Agriculture, Ecosystems and Environment 265 (2018) 350–362

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Nitrogen balances in organic and conventional arable crop rotations and their relations to nitrogen yield and nitrate leaching losses

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ARTICLE INFO

Keywords:
Organic farming
Biological nitrogen fixation
Nitrogen flow
Nitrate leaching

ABSTRACT

Nitrogen (N) flows in organic cropping systems differ considerably from those in conventional systems. The difference is particularly due to the N in organic materials in organic systems as opposed to the mineral N in fertilizer in conventional systems, which differently affect crop N supply and N losses. This implies different responses of conventional and organic cropping systems to N inputs and N management. Therefore, N flow dynamics were studied in a range of arable cropping systems with 4-year crop rotations at three different sites in Denmark varying in soil (coarse sand, loamy sand and sandy loam) and climatic conditions. The long-term field experiments included an incomplete factorial combination of (1) rotations with grass-clover in organic farming (OGC) or grain legumes in organic farming (OGL) or conventionally managed (CGL) systems, (2) with (+CC) and without (−CC) cover crops, and (3) with (+M) and without (−M) animal manure (in OGC and OGL), and with (+F) mineral fertilizer (in CGL). Cover crops in OGC and OGL included a mixture of perennial ryegrass and clover (at the sites with coarse sand and sandy loam soils) or winter rye, fodder radish and vetch (at the site with loamy sand soil), and cover crops in CGL included only perennial ryegrass at all the sites. Higher N input and N output was observed in CGL compared to OGC and OGL. The differences in annual N output in cash crops between CGL and OGL, and CGL and OGC after accounting for effects of differences in N inputs were 15 and 27 kg N ha^{-1}, respectively. The N output was related to N input, with a higher response to mineral N in both fertilizer and manure than to biological N fixation (BNF). The N surplus (difference between N input and N output) was significantly lower in OGL/−M+CC compared with other treatments. The recycled N in above-ground plant residues was highest in OGC/−M+CC where grass-clover cuttings were left in the field, followed by +CC treatments in OGL and CGL. The response of nitrate-N leaching to N input depended on soil type and precipitation, and leaching was reduced by the use of cover crops. The nitrate-N leaching increased with increasing N input at rates of 0.13–0.22 kg N kg^{-1} N input, and it increased with increasing N surplus at rates of 0.21–0.27 kg N kg^{-1} N surplus.

1. Introduction

Nitrogen (N) supply is fundamental in determining yields of any farming system (Watson et al., 2002). The primary concern in organic systems is how economically optimum yields can be sustained where chemical N input is not an option (Berry et al., 2003). Under European regulation, there are restrictions on input of animal manure from conventional systems into the organic systems, and in Denmark this option is expected to be phased out (Oelofse et al., 2013). In this context, internal N supply through biological N fixation (BNF), recycling of N and minimization of N losses is of utmost importance to sustain crop yields (Doltra and Olesen, 2013). However, there is a lack of information on the dynamics of N supply and losses in organic cropping system due to the scant data available from long-term experiments (Mäder et al., 2002).

Compared to conventional systems, organic cropping systems have a higher reliance on BNF and organic inputs (Mäder et al., 2002). There are large differences in N input between different organic cropping systems depending on the selection of N supplying crops (legumes), design of crop rotations and their interaction with soils and climate (Reinbott et al., 2004; Cavigelli et al., 2008; Olesen et al., 2009). For example, supply of N to the subsequent crop from legume-based green

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https://doi.org/10.1016/j.agee.2018.05.032
Received 16 January 2018; Received in revised form 23 May 2018; Accepted 31 May 2018
0167-8809/

manure and grain legumes can range from 17 to 200 kg N ha^{-1} (Rochester et al., 1998; Poudel et al., 2002; Reinbott et al., 2004; Cavigelli et al., 2008), and making proper use of the supplied N requires considerable care while designing the cropping sequence to achieve synchrony in N supply and crop N uptake (Crews and Peoples, 2005).

There is a large variation in crop N uptake and recycling in organic cropping systems. A study using data from the long-term organic crop rotation experiment in Denmark that we also report here indicated that the N content in wheat grain was positively correlated to the N accumulated in the preceding grass-clover green manure crop (Olesen et al., 2009), but the grain N content can be higher in a conventional rotation than in organic rotation (Doltra et al., 2011). The experiment also showed that enhancing crop N supply through manure and cover crops would enhance both dry matter and N yields (Shah et al., 2017). These studies found that such relations vary depending on the soil and climatic conditions. Recovery of the residual N from legume crops in the following crops can be as low as 15% and sometimes up to 33% in temperate regions (Peoples et al., 2009). When a ^{15}N labelled vetch was incorporated in soil, only 18% of the N in vetch was recovered in the following crop, but the retention of N in the soil was 30% higher than for fertilizer N application (Kramer et al., 2002). The amount of N stored in soil may be subject to loss following mineralization, if the N supply and uptake is not properly synchronized through robust cropping system design (Crews and Peoples, 2005).

