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Volatile organic compound emissions from straw-amended agricultural soils and their relations to bacterial communities: A laboratory study

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ABSTRACT

A laboratory study was conducted to investigate volatile organic compound (VOC) emissions from agricultural soil amended with wheat straw and their associations with bacterial communities for a period of 66 days under non-flooded and flooded conditions. The results indicated that ethene, propene, ethanol, i-propanol, 2-butanol, acetaldehyde, acetone, 2-butanone, 2-pentanone and acetophenone were the 10 most abundant VOCs, making up over 90% of the total VOCs released under the two water conditions. The mean emission of total VOCs from the amended soils under the non-flooded condition (5924 ng C/(kg·hr)) was significantly higher than that under the flooded condition (2211 ng C/(kg·hr)). One "peak emission window" appeared at days 0–44 or 4–44, and over 95% of the VOC emissions occurred during the first month under the two water conditions. Bacterial community analysis using denaturing gradient gel electrophoresis (DGGE) showed that a relative increase of Actinobacteria, Bacteroidetes, Firmicutes and γ-Proteobacteria but a relative decrease of Acidobacteria with time were observed after straw amendments under the two water conditions. Cluster analysis revealed that the soil bacterial communities changed greatly with incubation time, which was in line with the variation of the VOC emissions over the experimental period. Most of the above top 10 VOCs correlated positively with the predominant bacterial species of Bacteroidetes, Firmicutes and Verrucomicrobia but correlated negatively with the dominant bacterial species of Actinobacteria under the two water conditions. These results suggested that bacterial communities might play an important role in VOC emissions from straw-amended agricultural soils.

Introduction

Volatile organic compounds (VOCs) have received special attention because of their important impact on atmospheric photochemistry by the formation of tropospheric ozone (O_3) and secondary organic aerosols (SOA) (Singh et al., 1995; Atkinson, 2005). They can also affect biogeochemical processes in soil through altering the rates of carbon and nitrogen cycling (Smolander et al., 2006; Asensio et al., 2012) and stimulating or inhibiting the growth and activity of bacteria and fungi (Xu et al., 2004; Ramirez et al., 2010), and thus affect plant growth (Farag et al., 2006).

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Agricultural emissions are considered to be an important source of atmospheric VOCs. Previous field and laboratory measurements have quantified the VOC emissions from planted and unplanted agricultural soils, including non-methane hydrocarbons (NMHCs) (Redeker et al., 2003), volatile organic sulfur compounds (VOSCs) (Nouchi et al., 1997; Liu et al., 2010; Yi et al., 2013) and oxygenated volatile organic compounds (OVOCs) (Schade and Custer, 2004; Leff and Fierer, 2008). The available data suggest that the VOC emissions from agricultural fields are largely produced by the aboveground living crops, and change significantly with their growth stages (Nouchi et al., 1997; Redeker et al., 2003; Yi et al., 2013). Compared to aboveground living vegetation, dead crop straws have received less attention with respect to their influence on the VOC emissions from agricultural fields when they return into soils (Nouchi et al., 1997), although a recent study on VOC emissions from forest soils and leaf litter suggested that the decomposition of dead plant matter contributed substantially to VOC emissions from natural soils (Hellén et al., 2006).

Agricultural production generates a large amount of crop straws, approximately 2.5 billion tons per year globally (FAO, 2013) and 0.8 billion tons per year in China (Jiang et al., 2012). The crop straw is commonly incorporated into cultivated fields to provide plant nutrients and maintain soil fertility. It is estimated that 46.1% of crop straws are returned to agricultural soils every year in China (Jiang et al., 2012). A laboratory experiment on the VOC emissions from rice and maize straws showed that the emission of six VOCs (ethane, ethene, propane, propene, n-pentane and methyl chloride) totally reached 1.73 ng/gdw (g dry weight) per hour at 20°C and increased to 18650 ng/(gdw·hr) at 70°C (Derendorp et al., 2011). Therefore, the decomposition of the returned crop straw could release a mass of VOCs, and thus may influence the VOC emissions from agricultural soils.

