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Evaluation of the effects of plastic mulching and nitrapyrin on nitrous oxide emissions and economic parameters in an arid agricultural field

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A R T I C L E I N F O

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A B S T R A C T

Plastic film has been widely applied to address water shortages by reducing soil evaporation in arid and semi-arid regions, but it simultaneously affects soil nitrous oxide (N_2O) emissions. Moreover, after the application of plastic film, the ability of nitrification inhibitor to reduce N_2O emissions remains unclear. In this study, the chamber method was used to measure N_2O emissions and a modified diffusion equilibrium sampler was used to obtain N_2O concentrations in an oasis cotton field. Non-mulched and mulched treatments were used to investigate the influence of plastic mulching on soil N_2O dynamics, and mulched plus nitrapyrin treatment was used to evaluate the ability of nitrapyrin to reduce N_2O emissions under plastic mulching. Moreover, we also estimated the net economic return and cost related to an eventual environmental taxation on N_2O emission of these practices. In all treatments, the ridge soil was the origin of most N_2O (82–87%) emissions, which remained at low levels during the non-fertigation period (ranging from 0.4–17.1 g N ha^{-1} day^{-1}) and sharply increased after the split application of urea; emissions during the fertigation periods accounted for 57–85% of the total N_2O emissions in all treatments. Compared with the non-mulched treatment, the use of plastic film is a "win-win" strategy for both agricultural income (net economic returns increased by $436–522 ha^{-1} $year^{-1}$) and N_2O mitigation (emissions reduced by 19–28%), even without incentives. Although the addition of nitrapyrin to the urea reduced the cumulative N_2O emissions by 23–39% under plastic mulching, and therefore reduced the costs related to an eventual environmental taxation on N_2O emission by approximately $2 ha^{-1} $year^{-1}$, this benefit could not compensate for the additional cost of inputting nitrapyrin ($24 ha^{-1} $year^{-1}$) because this technique did not have a significant effect on cotton yields. Therefore, the use of nitrapyrin is probably a "lose-win" strategy for farmers and N_2O mitigation and not suitable for reducing N_2O emissions in oasis cotton fields.

1. Introduction

Nitrous oxide (N_2O) is an important trace gas in the atmosphere that contributes to global warming and stratospheric ozone destruction. Approximately 60% of the total anthropogenic N_2O emissions originate from fertilized agricultural soils through nitrification and denitrification processes (Smith, 2017). In addition, soil environmental factors (e.g., temperature and moisture) and management practices (e.g., tillage and irrigation) greatly affect N_2O emissions from agricultural fields (Burzaco et al., 2013; Scheer et al., 2013; Smith, 2017; Volpi et al., 2017).

The application of plastic film to agricultural fields is widely used to mitigate water shortages and improve crop yields in the arid and semiarid regions of China (Li et al., 2004; Liu et al., 2013a), and approximately 28% of arable lands are covered with plastic film in these regions (China Statistical Yearbook, 2014). This practice can significantly reduce (Berger et al., 2013), not affect (Liu et al., 2014b) or increase (Cuello et al., 2015; Kim et al., 2017) soil N_2O emissions. On the one hand, plastic mulching increases soil temperature and moisture, which in turn enhances the production of N_2O by stimulating nitrifier and/or denitrifier activities (Cuello et al., 2015; Kim et al., 2017). On the other hand, this practice promotes N uptake by plants, which then limits or reduces N_2O production through a decrease in soil mineral N content (Liu et al., 2014b). In addition, because soil N_2O emissions are the combined result of N_2O production, transport and consumption in the soil profile, plastic film can limit the transport of N_2O from the soil

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to the atmosphere, which likely reduces N_2O emissions by enhancing N_2O consumption during the diffusion process (Chapuis-Lardy et al., 2007). However, knowledge of the impact of plastic mulching on soil N_2O dynamics is very limited (Berger et al., 2013).

