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Research paper

Effect of biogas digestate, animal manure and mineral fertilizer application on nitrogen flows in biogas feedstock production

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ABSTRACT

The expansion of biogas feedstock cultivation may affect a number of ecosystem processes and ecosystem services, and temporal and spatial dimensions of its environmental impact are subject to a critical debate. However, there are hardly any comprehensive studies available on the impact of biogas feedstock production on the different components of nitrogen (N) balance. The objectives of the current study were (i) to investigate the short-term effects of crop substrate cultivation on the N flows in terms of a N balance and its components (N fertilization, N deposition, N leaching, NH_3 emission, N_2O emission, N recovery in harvested product) for different cropping systems, N fertilizer types and a wide range of N rate, and (ii) to quantify the N footprint of feedstock production in terms of potential N loss per unit of methane produced. In 2007/08 and 2008/09, two field experiments were conducted at two sites in Northern Germany differing in soil quality, where continuous maize (R1), maize–whole crop wheat followed by Italian ryegrass as a double crop (R2), and maize–grain wheat followed by mustard as a catch crop (R3) were grown on Site 1 (sandy loam), and R1 and a perennial ryegrass ley (R4) at Site 2 (sandy soil rich in organic matter). Crops were supplied with varying amounts of N (0–360 kg N ha^{-1}, ryegrass: 0–480 kg N ha^{-1}) supplied as biogas digestate, cattle slurry, pig slurry or calcium-ammonium nitrate (CAN).

Mineral-N fertilization of maize-based rotations resulted in negative N balances at N input for maximum yield (Nopt), with R2 having slightly less negative balances than R1 and R3. In contrast, N balances were close to zero for cattle slurry or digestate treatments. Thus, trade-offs between substrate feedstock production and changes of soil organic matter stocks have to be taken into consideration when evaluating biogas production systems. Nitrogen losses were generally dominated by N leaching, whereas for the organically fertilized perennial ryegrass ley the ammonia emission accounted for the largest proportion. Nitrogen balance of the ryegrass ley at Nopt was close to zero (CAN) or highly positive (cattle slurry, digestate). Nitrogen footprint (NFP) was applied as an eco-efficiency measure of N-loss potential (difference of N input and N recovery) related to the unit methane produced. NFP ranged between −11 and +6 kg N per 1000 m^3 methane at Nopt for maize-based rotations, without a significant impact of cropping system or N fertilizer type. However, for perennial ryegrass ley, NFP increased up to 65 kg N per 1000 m^3. The loose relation between NFP and observed N losses suggests only limited suitability for NFP.

1. Introduction

In the face of rising world energy consumption (IEA, 2015a), threats of climate change and the finite nature of fossil energy sources, bioenergy is regarded as having an essential role in contributing to climate change mitigation, resource conservation, energy security and rural development. Consequently, various measures related to climate and energy policies have been implemented, e.g. feed-in tariffs and fuel blending mandates, to promote different bioenergy pathways (IEA, 2015b). In Germany, the Renewable Energy Sources Act of 2000 (BMWi, 2017a), and in particular its amendments in 2004 and 2009, have promoted the anaerobic digestion of liquid animal manure and plant raw material. The support schemes have resulted in a substantial increase in the biogas maize acreage, reaching 900,000 ha in 2016 (DMK, personal communication). This represents 35% of the total maize acreage or 7.6% of arable land, since maize is the preferred substrate for co-fermentation due to its high yield performance and the availability of existing crop management technology. Although maize-

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based biogas production has been shown to have a positive energy balance and to contribute to greenhouse gas (GHG) saving (Claus et al., 2014; Gissen et al., 2014; Bacenetti and Fiala, 2015), potential adverse effects resulting from expansion of the maize area have triggered controversy. Maize is often grown continuously and overfertilization is still commonplace, which may result in considerable emissions of reactive nitrogen (N) to the atmosphere and to ground and surface waters. Furthermore, there may be adverse effects in terms of topsoil erosion (Laloy, 2010; Gutzler et al., 2014), soil organic matter degradation (Jans et al., 2010; Moors et al., 2010) and loss of biodiversity (Gevers et al., 2011; Sauerbrei et al., 2014). Consequently, amendments of the Renewable Energy Sources Act (EEG) implemented in 2012, 2014 and 2017 (BMWi, 2017b) substantially restricted further increase of biogas production, for instance by limiting the proportion of maize as co-ferment and by less attractive feed-in tariffs in new contracts. Extensive crop substrate cultivation will not decrease until the older 20-year contracts expire, and thereafter will largely depend on the purpose of any future EEG amendments. Therefore, a sustainable, resource-use efficient crop substrate production will continue to be relevant in the coming years.

The diversification of cropping systems has been intensively discussed as an alternative to continuous maize cultivation. Crop rotations have been shown to increase nutrient-use efficiency and productivity, to facilitate weed control, to reduce the yield risk and impacts of pests and diseases, and to improve soil structure, soil fertility and biodiversity (Cowell et al., 1995; Zegada-Lizarazu and Monti, 2011; Gaudin et al., 2015). A high methane hectare yield is essential for the GHG saving potential as well as for economic performance. While there exist differences in specific methane yield, i.e. methane produced per unit biomass, it is clear that biomass yield is the main determinant of methane hectare yield (Triolo et al., 2012; Rath et al., 2013; Barbanti et al., 2014; Gissen et al., 2014; Molinuevo-Salces et al., 2015).

