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Quantification of the effects of various soil fumigation treatments on nitrogen mineralization and nitrification in laboratory incubation and field studies

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HIGHLIGHTS

- Pic significantly increased soil mineral nitrogen during the first 2 weeks.
- All four fumigants retarded nitrification in both lab and field studies.
- Pic has a stronger inhibitory effect on nitrification compared to other fumigants.
- An S-shaped function described the $NO_3^- - N$ concentrations in lab incubation samples.

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ABSTRACT

Better quantification of nitrogen mineralization and nitrification after fumigation would indicate if any adjustment is needed in fertilizer application. The effects of chloropicrin (Pic), 1,3-dichloropropene (1,3-D), dimethyl disulfide (DMDS) and metham sodium (MS) fumigation on soil nitrogen dynamics were evaluated in lab incubation and field studies. Although some differences were observed in $NH_4^+ - N$ and $NO_3^- - N$ concentrations in lab incubation and field experiments, both studies led to the same conclusions: (1) Soil fumigation was shown to increase soil mineral nitrogen only during the first 2 weeks after fumigation (WAF). In particular, Pic significantly increased soil mineral nitrogen in both studies at 1 WAF. However, for all fumigant treatments the observed effect was temporary; the soil mineral content of treated samples recovered to the general level observed in the untreated control. (2) All the fumigation treatments depressed nitrification temporarily, although the treatments exhibited significant differences in the duration of nitrification inhibition. In both studies, for a limited period of time, Pic showed a stronger inhibitory effect on nitrification compared to other fumigant treatments. An S-shaped function was fitted to the concentrations of $NO_3^- - N$ in lab incubation samples. The times of maximum nitrification (t_{max}) in DMDS and MS treatments were 0.97 week and 1.03 week, which is similar to the untreated control (t_{max} = 1.02 week). While Pic has the longest effect on nitrifying bacteria, nitrification appears to restart at a later time (t_{max} = 14.37 week).

1. Introduction

Soil fumigation is a highly effective technique for the control of soil-borne pests (insects, nematodes, weeds, and fungal pathogens) in many vegetable, fruit, nut, ornamental, and nursery crops (Ajwa and Trout, 2004; Minuto et al., 2006; Desaeger et al., 2008; Santos et al., 2009; Haydock et al., 2010). Most fumigants are known to have a broad biocidal activity, killing most soil organisms (Ibekwe et al., 2010). Consequently, fumigants affect the microbial community and activity of non-target microorganisms, altering nutrient transformation in the soil, and may potentially have effects on soil fertility and the productivity of agricultural systems.

Fumigation has a marked effect on N mineralization. It increases mineralization rates, due to the mineralization of microbial biomass killed during fumigation (Lebbink and Kolenbrander, 1974; Shen et al., 1984; De Neve et al., 2004). In addition, it results in partial soil sterilization. Lysis of the dead microbes provides the surviving flora with new substrate, leading to enhanced mineralization (Müller et al., 2003). When soil organic matter decomposes, ammonia is liberated and then converted to nitrate under favorable soil conditions. This process, called nitrification, is significantly reduced by soil fumigation (Duniway, 2002). Fumigants are

Abbreviations: Pic, chloropicrin; DMDS, dimethyl disulfide; MS, metham sodium; 1,3-D, 1,3-dichloropropene; WAF, week after fumigation; wk, week.

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capable of retarding the biological oxidation of ammonia by reducing the activity of the nitrifying bacteria responsible for the first step in nitrification (Yamamoto et al., 2008; Brown and Morra, 2009). The inhibition of nitrification may cause an accumulation of soil ammonium and a reduction in soil nitrate. Indeed, some studies have shown increases in soil ammonium concentration in fumigated soils (Ebbels, 1971; Jenkinson and Powlson, 1976; Shen et al., 1984; MacNish, 1986; Zhang et al., 2011). Where soil mineral nitrogen exists to a large extent in the form of $NH_4^+ - N$ it may strongly reduce the accumulation of $NO_3^- - N$, thereby decreasing the leaching and denitrification losses of $NO_3^- - N$ significantly.

If substantial or prolonged changes in mineral nitrogen occur after soil fumigation, this would necessitate adjustments in nitrogen fertilizer application to improve nitrogen use efficiency. The overall objective of this study was to quantify the dynamic effects of fumigation on N mineralization and nitrification in laboratory incubation and field studies.

2. Materials and methods

2.1. Lab incubation study

Soil samples were collected from the top 20 cm of greenhouse soil in Tongzhou district, southeast of Beijing (34.6% sand, 51.8% silt and 13.6% clay; soil pH 7.1; organic matter 3.1%; bulk density 0.93 g cm^{-3}) where the field experiments were conducted. The greenhouse had grown cucumber and tomato in rotation for at least 3 years. The soil was sieved through a 2 mm screen and pre-incubated for 7 d at room temperature in the dark, before any treatments were applied.

