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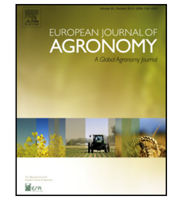

Effect of temperature and precipitation on nitrate leaching from organic cereal cropping systems in Denmark

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ABSTRACT

The effect of variation in seasonal temperature and precipitation on soil water nitrate (NO_3—N) concentration and leaching from winter and spring cereals cropping systems was investigated over three consecutive four-year crop rotation cycles from 1997 to 2008 in an organic farming crop rotation experiment in Denmark. Three experimental sites, varying in climate and soil type from coarse sand to sandy loam, were investigated. The experiment included experimental treatments with different rotations, manure rate and cover crop, and soil nitrate concentrations was monitored using suction cups. The effects of climate, soil and management were examined in a linear mixed model, and only parameters with significant effect ($P < 0.05$) were included in the final model. The model explained 61% and 47% of the variation in the square root transform of flow-weighted annual NO_3—N concentration for winter and spring cereals, respectively, and 68% and 77% of the variation in the square root transform of annual NO_3—N leaching for winter and spring cereals, respectively. Nitrate concentration and leaching were shown to be site specific and driven by climatic factors and crop management. There were significant effects on annual N concentration and NO_3—N leaching of location, rotation, previous crop and crop cover during autumn and winter. The relative effects of temperature and precipitation differed between seasons and cropping systems. A sensitivity analysis revealed that the predicted N concentration and leaching increased with increases in temperature and precipitation.

1. Introduction

In Europe, and specifically in Denmark, agriculture is generally considered as the main source of nitrate leaching to ground and surface waters (Askegaard et al., 2005). The loss of nitrogen (N) to aquifers and surface waters is an inevitable consequence of intensively managed agricultural systems due to the use of N fertilizers (Hansen et al., 2000a; Nielsen et al., 2012) and soil cultivation (Askegaard et al., 2011). In Denmark, agriculture accounted for approximately 81% of the N load to Danish watercourses and about 70% of the N inputs to the sea via water courses and atmospheric deposition during 1989–1996 (Hansen et al., 2000a). However, the nitrate leaching from agriculture in Denmark has been substantially reduced through governmental regulations setting standards for rates of manure and fertilizer application, use of catch crops (Kronvang et al., 2008) and encouraging additional measures such as organic farming (Askegaard et al., 2005). However, despite the decrease in N concentrations observed in surface water (Jeppesen et al., 2011) further reductions in N leaching are needed to achieve the goals of good ecological status of the aquatic environment as required by the EU Water Framework Directive.

Understanding the potential impacts of climate change on crop productivity, the hydrological and N cycles and fluxes is essential for ensuring food security and guaranteeing the sustainability of future water resources. Such impacts are well recognized and have been widely reported over the recent decades (Ritcey and Wu, 1999; Olesen et al., 2000a; Orlandini et al., 2008; Bindi and Olesen, 2011; Hatfield and Singer, 2011; Tao and Zhang, 2011; Trnka et al., 2011). Changes in the mean and variability of temperature and rainfall patterns have direct effects on crop yields. Changes in atmospheric CO_2 concentration and indirect effects through changes of the hydrological cycle also affect yields as well as biological and chemical transformations of carbon (C) and N in

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soils with associated leaching or gaseous losses of N (Allen and Ingram, 2002; Olesen et al., 2011). As the flux of soil mineral N is largely influenced by precipitation events the risk of N losses through leaching, and possibly N_2O emissions, may increase with increased precipitation. Increased N leaching during winter and early spring might also reduce N availability to the succeeding crop. Furthermore, the rate of soil organic matter (SOM) mineralization, which depends on the nature and abundance of SOM and on soil temperature, moisture and microbial activity, is expected to increase with increasing temperature (Thomsen et al., 2010; Contosta et al., 2011). Decomposition of SOM will lead to the build-up of inorganic N in the soil, resulting in an increased risk of nitrate (NO_3—N) leaching (Olesen et al., 2004; Thomsen et al., 2010) and a decrease in SOM, which in turn can reduce soil fertility affecting crop yields and N cycling. It is therefore critical to understand how soil N cycling and losses may be affected by climate change.

Several studies have addressed the potential effects of climate change on N leaching. Most of these studies are model based. For instance, Olesen et al. (2007a) modelled the impact of climate change on winter wheat yield and nitrate leaching by applying different impact models at site, regional and continental scales under a range of climate change scenarios. They projected a spatial pattern of changes in nitrate leaching over Europe for the period 2071–2100 showing a patchy variation indicating that local factors could be affecting N leaching under climate change. Furthermore, Patil et al. (2012) used the FASSET model to evaluate the sensitivity of winter wheat yield and soil N losses to stepwise changes in means and variances of climatic variables in Denmark. They showed an increase in N leaching from winter wheat with increasing temperature, in particular for sandy loam soil at temperature increases of above 2 °C. They also found higher simulated soil mineral N concentrations at crop harvest in summer at higher temperatures and, therefore, higher risk of NO_3—N leaching during autumn and winter, which was ascribed to less crop N uptake and increased mineralization of soil organic matter.

