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Research paper

# Net $N_2O$ and $CH_4$ soil fluxes of annual and perennial bioenergy crops in two central German regions

Katja Walter, Axel Don*, Heinz Flessa

*Thünen Institute of Climate-Smart Agriculture, Bundesallee 50, 38116 Braunschweig, Germany*

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The area used for bioenergy feedstock production is increasing because substitution of fossil fuels by bioenergy is promoted as an option to reduce greenhouse gas (GHG) emissions. However, agriculture itself contributes to rising atmospheric nitrous oxide ($N_2O$) and methane ($CH_4$) concentrations. In this study we tested whether the net exchanges of $N_2O$ and $CH_4$ between soil and atmosphere differ between annual fertilized and perennial unfertilized bioenergy crops. We measured $N_2O$ and $CH_4$ soil fluxes from poplar short rotation coppice (SRC), perennial grass-clover and annual bioenergy crops (silage maize, oilseed rape, winter wheat) in two central German regions for two years. In the second year after establishment, the $N_2O$ emissions were significantly lower in SRC (<0.1 kg $N_2O$–N $ha^{-1}$ $yr^{-1}$) than grassland (0.8 kg $N_2O$–N $ha^{-1}$ $yr^{-1}$) and the annual crop (winter wheat; 1.5 kg $N_2O$–N $ha^{-1}$ $yr^{-1}$) at one regional site (Reiffenhausen). However, a different trend was observed in the first year when contents of mineral nitrogen were still higher in SRC due to former cropland use. At the other regional site (Gierstädt), $N_2O$ emissions were generally low (<0.5 kg $N_2O$–N $ha^{-1}$ $yr^{-1}$) and no crop-type effects were detected. Net uptake of atmospheric $CH_4$ varied between 0.4 and 1.2 kg $CH_4$–C $ha^{-1}$ $yr^{-1}$ with no consistent crop-type effect. The $N_2O$ emissions related to gross energy in the harvested biomass ranged from 0.07 to 6.22 kg $CO_2$ equ $GJ^{-1}$. In both regions, Gierstädt (low $N_2O$ emissions) and more distinct Reiffenhausen (medium $N_2O$ emissions), this energy yield-related $N_2O$ emission was the lowest for SRC.


## 1. Introduction

Agriculture contributes to about 60% of global anthropogenic nitrous oxide ($N_2O$) emissions, mainly due to direct emissions from fertilized croplands [1]. The soil's natural ability to oxidize atmospheric methane ($CH_4$) is coincidentally lowered by land-use change from natural to cropland [2]. Rising concentrations of $N_2O$ and $CH_4$ in the atmosphere have a severe impact on climate change additional to the rapidly growing concentration of atmospheric carbon dioxide ($CO_2$) [1]. In the last decades, increasing efforts have been made by society and politics to reduce greenhouse gas (GHG) emissions. Bioenergy as substitute for fossil fuels is promoted in many industrialized countries as an option to reduce $CO_2$ emissions and mitigate climate change [3]. As a consequence, the land area used for bioenergy feedstock production grew rapidly, e.g. in Germany more than tripled from about 0.6 Mha in 2000 to 2.1 Mha in 2013 [4]. This area is mostly cultivated with annual crops like maize for biogas production or wheat and oilseed rape as biofuel feedstock [4]. The area for cultivation of dedicated, perennial bioenergy crops like poplar or willow in short rotation coppice (SRC), miscanthus or reed canary grass is still small throughout Europe [5]. In Germany, 0.02% of the cropland area was used for SRCs in 2013 [6]. Also the use of permanent grassland for bioenergy use is rather limited [5].

For the purpose of climate protection it is especially important to identify those bioenergy crops that have the greatest potential to reduce overall GHG emissions. It was shown that GHG emissions from annual bioenergy crops may be significantly higher than those from dedicated bioenergy crops [5,7,8]. This is especially true if soil carbon balance and field $N_2O$ emissions are taken into account [9–11]. High yields and low energy losses during bioenergy conversion are crucial to prevent additional direct or indirect land-use change, which may have severe feedbacks on GHG emissions, inter alia via loss of soil organic carbon (SOC) [12]. Thus, the best bioenergy option has to combine high (net energy) yields and low GHG

*Abbreviations:* $N_2O$, nitrous oxide; $CH_4$, methane; $CO_2$, carbon dioxide; GHG, greenhouse gas; SOC, soil organic carbon; SRC, short rotation coppice.