Resource-use efficient production of biomass used as substrate in biogas plants also implies that digestate is recycled to replace fossil-fuel based mineral fertilizer. During anaerobic digestion a high proportion of carbon is converted to methane, bringing about considerable changes in physical and chemical properties of digestate compared to undigested animal slurry, which may affect the C and N flows in the soil-plant system (Gutser et al., 2005; Odlare et al., 2008; Kolář et al., 2008). Generally, a reduction of the C/N ratio and an increase in the ratio of NH_4-N to total N and of pH value can be assumed (Gutser et al., 2005; Smith et al., 2007; Seppälä et al., 2013), which may result in a higher short-term N fertilizer value (Gutser et al., 2005; Chantigny et al., 2008; Cavalli et al., 2016; Baral et al., 2017). On the other hand, higher stability of the organic matter might be assumed since a large proportion of the more easily degradable C compounds is converted to methane. Interactions of N fertilizer type and crop species can be attributed to differences in N uptake dynamics (Sieling et al., 2013). The higher NH_4-N proportion together with a higher pH value, however, increases the risk of ammonia volatilization (Ni et al., 2012), which can be mitigated by low-emission application techniques (Webb et al., 2010) and manure treatment technologies (Fangueiro et al., 2015; Hou et al., 2016). Studies comparing the impact of digestate versus raw animal slurry on nitrous oxide emissions and N leaching vary widely and are inconsistent, since many factors affect the underlying processes (Chantigny et al., 2010; Pelster et al., 2012; Walsh et al., 2012; Senbayram et al., 2014; Severin et al., 2015; Svoboda et al., 2015; Baral et al., 2017). In summary, there is a range of studies available dealing with the impact of bioenergy cropping on partial aspects of the N balance. To our knowledge, however, there is no comprehensive study available quantifying all relevant components of the N balance with the goal of evaluating the environmental and agronomic impact of bioenergy cropping systems.

The objectives of the current study therefore are (i) to provide a synopsis of the N flows in the soil-plant system by means of an N balance and its components, based on data collected in the Biogas-Expert project, for evaluating the sustainability of biogas feedstock production depending on crop rotation, N fertilizer type and N rate, and (ii) to quantify the N footprint of substrate production in terms of potential N loss per unit methane produced. The Biogas-Expert project analysed the short-term impact of different N fertilizer types (digestate, animal slurries, mineral) on N flows in the soil-plant-atmosphere system for different cropping systems during 2 years at two sites in northern Germany, representing major landscapes. Partial aspects of crop N response (Herrmann et al., 2013; Sieling et al., 2013), ammonia emission (Gericke et al., 2011, 2012; Ni et al., 2012, 2013), nitrous oxide emission (Köster et al., 2011, 2013a,b, 2014, 2015; Senbayram et al., 2009, 2014), N leaching (Svoboda et al., 2013a,b, 2015) and GHG balance (Claus et al., 2014) have been documented, but no overall analysis of N flows had been conducted so far.

The following hypothesis will be tested:

- Continuous maize cultivation causes lower N balances than maize-wheat-catch crop rotations due to lower crop residues and higher N losses
- Perennial ryegrass ley results in a positive N balance, independent of N-fertilizer type and N rate
- N balances are higher for organic than mineral fertilizer; lower degradability of digestate causes higher N balances compared to animal manure
- The Nitrogen Footprint (NFP) provides a suitable indicator of the N loss potential.

2. Materials and methods

2.1. Experimental sites and treatments

The study is based on two field experiments conducted between autumn 2006 and spring 2009 at two sites in Schleswig-Holstein, northern Germany. Site 1, the experimental farm Hohenschulen (10.0°E, 54.3°N; 30 m a.s.l.), represents the Eastern Upland. The predominant soil was a Luvisol (IUSS, 2006) (170 g kg^{-1} clay, pH ($CaCl_2$) 6.7, 13 g kg^{-1}C_{org}, 1.1 g kg^{-1} N_{org} in 0–30 cm). The prevailing climate is humid temperate with an average annual precipitation of 773 mm and a mean annual temperature of 8.7 °C. The first experimental year (2007) was wetter (925 mm) and warmer (10.1 °C) than the long-term average, while 2008 was drier and warmer (722 mm, 9.8 °C). Site 2 (Karkendamm), representative of the Geest region, was characterized by a podzol (IUSS, 2006) (60 g kg^{-1} clay, pH ($CaCl_2$) 4.5–5, 75 g kg^{-1}C_{org}, 3.0 g kg^{-1} N_{org} in 0–28 cm). Mean annual temperature (10.3 °C in 2007, 9.7 °C in 2008) was higher than the long-term average (8.7 °C), whilst rainfall slightly exceeded the long-term average (821 mm) in 2007 (898 mm), but was less in 2008 (726 mm).

The experiment was established in autumn 2006 as a 4-factorial, completely randomized block design with 4 replicates and a plot size of 12 m × 12 m with 240 plots at Site 1 and 96 plots at Site 2. Treatments comprised the crop rotation (R1–R4, see Fig. 1), N fertilizer type (mineral N (calcium ammonium nitrate, CAN), digestate of co-fermented maize/pig slurry, pig slurry (only Site 1), cattle slurry (only Site 2)), and N fertilizer rate (4 levels, depending on crop, see Table 1). In rotation R1, which was tested at both sites, silage maize (*Zea mays* L.) was grown continuously. Rotation R2 consisted of silage maize and winter wheat for whole-crop use followed by an Italian ryegrass double crop. In the maize-winter wheat rotation R3, wheat was harvested for grain use and Italian ryegrass was replaced by mustard (*Sinapis alba* L.). Rotations R2 and R3 were only tested at Site 1, whereas at Site 2, a perennial ryegrass ley (R4) was investigated as an alternative to continuous maize. Each crop of each rotation was grown in each year, according to the principles of crop rotation experiments. At Site 1, winter wheat was grown the two years before the experiment started, whereas at Site 2 the preceding crop was a grass-clover sward.