long-term simulation experiments. This study aimed: (i) to evaluate the crop model APSIM against field trial data, in particular nitrogen (N) balance components N-uptake, leaching and soil mineral N, and (ii) conduct a simulation experiment for assessing suitable management practices over a long period using historical records (1980–2015).

Evaluation data consisted of two rotation types over two years (maize-maize and barley-mustard-maize) with two nitrogen (N) fertilizer schemes (zero and standard fertilizer: 160 for maize and 120 kg N/ha for barley) after the break-up of grassland. Experiments were carried out at three different sites with contrasting soils in north-west Germany. Results showed that APSIM was capable of simulating the crop rotations and fertilizer applications satisfactorily: Total biomass (n = 21) was reproduced with a root mean square error (RMSE) of 1139 kg/ha against an observed mean of 9915 kg/ha across crops. Total N uptake (n = 21) was simulated well with a RMSE of 22 kg/ha (against observed mean 144 kg/ha). Simulated soil mineral N in the top 0–30 cm (n = 253) and 0–90 cm (n = 33) showed a high index of agreement (IA) of 0.90 and 0.86, respectively. Comparisons observed vs simulated over time confirmed that APSIM was able to capture the N dynamics in the soil. Extractable soil water was also modelled well. Leached nitrate (n = 16) was simulated with a RMSE of 50 kg N/ha, whereby APSIM captured the high nitrate losses of up to 240 kg N/ha/winter period caused by the high mineralization and the fertilization. In the long-term the simulation experiment showed that fertilization of maize did not result in additional biomass, but in higher leaching losses. Mustard was effective in reducing nitrate leaching but is difficult to implement in practice. Finally, the study demonstrated that crop modelling complements conventional analysis very well in identifying environmentally sound and profitable management practices for complex situations in soil-crop systems such as grassland break-up.

## 1. Introduction

Agricultural production in the north-west of Germany is characterised by an intensive livestock production and regionally large nutrient surpluses (Sachverständigenrat für Umweltfragen, 2015). There is an on-going trend towards further intensification and larger farms along with an increasing biogas production based on maize (Offermann et al., 2016; Reheul et al., 2017). Grassland and arable land that has been used for grain is often changed to silage maize; in some areas maize is exceeding more than 50–60% of the total agricultural land (Statistisches Bundesamt, 2017). The break-up of permanent grassland typically leads to increased mineralisation from soil organic matter and plant residues with the risk of nitrogen (N) and carbon (C) emissions to the atmosphere and loss of N to the groundwater (Djurhuus and Olsen, 1997; Eriksen, 2001; Poeplau et al., 2011; Seidel et al., 2009) especially when farmers apply additional organic and/or mineral fertilizer. In this region, nitrate concentration exceeds the threshold of 50 mg of $NO_3$/l in some wells and often in leaching water (Umweltministerium Niedersachsen, 2016). Therefore, policy interventions have been implemented to reduce the related release of greenhouse gases and nitrate leaching (BMEL, 2017). That, in turn, has resulted in the need to develop sound management strategies in order to reduce N losses related to maize cultivation after conversion of grassland – including the choice of other crops and adjusted fertilizer

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management.

Against this background, Kayser et al. (2008) conducted a field trial at three sites comparing maize as a follow-up crop with a barley-mustard-maize rotation under zero and high N fertilizer input in the years 2003–2004. While production was only marginally increased by fertilization, nitrate leaching in winter was significantly higher when N was applied. Trials like these are an important step forward in understanding the N dynamics in such systems. However, field trial results are constrained by two points: firstly, not all variables of interest can be measured because of high costs and time requirements; secondly, measurements of variables like N leaching typically entail high uncertainty due to underlying assumptions made for the actual measurement (see also Wolf et al., 2005). In the case of Kayser et al. (2008), for instance, the used method (suction cups) made it very difficult if not impossible to measure nitrate leaching during the vegetation period. Furthermore, results are to some extent restricted to the prevailing weather and soil conditions during the trials. Especially, the year 2003 was exceptional and characterized by a severe long lasting drought and high air temperatures during summer (Ciais et al., 2005), demonstrating that extrapolating the measured results would not be representative for a longer series of years. Process-based eco-physiological modelling has become a common tool to investigate the inherent systematic connections of factors relevant for production by providing information on a range of variables (many of which are not measured) and to extrapolate crop management practices in time by running the models over a longer period. The Agricultural Production System Simulator (APSIM) has, for instance, been used to simulate nitrate leaching in sugar cane (Thorburn et al., 2010). Relevant to our experiments have been simulations by ANIMO for grassland-crop rotations in the Netherlands (Wolf et al., 2005) and DAISY for maize-winter wheat in China (Manevski et al., 2016). However, such detailed evaluations for nitrate leaching as presented in those studies are very rare in the literature. Moreover, recent model intercomparison studies in Europe showed that most models have considerable difficulties in simulating crop rotations and N dynamics (Kollas et al., 2015; Salo et al., 2016; Yin et al., 2017a, 2017b). Hence, there is an urgent need to further evaluate the models comprehensively for N dynamics. Having this in mind, our study aimed to (i) parameterize and evaluate the APSIM model for the field trials presented by Kayser et al. (2008), which provide detailed measurements of N dynamics in the soil, plant N uptake, and nitrate leaching, and (ii) apply the evaluated model to extrapolate the effects of fertilizer rate and crop rotation on biomass production, N uptake and nitrate leaching in the winter as well as in the vegetation period over a longer term period (i.e. 1980–2015).

