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Crop residues as driver for N_2O emissions from a sandy loam soil

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ABSTRACT

Nitrogen (N) cycling within agriculture constitutes a source of direct and indirect emissions of the potent greenhouse gas nitrous oxide (N_2O). We analysed relationships between N_2O emissions and C and N balances of four arable cropping systems under conventional or organic management within a long-term experiment on a loamy sand soil at Foulum in Denmark. All cropping systems included winter wheat, a leguminous crop (faba bean or grass-clover), potato and spring barley grown in different 4-crop rotations varying in strategies for N supply (fertilizer/manure type and rate, use of catch crops and green manure). Crops in both organic and conventional systems received N at rates below the optimum for crop production. Soil N_2O emissions were monitored in 2008–2009 in six selected crops which could be combined with data from other monitoring programs to calculate N_2O emission factors for each of the 16 crops and four entire crop rotations. Accumulated annual N_2O emissions were on average 0.8 to 0.9 kg N ha^{-1} y^{-1} and did not differ significantly between rotations. Soil N inputs in above- and belowground crop residues from main crops and catch crops were quantified by field measurements. Average nitrate-N leaching losses ranged from 39 to 56 kg N ha^{-1} y^{-1} and were lowest in rotations with catch crops; leaching was not correlated with N surplus or N input in fertilizer or manure. Crop yields of the organic rotations were 25 to 37% lower than in identical conventional rotations. As a consequence, yield-scaled N_2O emissions were lower under conventional management compared with the organic alternatives. There was no significant correlation between N_2O emissions and N input in fertilizer/manure, neither for annual emissions nor spring emissions. In contrast, N_2O emissions were correlated with N input in residues from the previous main crop and catch crop ($r = 0.56$, $p < 0.01$). This indicates that, besides nitrogen, degradable carbon provides an important and estimable driver for N_2O emissions in arable cropping systems.

1. Introduction

The growth of crops for food and feed depends to a large extent on nitrogen (N) availability (Galloway et al., 2008; Mueller et al., 2012) and, as a result, the intensification of crop production has led to a global increase in the annual use of mineral fertilizers from 86 to 107 Gg N between 2002 and 2010 (FAOSTAT, 2013). Crop production involves a risk of environmental impacts through atmospheric emissions of ammonia (NH_3), nitrous oxide (N_2O) and N oxides (NO_x), and through N leaching affecting the quality of ground- and surface waters. Nitrogen leaching, as well as NH_3 and NO_x emissions, are indirect sources of N_2O, a potent greenhouse gas with a global warming potential 298 times larger than CO_2 over a 100-yr period (Solomon et al., 2007).

In low-input systems, including organic farming, the N supply is mainly from biological N fixation and animal manure, if available. Yet, high and low-input crop production systems do not consistently differ with respect to N_2O emissions (Chirinda et al., 2010a; Petersen et al., 2006; Skinner et al., 2014). Petersen et al. (2006) compared organic and conventional crop rotations in five European countries and found a common relationship between total N input and annual N_2O emissions across systems and regions, although N input and N_2O emissions from organic systems were generally lower. Chirinda et al. (2010a), despite higher N input to conventional than to organically grown winter wheat, did not observe higher N_2O emissions, suggesting that N availability is not always the main control of emissions.

The processes leading to N_2O production in soil, i.e. nitrification, denitrification and nitrifier-denitrification, are influenced by several factors, including temperature, pH, moisture, porosity and substrate availability (Sahrawat and Keeney, 1986). Zhu et al. (2013) showed that oxygen availability is a key control of N_2O emissions, and demonstrated the relative importance for individ-

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ual processes. Their results implied that organic N sources such as crop residues and manure may have a higher potential for N_2O emissions than mineral N as a result of decomposer activity. This is supported by recent *meta*-analyses of relationships between crop residues and N_2O emissions (Shan and Yan, 2013; Chen et al., 2013; Lehtinen et al., 2014), but the influential pathways by which C and N inputs, soil properties and management affect N_2O emissions are complex (Chirinda et al., 2010b; Li et al., 2016).

The present study was planned to investigate sources of N_2O in organic and conventional cropping systems differing in C and N inputs, in part by the use of catch crops. We conducted measurements in an existing long-term study that included realistic, but widely different, N management regimes in arable farming systems. Both the conventional and the organic cropping systems in the study were fertilized with N below the economic optimum for crop production, in agreement with Danish regulations (Olesen et al., 2000). Combining new experimental results and selected data from other studies within the long-term field experiment (Chirinda et al., 2010a; Brozyna et al., 2013), allowed us to compare C and N balances and associated N_2O emissions representing four complete crop rotations. We hypothesized that N input via crop residues would be important for overall N_2O emissions in cropping systems with restricted application of fertilizer or manure N. It was further hypothesized that catch crops would reduce N leaching during winter (reducing indirect N_2O emissions), but increase the potential for direct N_2O emissions during spring.