* Corresponding author.
*E-mail address:* axel.don@ti.bund.de (A. Don).

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emissions along the production chain. Cropland management may enhance yield but also $N_2O$ emissions and may impact atmospheric $CH_4$ uptake. There are numerous pathways of microbiological $N_2O$ production in soils [13–15]. As a consequence, predicting direct $N_2O$ emissions is still a challenge [16,17]. Nevertheless, it has often been shown that soil nitrogen (N) and oxygen availability and soil temperature, water content, texture, pH and SOC content range among the most important determinants of $N_2O$ emissions from agricultural soils (e.g. [18–22]). Soil aeration is also closely linked to uptake of atmospheric $CH_4$ into soils [23,24] and $CH_4$ oxidation is influenced by soil nitrogen status [25,26], especially by the concentration of ammonium ($NH_4^+$) [27]. While N availability is mainly determined by fertilization, the crop-type and management activities like tillage affect soil parameters such as soil temperature, SOC content or bulk density. The choice of bioenergy crop may therefore influence $N_2O$ emissions and $CH_4$ fluxes through management activities like fertilization and tillage as well as crop specific changes in soil conditions like moisture and mineral N dynamics.

The cultivation of fast growing trees in SRCs is a promising form of dedicated bioenergy crops due to high biomass yields and low management and nutrient requirements. These plantations are often not fertilized because N recycling is effective and N export via harvest small [28,29]. Moreover a yield response to fertilization is often lacking [30–32], at least if SRCs are established on former croplands [33]. Except for weed control in the first year of planting [34], no herbicide application or tillage is required during the SRC's lifetime of about 20–25 years [35]. Also grasslands that contain a considerable fraction of clover may be used for several years without fertilization because they profit from symbiotic $N_2$ fixation [36]. In contrast, annual arable crops like maize, oilseed rape and wheat require intensive cropland management. Because high amounts of N are withdrawn from the field via harvest, the recommended annual fertilizer applications are about 150 up to >200 kg N $ha^{-1}$ $yr^{-1}$ [e.g. 37,38]. Considering N addition as one of the most important determinants of $N_2O$ emissions [20], direct field $N_2O$ emissions of those annual arable crops are expected to be higher compared to unfertilized, perennial bioenergy crops.

Some authors have already reported on lower $N_2O$ emissions from SRC than conventional crop rotations [39–42]. However, high $N_2O$ emission peaks have also been detected in the year after SRC establishment [43]. Also $N_2O$ emissions of grass-clover as part of a crop rotation were found to be small, whereas incorporation of its residues in the following spring lead to substantial $N_2O$ emissions [44]. The effects of perennial grass-clover cultivation on $N_2O$ emissions are, however, not well documented. More importantly, there is no field study with systematic comparisons of different bioenergy crops at different sites in order to assess which bioenergy crop has the lowest direct field GHG emissions related to its energy yield and if there are site specific differences in this regard.

In this study, net $N_2O$ and $CH_4$ fluxes were measured at three sites for two years to test the hypothesis that fields cultivated with unfertilized perennial bioenergy crops (i.e. recently established SRC and grassland) emit less $N_2O$ than fertilized annual bioenergy crops (i.e. maize, wheat and oilseed rape) since lack of fertilizer addition causes lower N availability for $N_2O$ production. We furthermore hypothesized that $CH_4$ uptake does not depend on the choice of bioenergy crop because $CH_4$ dynamics are rather driven by site dependent soil properties and weather conditions than by cropland management. We determined soil and environmental factors that influence the net exchanges of $N_2O$ and $CH_4$ in order to examine control-pathways of these fluxes. Finally, we test the hypothesis that the gross energy yield-related $N_2O$ emission is higher for fertilized annual bioenergy crops (silage maize or winter wheat) than for unfertilized perennial bioenergy crops (poplar SRC and perennial grassland with a grass-clover mix).

