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Nitrate leaching from organic arable crop rotations is mostly determined by autumn field management

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ABSTRACT

Two main challenges facing organic arable farming are the supply of nitrogen (N) to the crop and the control of perennial weeds. Nitrate leaching from different organic arable crop rotations was investigated over three consecutive four-year crop rotations in a field experiment at three locations in Denmark (12 years in total). The experimental treatments were: (i) crop rotation, (ii) catch crop and (iii) animal manure. Nitrate leaching was estimated from measured soil nitrate concentration in ceramic suction cells and modelled drainage. There were significant effects on annual N leaching of location (coarse sand > loamy sand > sandy loam) and catch crops (without > with). Including a grass-clover green manure on 25% of the area did not increase N leaching compared with crop rotations without green manure. Also the application of animal manure did not influence N leaching, probably because even in the manured treatments the application rate was lower than crop demand. The results identify management of crop and soil during autumn as the main determinant of N leaching. Nitrate leaching was lowest for a catch crop soil cover during autumn and winter (avg. 20 kg N ha^{-1}), a soil cover of weeds/volunteers had on avg. 30 kg N ha^{-1}, and the largest N leaching losses were found after stubble cultivation (avg. 55 kg N ha^{-1}). The N leaching losses increased with increasing number of autumn soil cultivations.

1. Introduction

Organic arable farming in Northern Europe currently faces two main challenges. The first is to provide the crops with sufficient amounts of nitrogen (N) (Berry et al., 2002; Olesen et al., 2007, 2009), and the second is to manage and control weeds (Stockdale et al., 2001), especially perennial weeds that constitute a major problem in Denmark. The ban on pesticide use in organic farming means that the weed control relies on competitive crops and on mechanical weeding.

The key N source in organic arable farming is symbiotic N_2 fixation in leguminous green manure, pulses and catch crops. Many organic arable farms also rely on import of animal manure, and in Denmark they are currently allowed to import up to 70 kg total-N ha^{-1} in animal manure of conventional origin per year. However, from 2015 this import may be gradually restricted with a total stop in 2021, which puts additional pressure on optimising N utilisation and reducing N losses (Alrøe and Halberg, 2008). A potential major loss of N from cropping systems is the leaching of nitrate-N (Knudsen et al., 2006). Besides constituting a loss of an important nutrition source from the root zone, nitrate leaching (N leaching) is a major cause of eutrophication of surface water bodies, particularly so under the climatic conditions in NW Europe with relative mild winters and excess rainfall in the autumn/winter period (Kronvang et al., 2005).

The amount of N leaching depends on several factors with soil and crop type being the major ones (Simmelsgaard, 1998). In crop rotations with legume-based leys or green manure, the largest N leaching losses take place in the autumn/winters following the ploughing of the sward (Stopes et al., 2002; Eriksen et al., 2004). The mineralization of N in crop residues, animal manure and soil organic matter (SOM) continues after crop harvest during autumn and mild winter periods, and significant amounts of N can be leached if the soil is left uncropped, especially from sandy soils with low water-holding capacity (Simmelsgaard, 1998). The inclusion of catch crops (cover crops) in crop rotations is a management tool that due to the prolonged soil cover and effective uptake of soil N deals with this temporal challenge (Thorup-Kristensen et al., 2003; Macdonald et al., 2005). Mechanical cultivation to control

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Table 1
Structure of the crop rotations.

Crop rotations		O1			O2			O4		
Cycles	Field no.	Crop	M[a]	CC[b]	Crop	M[a]	CC[b]	Crop	M[a]	CC[b]
1st cycle	1	S. barley:ley	50		S. barley:ley	50		Spring oat	40	+[e]
1997–2000	2	Grass–clover	0		Grass–clover	0		Winter wheat	70	+[e]
	3	Spring wheat	50	+[c]	Winter wheat	50	+[c]	Winter cereal	70	+[e]
	4	Lupin	0	+[d]	Peas/barley	0	+[d]	Peas/barley	0	+[d]
2nd cycle	1	S. barley:ley	50		S. barley:ley	50		Winter wheat	50	+[d]
2001–2004	2	Grass–clover	0		Grass–clover	0		Spring oat	50	+[d]
	3	Spring oat	30	+[c]	Winter cereal	50	+[c]	S. barley	50	+[c]
	4	Peas/barley	0	+[d]	Lupin	0	+[d]	Lupin	0	
Locations		JY			JY, FO, FL			FO, FL		
3rd cycle	1	Discontinued			S. barley:ley	60		S. barley	60	+[d]
2005–2008	2				Grass–clover	0		Faba bean	0	+[d]
	3				Potato	110	+[d]	Potato	110	
	4				Winter wheat	110		Winter wheat	110	+[d]
Locations					JY, FO, FL			JY, FO, FL		