In 1997, an organic arable crop rotation experiment was initiated at three locations in Denmark (Olesen et al., 2000b). The experimental treatments, the applied crop management, and the three experimental locations reflect well the range of arable organic farming systems as well as the range of soil types and climatic variation in Denmark. In the 1st four-year cycle of the rotations, Askegaard et al. (2005) showed significant effects of location (soil types and climate) and catch crops and no effect of crop rotation design and manure application on N leaching. After three consecutive four-year crop rotations cycles, Askegaard et al. (2011) identified autumn crop and soil management as the main determinant of N leaching, since surplus rainfall during autumn and winter causes soil mineral N to leach, and the concentration of soil mineral N will to a large extent be determined by plant uptake during autumn. In these two studies, the possible effects of the climatic factors on N leaching were not explicitly investigated. Therefore, we used data from this long-term crop rotation experiment to analyze the effect of the seasonal change in the climate variables (i.e. air temperature and precipitation) on NO_3—N leaching and concentration in winter and spring cereals.

We hypothesize that higher air temperature will increase the risk of N leaching through increased soil N mineralization of soil organic matter and crop residues leading to higher soil mineral N. As the flux of nitrate N out of the root zone is largely influenced by the difference between precipitation and evapotranspiration, we further hypothesize that NO_3—N leaching will increase with increasing autumn and winter precipitation. The objective of our study was therefore (i) to estimate the effect of air temperature and precipitation on NO_3—N concentrations and leaching from cultivation of winter and spring cereals grown in the long-term organic farming experiment, and (ii) to assess how N leaching and N concentration from cereal cropping systems in Denmark will respond to changes in temperature and precipitation using the developed empirical models.

2. Materials and methods

2.1. Experimental sites

This study used data from a long-term organic farming crop rotation experiment that included three treatment factors and three consecutive four-year crop rotation cycles from 1997 to 2008. The experiment is described in detail by Olesen et al. (2000b) and Askegaard et al. (2011); therefore, only a brief outline will be given here. The experiment was conducted at three locations representing different soil types and climate in Denmark (Olesen et al., 2000b). Jyndevad (54°54′N, 9°08′E) is located in southern Jutland on coarse sand, Foulum (56°30′N, 9°34′E) is located in Central Jutland on loamy sand, and Flakkebjerg (55°19′N, 11°23′E) in Western Zealand on sandy loam. Prior to the initiation of the experiment, in autumn 1996, a characterization of the soil at the experimental sites was conducted. Sixteen soil samples were randomly taken in each plot to 1 m depth to determine soil texture and organic matter content. The depth of the A horizon was determined as an average of 16 soil cores for each plot (Djurhuus and Olesen, 2000). Site details are given in Table 1. The content of topsoil SOM was least at Flakkebjerg despite the higher clay content, presumably as a result of previous decades of intensive arable crop cultivation with little organic inputs. The plant available soil water was 7.6, 19.3 and 14.2% (v/v) in the upper 1 m of the soil profile for Jyndevad, Foulum and Flakkebjerg, respectively (Askegaard et al., 2005). The larger clay content may have caused deeper rooting at Flakkebjerg and thus larger total effective capacities for plant-available water. There were no marked slopes or other elevation effects at Jyndevad, whereas the elevation varied about 3 m and 8 m across the site at Foulum and Flakkebjerg, respectively.

2.2. Experimental treatments

Three experimental factors were included in a factorial design: (1) crop rotation with proportion of grass–clover and pulses (pea (*Pisum sativum* L.), lupin (*Lupinus angustifolius* L.) or faba bean (*Vicia faba* L.)) in the rotation, (2) with (+CC) and without (−CC) catch crop, and (3) with (+M) and without (−M) animal manure applied as slurry. At each location the experiment had two replicates laid out in two separate blocks. Each block was further subdivided into two sub-blocks to better cover soil variation (Askegaard et al., 2005). At each location, all courses in each rotation were represented every year. The experimental plots were randomized within sub-blocks and were managed individually when necessary.

The three 4-year crop rotations (R1, R2 and R4) are shown in Table 2. These rotations differed in the use of a grass-clover green manure, which was present in rotations R1 and R2, but not in R4. Rotation R4 was not initially included at Jyndevad, because the coarse sandy soil was considered unsuitable for organic arable rotations without green manures. However, in 2005 changes were made to the experimental treatments, and the R1 rotation at Jyndevad was converted to an R4 rotation.

Ploughing before sowing of spring cereals was mostly carried out in spring at Jyndevad and Foulum and in November to December at Flakkebjerg. The grass-clover was spring-ploughed in R1 and followed by spring wheat (*Triticum aestivum* L.), and autumn-ploughed in R2, and followed by winter wheat in the two first cycles. In the 3rd cycle, the grass-clover was spring-ploughed at Jyndevad and Foulum, and autumn ploughed at Flakkebjerg prior to growing potato (*Solanum tuberosum* L.). Where present, catch crops