To enable direct comparisons, $N_2O$ emissions and $CH_4$ fluxes were measured on adjacent plots cultivated with different bioenergy crops. The investigations were conducted in two different central German regions in order to additionally take site effects into account. Differences between establishment stages were particularly considered by including the year of SRC and grassland establishment.

## 2. Material and methods

### 2.1. Site description

The study was conducted at three sites in two central German regions that differ with regard to soil and climatic properties, especially precipitation. There were poplar SRC and grassland plots at each site, while cropland plots were only available at two sites. Two study sites are located close to the village of Gierstädt (Gierstädt I: 51.06° N, 10.82° E, 189 m a.s.l., Gierstädt II: 51.07° N, 10.81° E, 193 m a.s.l.) in the Thuringian Arable basin. The climate is rather dry with a mean annual precipitation (MAP, 1981–2010) of 534 mm and a mean annual temperature (MAT, 1981–2010) of 9.2 °C [45]. At the Gierstädt I site, a short rotation coppice ($SRC_{GI}$) has been established with the poplar clone Max 4 (*Populus maximowiczii* × *Populus nigra*), planted in a 0.75 m × 0.5 m scheme on former cropland in 2008. On the same former cropland area, a mixture of perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) was sown in March 2011 ($G_{GI}$) for perennial grassland use with three to four cuts per year. Neither $SRC_{GI}$ nor $G_{GI}$ has been fertilized since its establishment (Table 1). During the experiment, there was no cropland used for annual bioenergy crop production adjacent to the $SRC_{GI}$ and $G_{GI}$ plots. The soil is a calcaric Cambisol with negligible stone contents in the topsoil (Table 2). The poplar trees are connected to the groundwater that is at about 2.4 m depth [46].

The Gierstädt II site is about 2 km north-west of Gierstädt I. Here, an SRC with the poplar clone Max 1 (*P. maximowiczii* × *P. nigra*; $SRC_{GII}$, double rows of 0.75 × 1.5 × 1 m) and grassland ($G_{GII}$) as in Gierstädt I were established on cropland in March 2011 (Table 1). The cropland adjacent to $SRC_{GII}$ and $G_{GII}$ was used for maize cultivation by a local farmer in 2011, 2012 and 2013 (annual crop; $A_{GII}$). The soil of the Gierstädt II site is a haplic Cambisol on marlstone [46]. The stone content of the topsoil is negligible and bulk density is lower than in Gierstädt I (Table 2).

In the other study area, the rural district of Göttingen, MAP is higher than at the Gierstädt sites (651 mm) and MAT is 9.2 °C [45]. This area's study site is situated on a hill close to the village of Reiffenhausen (51.40° N, 9.99° E, 323 m a.s.l.). As in Gierstädt II, poplar SRC with Max 1 ($SRC_R$) and grassland with a grass-clover mixture ($G_R$) were established on cropland in March 2011 (Table 1). Because winter barley had already been sown by the landowner before the sites could be rent for SRC and grassland establishment, he applied 46 kg N $ha^{-1}$ to the cropland shortly before $SRC_R$ and $G_R$ were established. One part of the cropland was then tilled with a cultivator to prepare the soil for SRC and grassland establishment. No fertilizer was applied during $SRC_R$ and $G_R$ land-use. The plots with annual crops in Reiffenhausen were cultivated with oilseed rape in 2011 ($A1_R$) and winter wheat in 2013 ($A2_R$). Both, $A1_R$ and $A2_R$, were adjacent to $SRC_R$ and $G_R$ and managed by local farmers. Due to wild boars in this region, the farmers did not grow maize. Since the crop rotations had already been decided by the farmers, it was not possible to include the same annual crop in the investigation in both years or to keep the same plot for annual bioenergy crop production. In consequence, the annual crops do differ between the sites and years (in