Nitrogen losses from organic cropping systems vary considerably depending on the site conditions and cropping system structure. Here we focus on the nitrate leaching losses, which under Danish conditions is the dominant loss pathway (Dalgaard et al., 2011). Also nitrate typically constitutes about 90% of total N in the soil solution of Danish arable soils, especially in the deeper soil layers (Vinther et al., 2006). Typically, nitrate leaching from long-term organic arable farming can range from around 100 kg N ha^{-1} in coarse sandy soils to 12 kg N ha^{-1} in sandy loam soils in Denmark (Askegaard et al., 2011). However, this can be affected by the amounts of N input to the systems (Stopes et al., 2002), and the selection of crops in a crop rotation sequence (Askegaard et al., 2005; Askegaard et al., 2011). The response of nitrate-N leaching to N input is reported to follow a non-linear response with increasing N loss as N input increases (Simmelsgaard, 1998; Wachendorf et al., 2004); however, this response may be contingent on the type of N input and the structure of the cropping system.

Nitrate leaching losses in organic cropping systems have been reported to be lower than in conventional systems, either due to a lower level of N input or due to the retention of legume N in soil for a longer period of time (Brown, 1993; Drinkwater et al., 1998). Other studies, however, contradict these findings and suggest that there is generally a lack of synchrony between the N supply and the N demand of crops when organic N inputs (animal manure and green manure) are used as a N source, and this asynchrony results in lower N recovery and higher nitrate-N leaching (Scheller and Vogtmann, 1995; Kirchmann and Bergström, 2001). Nitrate leaching per unit of production (output scaled nitrate-N leaching) can be higher in organic farming, even if the leaching per unit of land is low (Tuomisto et al., 2012), although a study by Mondelaers et al. (2009) showed the opposite.

Inclusion of cover crops in arable cropping systems plays an important role where there is a lack of synchrony between the crop N demand and the N supply from legumes, and therefore, can reduce the risk of N loss through capturing the residual N (Askegaard et al., 2005). Doltra et al. (2011) in their modelling study indicated that the cover crops can have beneficial effect on crop yield and also can reduce nitrate leaching, but proper management of the cover crops determines the effects.

There is limited data available on N flows in organic crop rotation systems, particularly from long-term studies. Furthermore, there is limited information available on how a particular design of an organic crop rotation affects N cycling and loss in different soil and climatic conditions. Therefore, we utilized data from long-term experiments on organic and conventional crop rotation in Denmark with a range of cropping system design under different soils and climatic conditions. The objectives of this study were to examine: 1) how N outputs relate to N inputs in manure/fertilizer and biologically fixed N as well as recycling of N in a range of organic and conventional crop rotations, and 2) how the nitrate leaching losses depend on N inputs, surplus, and recycling in crop residues as well as cropping system design. The following hypothesis were tested: i) the N output in cash crops is primarily determined by the N-inputs, but the efficiency of these vary among input types, and ii) the nitrate leaching depends primarily on N input, vegetation cover in autumn and site conditions.

2. Materials and methods

The data included in this study are from 2005 to 2008 from a field experiment that started in 1997 at three locations in Denmark. These sites were chosen to comprise three different soil types and climatic conditions; 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 basic soil characteristics of the three sites are shown in Table 1, and the climatic conditions during the growing season of the experimental period is shown in Fig. 1. The layout of the experiment is described in more detail by Olesen et al. (2000). A detailed description of crop management and crop yields during the period 1997–2008 is given by Shah et al. (2017). The measurements conducted in the experiment allowed quantification of all N inputs, including those in BNF, as well as N output in harvested products and N losses in nitrate leaching. These main elements in the N balance were related to cropping system design, allowing quantification of which factors affect N output and nitrate-N leaching losses.

2.1. Experimental treatments and crop management

During the period 1997–2004, the experiment included three treatment factors in a full factorial design: (1) organic rotations with grass-clover (OGC) or grain legumes (OGL), (2) with (+CC) and without (−CC) cover crops, and (3) with (+M) and without (−M) animal manure. However, from 2005 the −M/−CC combinations in both OGC and OGL were replaced with a conventional farming treatment (CGL), i.e. rotation including grain legumes with mineral fertilizer (+F) and with (+CC) and without (−CC) cover crops. The −M/−CC combinations were terminated and CGL treatment were started because the lack of adequate source of N supply and increased weed infestation over time in this treatment combination made the system non-viable from an agronomic perspective. This and other changes in crop management in 2005 are described in detail by Askegaard et al. (2011) and Shah et al. (2017). The prehistory of the CGL treatment varied between locations. At Jyndevad, the CGL treatments (+/−CC) were established on randomly selected plots which had one year of grass-clover in the

Table 1
Soil characteristics for the three experimental sites. The soil data is for the top 25 cm. Soil texture data is according to Olesen et al. (2000), other data are average of individual plots from samplings in autumn 2008. The plant available soil water (PAW) content to 0.8 (Jyndevad) and 1 m (Foulum and Flakkebjerg) depth is shown according to Djurhuus and Olesen (2000).

Soil characteristics	Jyndevad	Foulum	Flakkebjerg
Clay (g kg^{-1})	45	88	155
Organic C (g kg^{-1})	11.4	20.9	9.4
Organic N (g kg^{-1})	0.79	1.59	0.94
pH ($CaCl_2$) + 0.5	6.2	6.2	7.1
K (mg kg^{-1})	42.1	98.0	82.5
Olsen P (mg kg^{-1})	32.5	33.1	21.6
PAW to 0.8/1 m depth (mm)	66	193	142