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Crop production for biogas and water protection—A trade-off?

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ABSTRACT

In Germany the promotion of renewable energy has led to a rapid expansion of biogas production in recent years. Growing controversy surrounds this development due to potential environmental trade-offs caused by biomass production for co-fermentation, which is dominated by silage maize. The aim of the study was to evaluate the N-leaching potential following application of biogas residues and animal slurry to grassland and maize on a sandy soil in northern Germany.

The study was based on a field experiment conducted in northern Germany over two consecutive leaching periods (2007/2008 and 2008/2009). Treatments included N-fertilizer type (co-fermented biogas residue, cattle slurry, calcium ammonium nitrate) and N amount (grass: 0, 160, 320 and 480 kg N ha^{-1}; maize: 0, 120, 240 and 360 kg N ha^{-1}). The fertilizer amount was split into two (maize) or four (grass) dressings. Leachate was collected using ceramic suction cups installed at 60 cm depth. Water fluxes were simulated with a site-adapted model in which the soil water balance calculation was based on mechanistic approaches, while crop height and green area index were quantified by simple logistic growth equations. Nitrogen load was obtained by combining the simulated leachate amount with measured N concentration.

Water fluxes, crop height and green area index were satisfactorily simulated. Nitrate-N loss in grassland generally was very low, staying below the critical nitrate-N load, according to the EU drinking water threshold. At optimal N input, i.e. N input required for maximum yield, maize caused a considerable nitrate-N load (48–67 kg ha^{-1}), and it increased exponentially at higher inputs. Most of the variation of nitrate-N load among fertilizer types was explained by the proportion of fertilizer-N input as mineral N. For both grassland and maize, biogas residues had a similar nitrate leaching potential to animal manures. Maize achieved a substantially higher methane hectare yield (m_N^3 CH_4 ha^{-1}) than grassland. This could not overcompensate for its higher nitrate-N load, as indicated by the eco-efficiencies in terms of kg nitrate-N load per mega liter methane produced at optimal N input (maize: 7.7–14.7, grass: 0.3–2.9).

1. Introduction

Biomethane from anaerobic digestion of crop material and farmyard manure represents a renewable energy source, which may contribute to the ambitious commitments to offset CO_2 emissions and climate protection goals (Weiske et al., 2006). In Germany, the number of biogas plants is estimated to have increased to 7874 by 2013 (Fachverband Biogas, 2012) due to heavy subsidization. Most of the biogas is produced by co-fermentation of animal manure and crops, with silage maize being the dominant plant substrate, contributing to approximately 80% of the biomass in terms of fresh matter (DBFZ, 2012). Intensive livestock farming and biogas production have increased the proportion of arable land used for maize to 21.7% nationwide. At a regional level, the maize area can be as high as 70% of arable land, causing substantial public concern, and a limitation on the maize share of arable land has been discussed. Permanent grassland (i.e. swards older than 5 years) is used to a minor extent for biogas production (DBFZ, 2012); its lower use is mainly due to its lower yield and thus higher costs per hectare. It might, however, gain importance if political restrictions on maize cultivation, higher substrate costs and increased competition for land make grassland more attractive.

Another challenge related to the expansion of biogas production is the efficient use of biogas residues (BR). These are produced in

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large amounts and should be recycled in a sustainable way in order to replace fossil-fuel based mineral fertilizer. In order to achieve sustainable biogas production, conflicts with other environmental protection objectives such as the Water Framework Directive (EC, 2000) should be prevented; this is especially relevant on light sandy soils that have high nitrogen leaching potential (Verloop and Schröder, 2005; Schröder et al., 2007). During anaerobic digestion, the fermentation substrate is subject to transformations, bringing about substantial changes in physical and chemical properties of the BR, compared to that of animal slurry, which may modify the C and N flows in the soil–plant system. In brief, the ratio of NH_4-N to total-N increases, pH value increases, and the C/N ratio decreases (Gutser et al., 2005; Odlare et al., 2008; Gemmeke et al., 2009). Compared with undigested slurry, the higher mineral nitrogen share of BR together with reduced viscosity (Weiland, 2010) may result in a higher short-term N availability and N-use efficiency (Gutser et al., 2005; Herrmann et al., 2012a). If, however, the N supply via BR and the crop demand are not synchronized, the application of BR may carry a higher N-leaching risk. This applies in particular to maize, where organic fertilizer is commonly applied before sowing or at early growth stages, i.e. at a time when plant N uptake is low (Aufhammer et al., 1996; Schröder et al., 1996). In permanent grassland, on the other hand, N fertilization is split into several dressings applied at intervals according to the number of cuts thereby reducing the leaching risk, and the established root system ensures a rapid N uptake. However, due to the need for several fertilizer dressings, the risk of ammonia emission after BR application is increased (Wulf et al., 2002; Gericke, 2009; Nyord et al., 2012; Quakernack et al., 2012). Studies on the N-leaching risk after BR application compared to that of other N-fertilizer sources are few, and findings are inconsistent. Whereas Brenner and Clemens (2005), Pötsch (2005) and Jørgensen and Petersen (2006) found increased or similar amounts of N loss for digested and undigested slurry, the Sächsische Landesanstalt für Landwirtschaft (1999) reported a reduction of N leaching for digested slurry.