2. Materials and methods

In order to investigate drivers of N_2O emissions we used data from a long-term crop rotation experiment. The experimental approach of the study was as follows (with reference to subsections below for further details): Data from all crops within 4-year rotations were analysed, allowing different cropping systems to be compared (Section 2.1). This enabled comparisons of similar rotations managed either conventionally (with mineral fertilizers) or organically (with use of manure). The three organic rotations further differing in the use of manure for fertilisation, inclusion of a whole-year green manure crop, and use of legume-based catch crops. Nitrous oxide emissions were monitored in comparable organic and conventional rotations in 2008–2009 (Section 2.2); this complemented measurements of N_2O emissions from the same long-term experiment and period previously reported (Chirinda et al., 2010a; Brozyna et al., 2013) to allow estimation of N_2O emissions at the crop rotation level. Determination of crop and catch crop biomass allowed estimation of C and N inputs, outputs and balances (Sections 2.3 and 2.6), including nitrate leaching (Section 2.4). We used these different sources of data to test the hypothesis that N input in crop residues rather than in fertilizer and manure is the major driver of N_2O emissions when comparing cropping systems varying greatly in sources of N inputs (Section 2.7).

2.1. Cropping systems and management

The study was conducted during 2006 to 2009 within a long-term crop rotation experiment initiated in 1997 on a loamy sand soil near Foulum, Denmark (56°30′N, 9°34′E). The site, soil properties and experimental design have been presented previously (Olesen et al., 2000; Chirinda et al., 2010a). Three main cropping systems for cereal production were represented (O2, O4 and C4) differing with regard to leguminous crops in the rotation, use of catch crops (CC), and application of animal manure (M) or inorganic fertilizer (IF). Rotations O4 and C4 were based on cash crops: spring barley (*Hordeum vulgare* L.), faba bean (*Vicia faba* L.), potato (*Solanum tuberosum* L.) and winter wheat (*Triticum aestivum* L.) in the specified sequence. In O2, faba bean was replaced by a grass-clover mixture of perennial ryegrass (*Lolium perenne* L.), white clover (*Trifolium repens* L.) and red clover (*Trifolium pratense* L.) serving as a green manure. The faba bean crop in C4 and O4 was replaced with a mixture of spring barley and pea (*Pisum sativum* L.) in 2009 to avoid soil borne diseases.

In this study, four different 4-crop rotations were analysed. All crops in each rotation were represented every year in each of two completely randomized blocks. One rotation (C4-CC+IF) was managed conventionally and three rotations (O4-CC+M, O2+CC+M and O2+CC-M) organically. Hence contrasts differing in source of N fertilizer (C4+IF vs. O4+M), use of catch crops (O2-CC vs. O2+CC), and proportion of cash crops (O4-CC vs. O2-CC) were represented. Catch crops were only represented in O2+CC where a catch crop of perennial ryegrass, chicory (*Chicorium intubus* L.), and white and red clover was undersown in winter wheat in May, and incorporated the following spring. The C4 rotation received mineral fertilizer N (NH_4NO_3), phosphorus (P) and potassium (K), whereas manure (untreated or digested pig slurry, see below) was used in the organically managed O2 and O4 rotations. The application rates and quality of slurry used in O4 and O2 is shown in Table 1 in terms of dry matter (DM), carbon (C) and N. Mineral fertilizers were broadcast, and slurry was injected to 8 cm depth, except in winter wheat, where slurry was surface-applied by trail hoses.

Nitrogen fixation by legumes was part of the N supply in all cropping systems, but O2+CC-M depended solely on N fixation in grass-clover, which was recycled by leaving grass-clover cuts to decompose in the field. In the O2 rotation with manure application (O2+CC+M) grass-clover cuts were removed for (simulated) digestion of the green manure for biogas production and recycling of digestate as fertilizer. Therefore less organic matter was retained in the field in O2+CC+M compared with O2+CC-M where grass-clover cuttings were left on the soil as mulch. Actual digestion of the harvested grass-clover was not possible at the small scale (8 m × 15 m plots) of the field experiment, and instead equivalent amounts of N in digested pig slurry were applied (Brozyna et al., 2013).

Pesticides were used in the C4 rotation for weed, pest and disease control. In the organic rotations, mechanical weed control was used, whereas pests and diseases were not controlled. Field operations during the monitoring period are shown in Supplementary materials (S1).

2.2. Monitoring of N_2O emissions

Emissions of N_2O were determined between 14 April 2008 and 11 May 2009 in six crops, i.e., spring barley, faba bean and potato of the rotations C4-CC+IF and O4-CC+M. Emissions of N_2O in the fourth crop of these rotations, winter wheat, were included in a parallel monitoring programme (Chirinda et al., 2010a); however, this was terminated in September 2008, and hence N_2O emissions during autumn-winter and spring 2009 had to be estimated (see Section 2.7). As recommended by Smith and Dobbie (2001), during the growing season fluxes of N_2O were measured bi-weekly, but with more intensive monitoring in April and May following field operations, and only one campaign in July. During winter (October-February), N_2O emissions were also measured monthly, as several monitoring programs (Mutegi et al., 2010; Petersen et al., 2011) at this field site have consistently found winter emissions to be low in the absence of decaying plant material (Li et al., 2015). While the lower frequency of measurements outside of the spring season potentially added to the uncertainty of annual emissions estimates, the main aim of this study was to compare emissions from different cropping systems, and therefore measurements were most frequent during periods with expected treatment effects. Two-part static chambers were used following the methodology described for the Foulum site by Chirinda et al. (2010a). Permanent cham-