Reducing N_2O emissions from agricultural soils has become a major topic related to addressing global warming, and the addition of nitrapyrin to N fertilizers is recommended as an effective method that inhibits the transformation of nitrite (NO_2^-) to nitrate (NO_3^-) (Bremner and Blackmer, 1978; Ma et al., 2015) by reducing the abundance of ammonia-oxidizing bacteria (Cui et al., 2013; Xi et al., 2017) or archaea (Yao et al., 2016). However, previous studies based on field and laboratory experiments have reported that the addition of nitrapyrin decreased (Bremner et al., 1981; Bronson et al., 1992; Burzaco et al., 2013; Li et al., 2015; Scheer et al., 2016; Xiong et al., 2013; Zhang et al., 2015) or did not affect N_2O emissions from agricultural soils (McTaggart et al., 1997; Parkin and Hatfield, 2010), and these differences varied with soil environmental conditions (Chen et al., 2010; Chen et al., 2017), precipitation (Omonode and Vyn, 2013), soil organic matter content (Awale and Chatterjee, 2017) and the timing of fertilization (Parkin and Hatfield, 2010). The use of plastic film increases soil temperature and moisture (Cuello et al., 2015), which can probably limit the ability of nitrapyrin to reduce N_2O emissions in the field (Chen et al., 2010), but this has not yet been evaluated.

Agricultural practices are determined by farmers' choices, and therefore it is necessary to think beyond greenhouse gas mitigation and assess the economic feasibility of these practices without incentives (Scheer et al., 2016), because some greenhouse gas mitigation targets may not base on an economically feasible strategy at a reasonable economic cost (Wu et al., 2015). To our knowledge, few studies have evaluated the effects of plastic mulching and nitrapyrin on N_2O emissions based on economic returns (Oliveira Silva et al., 2015; Randall and Vetsch, 2005; Xiong et al., 2013). The National Development and Reform Commission of China plans to adopt the nationwide carbon market as one of its important policies in 2017 (Cai et al., 2016). Therefore, the environmental externality caused by N_2O emissions would be internalized, immediately influencing farmers' behaviour. In this context, it is important to identify "win-win" strategies that can both increase (or at least not decrease) agricultural income and reduce N_2O emission from agricultural fields (Coderoni et al., 2015; Li et al., 2017). Indeed, if the cost of plastic mulching or nitrapyrin cannot be compensated by increasing crop yields and reducing N_2O emissions (producing a "lose-win" situation), this practice should not be employed (Randall and Vetsch, 2005).

In general, the use of plastic film significantly increases crop yields (Qin et al., 2015), which means that this practice would probably produce a "win-win" or "win-lose" situation as this technology has been documented to both reduce or increase N_2O emissions. In general, the use of nitrapyrin slightly improves grain yields using suitable fertilization methods. Burzaco et al. (2014) found that adjusting N application method close to the time of N uptake by plants reduced the benefit of nitrapyrin on yield. In a semi-arid region of China, the split application of N fertilizer under mulching increased the N-use efficiencies of wheat and maize (Wang et al., 2016), which probably made crop yield insensitive to nitrapyrin addition. Moreover, in the Jiangsu Province of China, Xiong et al. (2013) found that nitrapyrin addition was only suitable for reducing high N_2O emissions (13.9 and 17.5 kg N ha^{-1} year^{-1}) from vegetable fields at high N fertilization rates (1300 and 1733 kg N ha^{-1} year^{-1}, respectively), if its benefit of reducing high N_2O emissions was greater than the cost of the nitrapyrin. In the oasis cotton fields of China, N fertilization rates range from 240 to 360 kg N ha^{-1} year^{-1}, and cumulative N_2O emissions range from 2.9 to 5.5 kg N ha^{-1} year^{-1} (Lv et al., 2014). Therefore, even though we considered the benefit of N_2O reduction associated to taxation following the use of nitrapyrin, this practice is probably not suitable for reducing N_2O emissions in this agricultural system if it does not increase the net benefit (a "lose-win" situation). The objectives of this study were to evaluate the effects of plastic mulching on N_2O emissions and the ability of nitrapyrin to reduce N_2O emissions under plastic mulching. In general, the use of plastic film increases crop yields; if this practice could also reduce N_2O emissions, this practice could be a "win-win" strategy for both the farmer and the environment. If the use of nitrapyrin does not significantly increase cotton yields under mulching, we hypothesize that the benefit of nitrapyrin in reducing the N_2O emissions cannot compensate for the private cost of its input (a "lose-win" strategy).