To study the effects of fumigants on mineral nitrogen in soil, 500 g soil samples were placed in 2.5 L desiccators, treated with 0.25 g $(NH_4)_2SO_4$ (equivalent to 100 mg N kg^{-1} soil) and mixed thoroughly. The experimental design consisted of four fumigant treatments (chloropicrin, Pic; 1,3-dichloropropene, 1,3-D; dimethyl disulfide, DMDS; metham sodium, MS) and a control in three replicates. Fumigants were added into the desiccators at typical field application rates for each chemical (Pic 53 mg kg^{-1}, 1,3-D 39 mg kg^{-1}, DMDS 68 mg kg^{-1}, MS 54 mg kg^{-1}) (Spokas et al., 2006). The desiccators were sealed with vaseline and left for 7 d in the dark at 25 °C.

2.2. Experimental design of field study

Field experiments were conducted in the same tomato greenhouse in Tongzhou district, southeast of Beijing (116°44′E, 36°53′N). The field experimental design consisted of four fumigant treatments and an untreated control randomized in a complete block design with three replicated plots. The fumigant treatments, doses and application methods are summarized in Table 1.

A drip irrigation system was setup in the experimental area, with emitters 30 cm apart and an emitter flow rate of 1.9 L h^{-1} at 1 atm. The distance between drip tapes was the width of the tomato planting beds (80 cm). Before fumigation, 45 g m^{-2} diamine phosphate and 1.5 kg m^{-2} organic fertilizer were applied to the soil.

All fumigants were applied on 11 July. After fumigation, the soil was covered with 0.04 mm-thick polyethylene film (Hebei Baoshuo Co., Ltd.) for approximately 1 week, and then tilled to disperse the fumigants 1 week before transplanting tomatoes.

2.3. Soil sampling and analysis

After 7 d lab fumigation, all the desiccators were taken to a ventilation hood to remove the fumigant gases, and the soil in each desiccator was mixed thoroughly. Soil samples were collected at 0, 1, 2, 4, 8, 12, 16, 20 and 24 weeks after fumigation (WAF; 0 WAF was defined as before fumigation, and 1 WAF was defined as the date when the fumigants were removed). The soil moisture content in each desiccator was maintained gravimetrically after each sampling.

In the field experiment, soil samples from the top 20 cm depth were collected at 1, 2, 4, 8, 12 and 16 weeks after fumigation (WAF; 1 WAF was defined as the date when the plastic fumigation film was removed).

Weigh 10.00 g of soil samples, add 40 ml of 2 *M* KCl extraction solution, shake for 0.5 h at room temperature, and filter the soil slurries. Soil mineral nitrogen (defined as $NH_4^+ - N$ and $NO_3^- - N$) were determined by standard automated colorimetric techniques based on the Berthelot reaction, and cadmium reduction method, respectively (using a Futura Continuous Flow Analytical System, Alliance instruments, France).

2.4. Data analysis

In previous studies, the percentage inhibition of nitrification by chemicals was calculated from $[(C–S)]/C \times 100$, where S = amount of $NO_3^- - N$ produced in the soil sample treated with chemicals, and C = amount of $NO_3^- - N$ produced in the control (no chemicals added) (McCarty and Bremner, 1989; Abbasi et al., 2011). The formula may be suitable for our lab study only, because lab incubation is a closed system and soil $NO_3^- - N$ is unable to move easily. In contrast, soil $NO_3^- - N$ in field conditions is highly mobile and prone to leaching. So, for the field study, it is more appropriate to calculate the percentage inhibition of nitrification by chemicals in the following manner: $[(S–C)]/C \times 100$, where S = amount of $NH_4^+ - N$ accumulated in the soil sample treated with chemicals, and C = amount of $NH_4^+ - N$ accumulated in the control (no chemicals added).

To assess the effect of fumigant treatments on nitrification in our lab incubation study, an S-shaped function was fitted to the $NO_3^- - N$ concentrations of treated soil samples (Zhang et al., 2000; De Neve et al., 2004) using the following equation:

$$NO_3^- - N(t) = NO_3^- - N(0) + N_A[1 + \beta \exp(-k\,t)]^{-1} \quad (1)$$

where N_A (mg N kg^{-1} soil) is the potential amount of N nitrified, β is a dimensionless quantity that determines the position of the inflection point, k is the nitrification rate constant (week^{-1}), and

Table 1
Fumigant dose and application method in field study.

Soil fumigant	Dose	Chemical structure	Percent a.c.	Application methods
Pic	500 kg ha^{-1}	CCl_3NO_3	99	Manual injection
DMDS	800 L ha^{-1}	$C_2H_6S_2$	99.5	Irrigation system
MS	1000 L ha^{-1}	$C_2H_4NNaS_2$	42	Irrigation system
1,3-D	200 kg ha^{-1}	$C_3H_4Cl_2$	93	Irrigation system
Control	NA	NA	NA	NA

Pic = chloropicrin; 1,3-D = 1,3-dichloropropene; DMDS = dimethyl disulfide; MS = metham sodium; a.c = active component; NA = not applicable.