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Biogas cropping systems: Short term response of yield performance and N use efficiency to biogas residue application

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ABSTRACT

The promotion of electricity generation from renewable energy sources has led to a substantial expansion of biogas production in Germany, with most biogas plants co-digesting slurry and crops, and maize being by far the most dominant substrate. At present only limited information is available on the agronomic and environmental performance of biogas cropping systems, and on the fertilizer value of biogas residues. In a two-year field experiment at two sites in northern Germany differing in soil quality, we analyzed the dry matter (DM) yield, N yield, methane yield, and the N balance of different cropping systems: (i) maize monoculture (R1), (ii) maize–whole crop wheat followed by Italian ryegrass as a double crop (R2), (iii) maize–grain wheat followed by mustard as a catch crop (R3), and (iv) perennial ryegrass ley (R4). Rotations R1, R2 and R3 were grown at Site 1 (sandy loam), whereas R1 and R4 were tested at Site 2 (humus sand). Crops were supplied with varying amounts (0–360 kg N ha^{-1}, ryegrass: 0–480 kg N ha^{-1}) of biogas residue, cattle slurry, pig slurry, or mineral N fertilizer, which allowed quantifying their N use efficiency in terms of apparent N recovery (ANR) and relative N fertilizer value (RNFV).

No significant interactions of crop rotation and fertilizer type on DM and methane yield, plant N recovery, as well as N balance, were detected at Site 1, where R1 (19.3 t DM ha^{-1}; 6750 m^3_N CH_4 ha^{-1}; N: norm conditions, i.e. 273 K, 1024 hPa) clearly out-yielded R2 (16.8 t DM ha^{-1}; 5351 m^3_N CH_4 ha^{-1}) and R3 (12.8 t DM ha^{-1}), while R2 had a higher plant N recovery. At Site 2, the perennial ryegrass ley achieved substantially lower maximum DM and methane yield (13.9 t DM ha^{-1}; 4251 m^3_N CH_4 ha^{-1}) than maize monoculture (17.3 t DM ha^{-1}; 6038 m^3_N CH_4 ha^{-1}). Fertilizer type affected grass performance: application of biogas residue resulted in lower yield and N recovery, but higher N balance than mineral fertilizer and cattle slurry. The N use efficiency of biogas residue application depended on the crop rotation. Biogas residue resulted in higher ANR and RNFV compared to pig slurry in R1, whilst in R2 the reverse occurred, and effects were similar to cattle slurry in R4. The results revealed that, except for grassland, substrate cropping based on biogas residues can exploit the yield potential without causing high N surplus.

1. Introduction

Biomass energy, i.e. electricity, heat or fuel generated from organic matter such as agricultural waste or energy crops, is considered an important renewable energy source which may contribute to climate change mitigation (Sims et al., 2006; McCarl, 2010). Biomass production systems thus should aim at maximizing the capacity and efficiency to absorb and to convert solar energy into harvestable plant material, while minimizing inputs and environmental impact (Sims et al., 2006). From this perspective, biomass conversion pathways which can use the whole crop instead of specific plant organs, e.g. biogas (anaerobic digestion) or cellulosic ethanol production, seem to be more efficient (Johnson et al., 2007; Don et al., 2012).

Although bioenergy is increasingly promoted in the EU to achieve energy security and climate protection objectives, biomass used for energy generation is not per se environmentally benign, since its production is inevitably associated with negative side effects such as greenhouse gas (GHG) emission or N leaching (Don et al., 2012; Hennig and Gawor, 2012). According to the principles of ecological intensification (Doré et al., 2011), it is therefore essential to develop biogas cropping systems which allow maximization of production per unit area by an optimized crop and soil management in order to protect soil and water bodies. Biomass yield and N use

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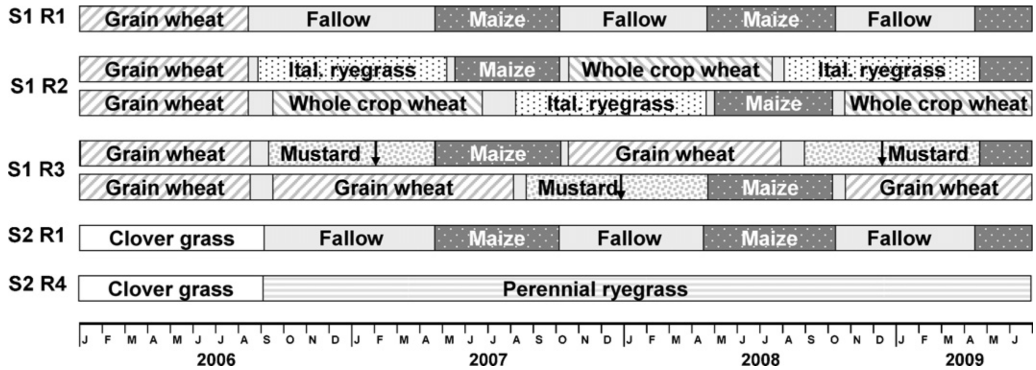

Fig. 1. Schematic representation of the tested crop rotations (R1, R2, R3, R4) grown at Site 1 (S1: Hohenschulen) and Site 2 (S2: Karkendamm). The experiment was established in August 2006. Yields of the experimental years 2007 and 2008 were included in the current study. The arrows denote the date when mustard froze off.

