



VOC emissions and carbon balance of two bioenergy plantations in response to nitrogen fertilization: A comparison of *Miscanthus* and *Salix*[☆]

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ABSTRACT

Energy crops are an important renewable source for energy production in future. To ensure high yields of crops, N fertilization is a common practice. However, knowledge on environmental impacts of bioenergy plantations, particularly in systems involving trees, and the effects of N fertilization is scarce. We studied the emission of volatile organic compounds (VOC), which negatively affect the environment by contributing to tropospheric ozone and aerosols formation, from *Miscanthus* and willow plantations. Particularly, we aimed at quantifying the effect of N fertilization on VOC emission. For this purpose, we determined plant traits, photosynthetic gas exchange and VOC emission rates of the two systems as affected by N fertilization (0 and 80 kg ha⁻¹ yr⁻¹). Additionally, we used a modelling approach to simulate (i) the annual VOC emission rates as well as (ii) the OH[•] reactivity resulting from individual VOC emitted. Total VOC emissions from *Salix* was 1.5- and 2.5-fold higher compared to *Miscanthus* in non-fertilized and fertilized plantations, respectively. Isoprene was the dominating VOC in *Salix* (80–130 µg g⁻¹ DW h⁻¹), whereas it was negligible in *Miscanthus*. We identified twenty-eight VOC compounds, which were released by *Miscanthus* with the green leaf volatile hexanal as well as dimethyl benzene, dihydrofuranone, phenol, and decanal as the dominant volatiles. The pattern of VOC released from this species clearly differed to the pattern emitted by *Salix*. OH[•] reactivity from VOC released by *Salix* was ca. 8-times higher than that of *Miscanthus*. N fertilization enhanced stand level VOC emissions, mainly by promoting the leaf area index and only marginally by enhancing the basal emission capacity of leaves. Considering the higher productivity of fertilized *Miscanthus* compared to *Salix* together with the considerably lower OH[•] reactivity per weight unit of biomass produced, qualified the C₄-perennial grass *Miscanthus* as a superior source of future bioenergy production.

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1. Introduction

The assumed increased global energy demand in the future (International Energy Agency, 2011), the obvious scarcity of natural resources, as well as economic aspects will enforce the development of renewable energy technologies compared to usage of traditional fossil fuels (Chu and Majumdar, 2012; Moriarty and Honnery, 2012). Power generation from bioenergy crops is considered a remarkable renewable energy source (Bentsen and

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Felby, 2012) and European Community (EC) countries have stipulated biomass to account for 56% of renewable energy generation by 2020, corresponding to an increase in bioenergy generation from 3.8 EJ in 2005 to 10.0 EJ (Bentsen and Felby, 2012).

The cultivation of short rotation coppices (SRC) with fast growing woody plant species seems to be promising considering yield, energy output, economic and ecological aspects and, therefore, has high establishing potential in large areas of Europe (Ericsson et al., 2009; Gauder et al., 2012; Werner et al., 2012; Aust et al., 2014; Schweier et al., 2017). For such bioenergy plantations, SRC of willow (*Salix* spp.) or poplar (*Populus* spp.) are often recommended in Central Europe (Boehmel et al., 2008), because their woody biomass has better combustion properties than non-woody solid biofuels (Gauder et al., 2012). Besides SRC, perennial grasses with high growth potential are recommended for high-yield bioenergy plantation systems (Boehmel et al., 2008). The C₄-plant *Miscanthus* spp. is a promising species due to its high production capability in temperate regions (Lewandowski et al., 2000; Heaton et al., 2010; Gauder et al., 2012).

Despite positive reputation of bioenergy plantations in general, ecological assessments have highlighted potentially negative effects of some cropping systems (Rowe et al., 2009, 2013; Cherubini et al., 2011; Schweier et al., 2017). In particular, the emission of nitrous oxide (N₂O) is able to counteract the reduction of the global warming potential by C sequestration (Mosier, 1994). Triggered by application of N-fertilizer, N₂O emission may even overcompensate the effect of C sequestration (Crutzen et al., 2008) and it additionally worsens the greenhouse gas (GHG) balance of a given plantation system because of the high energy input needed for fertilizer production (Kongshaug, 1998; Schweier et al., 2017). Depending on the history of a plantation, also CO₂ release from the soil C stock can affect the GHG balance of such systems (Searchinger et al., 2008).