[a] M: manure application target rates in +M treatments. Unit: kg NH_4-N ha^{-1} in 1st and 2 cycle and kg total-N ha^{-1} in 3rd cycle.
[b] CC: crops succeeded by catch crops in +CC treatments.
[c] Monocultures or mixtures of non-N_2-fixing catch crop.
[d] Mixtures of N_2-fixing and non-N_2-fixing catch crop.
[e] White clover.

perennial weeds after crop harvest in the autumn often precludes an effective use of catch crops and thus leaves the soil exposed to N leaching.

In 1997 an organic arable crop rotation experiment was initiated at three locations in Denmark (Olesen et al., 2000). Studies of N leaching in the 1st four-year cycle of the rotations showed significant effects of soil type and catch crops and no effect of crop rotation design and manure application (Askegaard et al., 2005). After 12 years with three four-year cycles the crop rotation experiment provides sufficient data for a comprehensive analysis of N leaching as affected by crop rotation, animal manure and catch crop. The crop management in the experiment was adapted over the duration of the experiment to deal with changes in local problems, in particular with respect to need for weed control. The experimental treatments in combination with the applied management reflects the range of arable organic farming systems in Denmark, and further the three locations cover the range of soil types and climatic variation in Denmark. The data from this experiment therefore offers an opportunity to analyse what the main determining factors are for N leaching from organic arable systems.

We hypothesized that the input of carbon and N in grass-clover green manures and catch crops would increase SOM as indicated by Schjønning et al. (2007) and that this over time would increase N leaching. We further hypothesized that management of the non-vegetated period in autumn and winter would affect N leaching. The objective of the study was thus to estimate the effect of both N input and crop and soil management on N leaching in typical organic arable cropping systems in Denmark.

2. Materials and methods

This study used data from a field experiment established at three locations in Denmark with different soil types and climate. Jyndevad is located in Southern Jutland on coarse sand (Orthic Haplohumod), Foulum is located in Central Jutland on loamy sand (Typic Hapludult) and Flakkebjerg is located in Western Zealand on sandy loam (Typic Agrudalf). The clay content of the 0–25 cm topsoil at the three locations was 4.5, 8.8 and 15.5%, respectively. A detailed characterisation of the locations is presented in Djurhuus and Olesen (2000).

2.1. Experiment treatments and crop management

The N leaching measurements were carried out in an organic crop rotation experiment with three treatment factors in a factorial design. The experimental treatment factors until 2005 were: (1) proportion of grass-clover and pulse crops in the crop rotation, (2) with (+CC) and without (−CC) a catch crop, and (3) with (+M) and without (−M) animal manure. The factorial combination of these factors were maintained during the entire 12-year period from 1997 to 2008. However, from 2005 the −CC/−M combination was excluded, because this treatment combination over time led to a fertility level that was unrealistically low for practical farming. Several other changes in the crop rotations and their management were made in 2005 to reflect also arable crop rotations that include row crops (potato in this case). The crop rotations were also adjusted to have the same rotations at all locations. The changes made in 2005 did not affect the principal differences between experimental treatment factors.

Until 2005, three 4-year crop rotations were compared (Table 1). These rotations differed in the use of a grass-clover green manure, which was included in crop rotations O1 and O2, but not in O4. The crop rotations O1 and O2 were tested at Jyndevad, and O2 and O4 were tested at Foulum and Flakkebjerg. Rotation O4 was not included at Jyndevad, because the coarse sandy soil was considered unsuitable for organic arable rotations without green manures. However, from 2005 onwards, crop rotation O1 was converted to O4, whereas the other treatments were maintained. Crop rotation O2 was maintained at all three locations throughout the experiment.

All fields/crops in all crop rotations were represented every year in two replicates, giving a total of 64 plots at each location in the 1st and 2nd cycles (2 crop rotations per location × 4 crops per rotation × 4 manure/catch crop treatments (+M/−CC; +M/+CC; −M/+CC; −M/−CC) × 2 replicates = 64), and a total of 48 plots at each location in the 3rd cycle (2 crop rotations per location × 4 crops per rotation × 3 manure/catch crop treatments (+M/−CC; +M/+CC; −M/+CC) × 2 replicates = 48). Each replicate was layed out as a complete block, which was further subdivided into two sub-blocks. The sub-blocks were introduced to better cover soil variation and reduce random error and constructed by confounding the three-way interactions between crop rotation, catch crop and manure treatments with the sub-blocks—meaning that the main effects and