The aim of the study therefore was to evaluate the nitrogen leaching potential following biogas residues and animal slurry application to grass and maize on a sandy soil in northern Germany. The work was conducted within the framework of the interdisciplinary Biogas-Expert project, initiated to contribute to a sustainable optimization of N flows in the soil–plant–fermenter system, based on field experiments and the application of a soil–plant model. It was hypothesized that, due to changed characteristics during fermentation

- biogas residues applied to maize are more prone to N-leaching losses compared to animal manure,
- the risk of N leaching after applying BR may be mitigated if grass, instead of maize, is used for substrate production, and
- the expected higher N-loss in maize compared to grass will be overcompensated by a higher methane hectare yield, resulting in a reduced N load per unit of methane produced.

2. Materials and methods

2.1. Experimental site

The study is based on a field experiment conducted between autumn 2006 and spring 2009 at the Karkendamm experimental farm (E 9°57′, N 53°55′, 17 m a.s.l.) of Kiel University located in the federal state of Schleswig-Holstein, northern Germany. The site represents the Geest region, which developed after the Weichselian glacial age. Due to permeability of the light soils and the nutrient losses associated with intensive dairy farming, many groundwater bodies in the Geest region are of poor status according to the EU Water Framework Directive, as indicated by a high proportion of groundwater wells exceeding the 50 mg NO_3 l^{-1} (=11.3 mg NO_3-N l^{-1}) nitrate threshold. The soil is classified as a highly permeable, gleyic podzol (40 g kg^{-1} clay, pH 4.5–5.3, 37 g kg^{-1} organic C, 1.9 g kg^{-1} organic N in 0–28 cm). Tracer experiments on nearby field plots did not show lateral flow. Long-term annual precipitation and mean air temperature are 821 mm and 8.7 °C, respectively. In 2007, precipitation was higher at 1040 mm and the mean temperature was 10.3 °C, while in 2008 rainfall was 723 mm and mean temperature was 9.7 °C (Fig. 1).

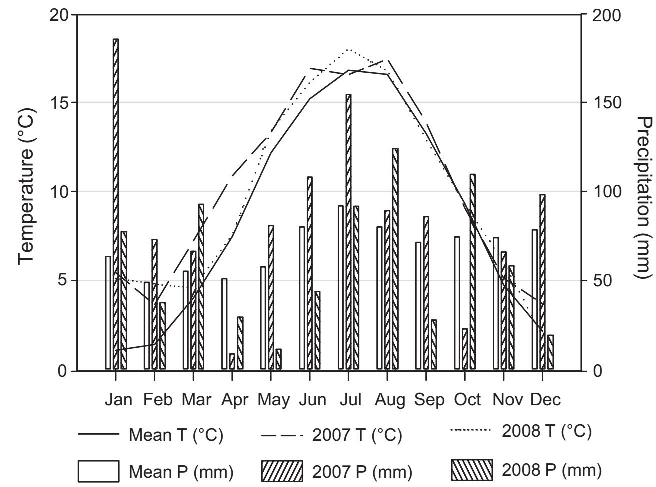

Fig. 1. Temperature (*T*, °C) and precipitation (*P*, mm) data at Karkendamm experimental sites provided for experimental years 2007 and 2008, and for the long-term average (1961–2008; station Quickborn, provided by the Deutscher Wetterdienst).

2.2. Treatments, trial management and crop measurements

The field experiment was established as a 4-factorial randomized block design with four replicates and a plot size of 12 m × 12 m. Treatments comprised different substrate production system (maize monoculture, perennial ryegrass ley), N-fertilizer type, and N amount. Nitrogen fertilization was varied in 4 levels and was applied as calcium ammonium nitrate (CAN), co-fermented BR and cattle slurry, applied to the same plots each year. Monofermented BR and pig slurry were applied only at the highest N level. Table 1 presents the target and actually applied N rates, which for some treatments unfortunately differed. Biogas residues were obtained from nearby commercial biogas plants as monofermented maize or co-fermented maize/pig slurry. Fig. 2 provides an overview of the crop management measures and growth samplings.

Maize (*Zea mays*, cvar. Ronaldinio, mid-early) was sown in mid-to-late April in rows 0.75 m apart with a plant density of 10 plants m^{-2} following seedbed preparation by plough and harrow. In maize, the N fertilizer was split into two dressings: before sowing, with immediate incorporation, and at the 3-leaf stage, see Table 1 and Fig. 2. Perennial ryegrass (*Lolium perenne*, cvar. Fennema (50%), Edda (50%)) was sown in early September 2006 with 30 kg seed ha^{-1} and a row distance of 10 cm, and received N fertilizer in 3 or 4 dressings. Organic fertilizers were generally applied using a dribble bar system. Nitrogen content of the organic fertilizers was analyzed before application to calculate the volumes required. During fertilization, samples were taken to determine the actual N content and further characteristics (Table 2). Dried organic fertilizer samples were analyzed for C and N content by a CN analyzer (Vario Max CN, Elementar Analysensysteme, Hanau, Germany). Before drying (105 °C), the samples had been acidified to pH 5 using 10% HCl to avoid extensive ammonia volatilization.