An additional environmental impact receiving more attention in the last years is the emission of volatile organic compounds (VOCs) (Ashworth et al., 2013; Graus et al., 2013). VOCs play an important role in air chemistry; depending on their hydroxyl radical (OH[•]) reactivity, they contribute to the formation of tropospheric ozone (Atkinson and Arey, 2003), and to aerosol formation, the latter counteracting global warming (Claeys et al., 2004). VOCs indirectly affect global warming by quenching atmospheric (OH[•]) concentrations thereby increasing the half-lifetime of atmospheric methane, whose degradation depends on the OH[•] availability (Pike and Young, 2009). Although thousands of different VOCs are emitted into the atmosphere by vegetation, the emission of isoprene is quantitatively of highest significance as it contributes about 44% to the total annual biogenic VOC emission of about 1150 Tg C (Guenther et al., 1995, 2012). Most woody species used in bioenergy plantations such as poplar, willow, oil palm and eucalypts are strong isoprene emitters and expanding the area of such plantations might have considerable impacts on regional air quality (Wiedinmyer et al., 2006; Ashworth et al., 2012, 2013; Copeland et al., 2012; Rosenkranz et al., 2015).

In the present study, we concentrate on the bioenergy plants *Miscanthus* and *Salix*. It is expected that these cropping systems will have a significant share of future's sustainable energy sources (Fischer et al., 2005; Styles et al., 2008). Both species can achieve high biomass yields in temperate climate zones (Price et al., 2004; Wilkinson et al., 2007; Boehmel et al., 2008; Gauder et al., 2012), but while willow is known as high isoprene emitter, *Miscanthus* is supposed to emit only minor amounts of less reactive VOCs (Copeland et al., 2012). However, emissions might change with fertilization, although the direction of the change has not been conclusively evaluated, since it depends on species and type of emission (Harley et al., 1994; Monson et al., 1994; Litvak et al., 1996;

Ormeño and Fernandez, 2012).

Investigations regarding the sensitivity of VOC emissions of *Salix* or *Miscanthus* to N fertilization have not been reported. In particular, the usual management of willow SRC involves fertilization (Jug et al., 1999), while *Miscanthus* is able to fix atmospheric nitrogen and, thus, requires low if any fertilizer input (Heaton et al., 2008; Rowe et al., 2009). The present study aims to narrow this gap by determining the emission of VOCs from *Miscanthus* and *Salix* at leaf and plantation level and, thus, to quantify the impact of N fertilization on these emissions. Moreover, by considering biomass increment, we aimed at estimating the potential C sequestration by these cropping systems. It was hypothesized that (i) *Miscanthus* is preferable over *Salix* plantations because of lower isoprene and other VOC emissions, hence, lower OH[•] reactivity, and that (ii) the application of fertilizer further enforces this difference due to enhanced isoprene emissions from *Salix*.

2. Materials and methods

2.1. Experimental site and field trial description

The field experiment was performed in Southwest Germany at the University of Hohenheim research station, Ihinger Hof (48.75°N and 8.92°E, 480 m asl). Details of the field site are given in Gauder et al. (2012). In 2002, the experimental site with willow (*Salix schwerinii* × *viminalis* "Tora") and *Miscanthus* (*M. x giganteus*) plants was established (Boehmel et al., 2008). The trial was a complete split-plot design with main plots for the cropping system, which were replicated four times. These main plots were divided into two subplots with an area of 160 m² each with different N-application levels. Hence, every subplot was also four times replicated in total. Within each subplot, sampling was done with at least a 2 m buffer to the border. On the experimental plots, either 0 kg N ha⁻¹ yr⁻¹ or 80 kg N ha⁻¹ yr⁻¹ were applied annually as ammonium stabilized N-fertilizer (Entec26; K + S Nitrogen GmbH, Mannheim, Germany) which contained 7.5% nitrate-N, 18.5% ammonium-N, 13% sulphur and DMPP as N stabilizer. All other nutrients were held in optimum ranges. The agricultural treatments were in accordance to common cultivation practices. The *Miscanthus* plots were harvested each year in late winter or early spring. In 2010, the *Miscanthus* plots were harvested in March and fertilizer was lastly applied on the respective subplots on April 9th, 2010, before the new sprouts emerged. The *Salix* SRC was harvested in 2003, one year after planting. Afterwards the rotation time was three years. The last harvest was on February 2nd, 2009. Fertilizer was applied last on April 21st, 2010. No weed control was carried out in 2010 for both crops.

2.2. Plant biomass data determination

The planting density of the *Salix* coppice was 20,000 plants ha⁻¹. During our measuring campaign end of June 2010, the number of shoots per tree (n = 4) was counted and the shoots were distinguished into three classes according to height (i.e. small shoot: 0–2 m; middle shoot: 2–4 m; long shoot: 4–7 m). In the *Miscanthus* plots, plant density (ha⁻¹) was calculated annually by counting the number of shoots per m². For both species, shoot height of four plants was assessed (n = 4). Subsequently, the fresh leaves of every shoot were collected and their areas were determined using scanner (CanonScan Lide 70, Canon, Amsterdam, The Netherlands) and an image analyzer software (GSA Image Analyser, GSA GmbH, Rostock, Germany). The obtained leaves were oven-dried (60 °C, 48 h) and, thereafter, we determined the dry weights. From these data, mean leaf area, weight per plant and leaf area index and specific leaf weight per ha, as well as mean stand

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