2. Materials and methods

2.1. Study site and experimental design

A field experiment was conducted at an oasis cotton field in Northwest China (40°37′N, 80°45′E; altitude: 1028 m) in 2014 and 2015. Over the past 30 years (from 1986 to 2015), the annual mean air temperature is 11.6 °C, the annual mean precipitation is 63 mm and approximately 74% precipitation occurs from June to October, and the mean annual evaporation from free water surface is 2500 mm. In the 0–10 cm layer, the soil texture was silt loam with 44% sand (0.02–2 mm), 50% silt (0.002–0.02 mm) and 6% clay (< 0.002 mm); the soil organic carbon, soil C/N ratio, bulk density and pH (1:5 with distilled water) were 8.0 g C kg^{-1}, 11.9, 1.5 g cm^{-3} and 7.6, respectively.

The experiment included non-mulched (NM), mulched (M) and mulched plus nitrapyrin (M + NI) treatments. Each treatment was replicated three times, assigned in a completely randomized design and applied to plots that were 10 m long and 6 m wide. The NM and M treatments were used to investigate the influence of plastic mulching on soil N_2O emissions. In the NM treatment, both the ridge and furrow soils remained uncovered. In the M treatment, the ridge soils (1.0 m wide) were covered with plastic film (1.2 m wide and 0.02 mm thick) during sowing; the plastic film was maintained for the duration of the growing period and the edge of the film was sealed into the soil; the furrow soil (0.5 m wide) remained uncovered (Fig. 1). In the M + NI treatment, we uniformly applied water-soluble nitrapyrin (Aofutuo Chemical, 24% EC, Zhejiang, China) 4 times via fertigation at a rate of 350 ml ha^{-1} year^{-1} together with the split application of urea to evaluate its ability to reduce N_2O emissions under plastic mulching.

The arable fields were seeded with cotton (*Gossypium herbaceum* L.) at a density of 266,667 plants ha^{-1}. In the three treatments, urea (60 kg N ha^{-1} year^{-1}), diammonium phosphate (20 kg N ha^{-1} year^{-1}) and potash (40 kg K ha^{-1} year^{-1}) were simultaneously incorporated into the soil with tillage. The field was first ploughed using a tractor with a moldboard (30 cm depth), and then break clods using a cultivator (6 cm depth). After two days, ridge soils (100 cm wide and 5 cm high) were formed with a ridging plough. During the irrigation period in both 2014 and 2015, 40 mm of irrigation water was uniformly applied 8 times to support total 320 mm water (Fig. 2b), and during the fertigation period (from 9 July to 8 August in 2014 and from 5 July to 28 July in 2015), urea (320 kg N ha^{-1}) was dissolved in the irrigation water and uniformly applied 4 times (Fig. 2b). After harvest, all the cotton residues were incorporated into the soil during the next tillage. Information about the timing of tillage, sowing, plastic mulching, irrigation and fertilization is given in Table 1.

2.2. Sampling and analysis

Gas samples were collected twice per week between 11:00 and 13:00 during the fertigation period and every seven to ten days during the non-fertigation period. N_2O emissions from the ridge and furrow soils were measured using the closed-chamber method. Measurement details are described by Yu et al. (2016). Briefly, a base (stainless steel, 30 cm long, 15 cm wide and 5 cm high) was inserted 5 cm into the ridge or furrow soils, and the chamber (stainless steel, 30 cm long, 15 cm