## 2. Material & methods

### 2.1. Site conditions & experimental data

Data for model evaluation was derived from the Kayser et al. (2008) experiment conducted at three sites in the district of Cloppenburg in north-west Germany. The climate of the region is characterised as maritime. Long-term average annual temperature in this region is 9.6 °C and the average annual precipitation 776 mm (Table 1).

We briefly describe the three sites and the design of the experiment and refer to Kayser et al. (2008) for more detailed information. The three soils selected for the experiment differed in their properties (Table 2; Suppl. Material: Table 1): Site one (Dwergte I) is a sandy loam in the top layer (> 60% sand) with an organic carbon content of 1.9%. This soil type called plaggen (Plaggic Anthrosol) is a result of incorporation of large amounts of organic matter by farmers over centuries. Despite its sandy texture this soil type has good plant available water capacity and nutrient retention (Blume and Leinweber, 2004). Below the 110 cm depth in the soil profile there is a sharp decline in the organic carbon content. Site two (Dwergte II) has a high organic carbon (2.0-2.9%) and a sand content of 77–79% up to 60–70 cm depth, below it becomes a pure sand (sand content > 96%) with very low levels of soil organic carbon (0.1%). Finally, site three (Augustendorf) is a gleyic podzol with a degraded peat layer at the top (Table 2 & Suppl. Material: Table 1). Dwergte I has been used as grassland for at least 13 years, Dwergte II and Augustendorf even for more than 15 years before the experiment started. All three experimental sites had no slope and were on flat areas.

The experiment was designed to compare maize-maize with spring barley-mustard-maize rotation for two years (2003–2004) under zero and high fertilization after break-up of the permanent grassland swards. There were 36 plots (4 treatments per site x 3 sites x 3 replicates) with a size of 96 $m^2$ each. The grassland on the three sites were ploughed in spring 2003 after the swards had been treated by a total herbicide (Glyphosate) followed by rotary tillage.

Spring barley (*Hordeum vulgare* L. cv Orthega) was sown on 28 March or 3 April 2003. After barley was harvested, yellow mustard (*Sinapis alba* L.) was sown as a catch crop in mid-August on the site Augustendorf and at the beginning of September on the sites Dwergte I and II. In the first year, maize (*Zea mays* L. cv Banguy) was sown on 25 April or 6 May. In the second year, maize was planted in all plots on 21 April 2004. Plots were fertilized with P and K to prevent nutrient limitations other than N and plots were kept weed free. Due to the relatively low pH values of the plots, lime was applied at a rate of 1000 kg CaO/ha in mid-April 2003. The plots were either not fertilized with N or N fertilizer was applied in mineral form as calcium ammonium nitrate. The synthetic N fertilizer (CAN) was applied by hand for each plot and mixed with the top soil by raking or harrowing using a tractor, tillage depth would usually be 5–10 cm. For the barley plots, N fertilization amounted to 120 kg N/ha (80 kg N at the time of sowing and 40 kg N/ha at 5 May) and for the maize plots 160 kg N/ha (120 kg N at time of sowing and 40 kg N/ha in early June). This practice reflects current standard fertilizer rates applied by farmers in the region.

To determine the N uptake biomass yields of the plots were recorded. Sampling area was 24 $m^2$ for barley and 15 $m^2$ for maize. In case of barley, samples of grain and straw were taken for dry matter and nutrient analysis, and for maize, samples of the harvested whole-plant (above stubble) were used. All samples were dried at 60°C and the N content determined using macro-N analysis according to Dumas. Nitrate leaching was investigated using a permanent vacuum-controlled suction cup system installed at Dwergte I and II. At a depth of 75 cm four suction cups in each plot were installed to collect leaching water. Samples for laboratory analysis were collected from each suction cup weekly or fortnightly. Nitrate was determined photometrically and nitrate leaching losses were calculated as a product of the nitrate

**Table 1**
Long-term average climate conditions for the region represented by the weather station Großenkneten (1980–2015).Precipitation is average monthly sum, solar radiation, max and min temperature is monthly average of the daily value.

| Parameter | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Precipitation (mm/month) | 71 | 48 | 58 | 44 | 56 | 73 | 79 | 72 | 66 | 68 | 66 | 76 | 776 |
| Max temperature (°C) | 4.1 | 4.8 | 8.8 | 13.6 | 17.8 | 20.2 | 22.8 | 22.5 | 18.5 | 13.5 | 8.0 | 4.8 | 13.3 |
| Min temperature (°C) | −0.8 | −0.9 | 1.2 | 3.6 | 7.4 | 10.1 | 12.3 | 12.0 | 9.3 | 6.1 | 2.7 | 0.3 | 5.3 |
| Solar radiation (MJ/m2) | 2.1 | 4.4 | 8.2 | 13.8 | 17.5 | 17.9 | 17.6 | 15.0 | 9.9 | 5.7 | 2.6 | 1.6 | 9.7 |