Microorganisms play a critical role in soil VOC emissions (http://bioinformatics.charite.de/mvoc/) (Lemfack et al., 2014). Soil bacteria are capable of producing a diverse array of VOCs, including alcohols, ketones, aldehydes, esters, carboxylic acids, lactones, terpenes, sulfur and nitrogen compounds, and aliphatic and aromatic hydrocarbons during the decomposition of organic substances (Leff and Fierer, 2008; Gray et al., 2010; Ramirez et al., 2010). Some VOCs are characteristically produced by specific phylogenetic groups or species. For instance, the VOC spectra of *Pseudomonas* species are dominated by alcohols, aldehydes, ketones, alkanes and alkenes, whereas *Aspergillus* and *Penicillium* species release distinct alcohols, ketones and furans, and *Streptomyces*, *Bacillus* and *Pseudomonas* are known to produce S-containing volatiles (Gerber, 1968; Medsker et al., 1968, 1969; Dickschat et al., 2005). On the other hand, soil microbes can readily consume a wide range of VOCs and may represent an important sink for VOCs in terrestrial ecosystems (Smolander et al., 2006; Leff and Fierer, 2008). Furthermore, the microbial production or consumption of soil VOCs also depends on the presence of substrates and environmental conditions in the soils (Blom et al., 2011). Several studies have revealed that straw return shifted the microbial diversity and structure in cultivated fields (Tanahashi et al., 2005; Asari et al., 2007; Huang et al., 2012), with an increase of γ-Proteobacteria and a decrease of Sphingobacteria and Verrucomicrobia in the amended soil compared to the control soil. However, the corresponding changes in the VOC emissions from straw-amended agricultural soils are still unknown, so a study on the relations of the VOC emission to bacteria communities would be useful for clarifying the role of bacteria communities in the VOC emission from straw-amended agricultural soils, as well as understanding the microbial mechanism of soil VOC emissions.

Cultivated soils used for upland crop production are mostly under aerobic conditions, and soils for irrigated rice production are flooded for various lengths of time. In our previous study (Wang et al., 2015), we measured the C_2–C_5 NMHC emissions from straw-amended agricultural soils under non-flooded and flooded conditions, and found substantially higher light alkene emissions from agricultural soils after straw return, particularly under non-flooded conditions. We also found a significant correlation of the C_2–C_5 NMHC fluxes with microbial biomass C, respiration rate and population in amended agricultural soils. However, the emissions of other VOCs and the roles of specific microbial species remain unidentified. In the present study, a more specific and comprehensive survey was conducted on VOC emissions, including alkanes, alkenes, alcohols, aldehydes, ketones, furans, esters, sulfides and halocarbons, as well as the bacterial community structure in straw-amended agricultural soils under non-flooded and flooded conditions. The goals were to determine how the VOC release patterns and bacterial community structures varied with incubation time in straw-amended soils under two water conditions, and to study the relationship between soil VOC emissions and bacterial communities in straw-amended agricultural soils.

1. Materials and methods

1.1. Soil and straw collection

The soils used in the experiment were sampled from the 0–5 cm layer of a typical subtropical paddy field under rice-wheat crop rotation in May 2013 after wheat harvest in Wuhu, China (N 31°16.804′, E118°35.164′). The soil is characterized as gley paddy soil with a clay loam texture (22.4% clay, 40.1% silt, 37.5% sand), bulk density of 1.30 g/cm^3, pH of 5.18, water holding capacity of 80%, total-C content of 18 g/kg, total-N content of 5.1 g/kg, total-S content of 1.7 g/kg, available-S content of 36.8 mg/kg and available-P content of 7.35 mg/kg. After collection, soils were air-dried, ground and passed through a 2-mm sieve, then stored in a cool and dry place for use.

Fresh wheat straw was collected immediately after harvesting in the same field at the same time. The wheat straw characteristics were as follows: total-C content of 395 g/kg, total-N content of 4.5 g/kg, total-S content of 0.65 mg/kg, and water content of 7%. After collection, the wheat straw was air-dried and cut to 0.5 cm for use.

1.2. Incubation experiment

The experiment was performed in the laboratory. Self-made reactors were employed to incubate agricultural soils before and after amendment of wheat straw, and dynamic chambers were used to collect gas samples. The design and operation of the reactors and the chambers has been described in detail