efficiency are important factors for the CO_2 saving potential of biogas production (Börjesson and Tufvesson, 2011; Claus et al., 2012; Dressler et al., 2012). The replacement of fossil-fuel based fertilizers by biogas residues without yield penalties, seems a key element for an ecological intensification of biogas cropping (Doré et al., 2011). In this respect, the changes of chemical and physical properties of the substrate during anaerobic digestion and their consequences for the fertilizer value of biogas residues have to be taken into account (Gutser et al., 2005). Biogas residues are often assumed to have a higher short-term N availability than undigested animal manure due to an increased ammonia-N content (Gutser et al., 2005; Kolář et al., 2008), but soil N dynamics after application can vary substantially, depending on biogas residue composition and stability (Alburquerque et al., 2012). Studies evaluating the fertilizer value of biogas residues on field level, however, are scarce (Bermejo, 2012; Gagnon et al., 2012; Herrmann et al., 2012).

Another challenge refers to the impact of bioenergy production on crop diversification. Over the last decades, agricultural policy and the pressure for cost-effectiveness and specialization has resulted in little diversification of crop rotations (Bio Intelligence Service, 2010; Tomich et al., 2011). This trend may be further reinforced by European and national climate change policies, which can spark considerable structural changes at the farm level, but also on larger scales. This, for instance, has occurred in Germany, where a substantial expansion of maize cultivation for substrate supply has been observed through the subsidization of biogas production. Critics fear that this ongoing development may lead to ecological disservices (EEA, 2007), especially in hot spots of biogas production in north-western and southern Germany, i.e. areas with existing high livestock density and a high proportion of maize grown in monoculture.

The introduction of catch crops, double-cropping, and crop rotations as alternatives to maize monocultures are currently being intensively discussed as a means to reduce potential negative impact of maize monoculture and to enhance biomass yield (Karpenstein-Machan, 2001; Vetter et al., 2009). Crop rotations with nearly year-round soil cover thus would provide the opportunity to exploit the high photosynthetic capacity of the C4 crop maize in summer, and also to use the potential of C3 crops in spring and autumn (Baker and Griffis, 2011). In addition to increased productivity, benefits can be anticipated from improved internal resource utilization and soil quality, as well as from reduced disease pressure and environmental impact (Hartwig and Ammon, 2002; Zegada-Lizarazu and Monti, 2011). The effect of catch or double crops on maize yield, C and N flows, and environmental effects has been the subject of several studies (Schröder et al., 1996; Ritter et al., 1998; Constantin et al., 2010, 2011; Gabriel and Quemada, 2011), but only few studies are available on the performance of silage maize rotated with whole crop cereals and catch or double crops (Constantin et al., 2010, 2011; Fletcher et al., 2011).

While a previous paper (Herrmann et al., 2012) solely focused on the maize crop, the objective of the current study was to evaluate whole biogas cropping systems, supplied with different N fertilizer types (mineral, liquid animal manure, biogas residue) at varying N amounts with respect to DM yield, methane yield, and plant N recovery. In addition, the fertilizing effect of biogas residues was evaluated in terms of its N use efficiency and relative N fertilizer value. It was hypothesized that (i) under the climatic conditions of northern Germany, which are marginal for maize production, a crop rotation including C3 and C4 crops as well as a double crop would achieve higher yield and lower N loss potential than maize monoculture, and (ii) biogas residues would have a higher fertilizing efficiency than liquid animal manure.

2. Materials and methods

2.1. Study sites and soils

A field trial was carried out at two sites in northern Germany between August 2006 and May 2009. At Site 1, the Hohenschulen Experimental Farm (10.0°E, 54.3°N, 30 m a.s.l.), the predominant soil was a pseudogleyic sandy loam (Luvisol: 170 g kg^{-1} clay, pH 6.7, 13 g kg^{-1} C_{org}, 1.1 g kg^{-1} N_{org} in 0–30 cm), whereas Site 2, the experimental farm 'Karkendamm' (9.9°E, 53.9°N, 17 m a.s.l.) was dominated by a coarse humus sandy soil (gleyic Podzol: 60 g kg^{-1} clay, pH 4.5–5, 75 g kg^{-1} C_{org}, 3.0 g kg^{-1} N_{org} in 0–28 cm).

The climate of northern Germany is humid temperate with a long-term mean annual temperature of about 8.4 °C. Total rainfall averages 800 mm annually with only small variations between the sites; ca. 400 mm occurs during the main growing season (April–September). At Hohenschulen, temperature and precipitation in the 2007 experimental year were substantially higher (926 mm; 10.1 °C) than the long-term average, whereas 2008 was slightly drier (722 mm) and warmer (9.8 °C). At Karkendamm, mean annual temperature (10.3 °C in 2007, 9.7 °C in 2008) was higher than the long-term average, whilst rainfall slightly exceeded the long-term average in 2007 (898 mm), but was less in 2008 (726 mm).

2.2. Experimental design

The field experiment was established in autumn 2006 as a 4-factorial randomized block design with four replicates and a plot size of 12 m × 12 m. At Site 1, winter wheat was grown during the two years before the project started, whereas at Site 2 the preceding crop was a white clover-grass sward (Fig. 1). Experimental