Agriculture, Ecosystems and Environment 240 (2017) 194–205

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Anaerobic soil disinfestation impact on soil nutrients dynamics and nitrous oxide emissions in fresh-market tomato

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A R T I C L E I N F O

Article history:
Received 10 December 2016
Received in revised form 16 February 2017
Accepted 18 February 2017
Available online xxx

Keywords:
Biological soil disinfestation
Molasses
Composted poultry litter
Nitrous oxide
Phosphorous
Potassium
Chemical soil fumigation

A B S T R A C T

Anaerobic soil disinfestation (ASD) is proposed as a pre-plant, non-chemical soil disinfestation technique to control several soilborne phytosanitary issues. Limited information is available on the impact of ASD on soil fertility, plant growth, and potential nutrient loss. The objectives of the current study were to evaluate the effects of ASD applied using composted poultry litter (CPL) and molasses as amendments, on soil redox potential, pH, temperature, soil nutrient content, plant biomass and nutrient accumulation, and nitrous oxide (N_2O) emissions. A field study was conducted on fresh-market tomato (*Solanum lycopersicum* L.) at two sites, Immokalee and Citra, FL, comparing ASD applied using a mix of CPL at the rate of 22 Mg ha^{-1} and two rates of molasses [13.9 (ASD1) and 27.7 m^3 ha^{-1} (ASD2)] as a carbon-source to chemical soil fumigation (CSF). ASD treatment had a significant impact on soil redox potential, but did not affect soil pH or temperature. Soil treatment did not affect nitrous oxide emissions from intact polyethylene mulched beds at either location. Emissions ranged from 0 to 0.378 μg m^{-2} h^{-1} and from 8.8 to 39.8 μg m^{-2} h^{-1} in Immokalee and Citra, respectively. However, on day 21 after punching holes in the polyethylene film to transplant, N_2O emissions ranged from 1.56 to 4.83 and from 303.4 to 1480.1 μg m^{-2} h^{-1} in Immokalee and Citra, respectively. Emissions were higher in ASD than in CSF plots in Citra, but not in Immokalee. Molasses and CPL used in ASD treatments increased soil nutrients content, and particularly the availability of P and K. Results show no clear evidence of an increased risk of N loss with ASD compared to CSF. However, pre- and post-planting nutrient management should be adjusted to take into account the nutrients provided through the molasses and CLP application.

1. Introduction

Anaerobic soil disinfestation (ASD) is a pre-plant non-chemical soil disinfestation treatment proposed as an alternative to chemical soil fumigation (CSF) for the control of several soil-borne diseases, plant-parasitic nematodes, and weeds in a variety of crops (Rosskopf et al., 2015; Shennan et al., 2014; Shinmura et al., 1999). The basic principle of the technique, known also as 'biological soil disinfestation', is to create an anaerobic soil environment by incorporating readily decomposable carbon (C) rich organic amendments into the soil, which is saturated with water and covered with impermeable polyethylene film to prevent the diffusion of oxygen from the soil surface (Butler et al., 2014a; Shennan et al., 2014). The temporary shift of the soil environment, from aerobic to anaerobic conditions, that occurs for a few days, stimulates the growth of facultative and obligate anaerobic microorganisms, including *Clostridia* and *Bacilli* groups (Mowlick et al., 2012, 2013a,b; van Agtmaal et al., 2015). Under anaerobic conditions, these microorganisms decompose the labile C, producing organic acids, aldehydes, alcohols, ammonia, and

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http://dx.doi.org/10.1016/j.agee.2017.02.025
0167-8809/

volatile organic compounds that are suppressive or toxic for several soil-borne pests and plant pathogens (Momma, 2008; Momma et al., 2006; Oka, 2010; van Agtmaal et al., 2015).

While the exact mechanism of pest control has not been fully elucidated, the ASD technique proved to be effective against a number of soilborne pests (Butler et al., 2012a,b; Lamers et al., 2010; Momma, 2008; Rosskopf et al., 2015; Shennan et al., 2014). Besides soil pest control, the transient variation of soil redox potential, pH, and microbial populations caused by the ASD treatment (Momma, 2008; Momma et al., 2006), combined with amendment of the soil with organic matter, may have a significant impact on soil nutrient content and dynamics, plant nutritional status and growth, as well as on the loss of nutrients to the environment (Rosskopf et al., 2015). In previous studies, ASD applied on different vegetable crops, increased soil nutrient content, improved plant growth, and provided higher fruit yield compared to the fumigated control (Butler et al., 2014a; Di Gioia et al., 2016). Nevertheless, information on the potential environmental impact of the ASD technique is inadequate and there are concerns about the potential risks of nutrient loss, especially during the treatment period prior to transplanting. It is possible that nutrients, particularly inorganic N, may be immobilized into the soil microbial biomass or may be subject to losses, principally through leaching out of the root zone (Benoit et al., 2015). As anaerobic conditions are created during the ASD treatment, N losses may occur by denitrification with the reduction of nitrate (NO_3^-) to gaseous forms of N, including N_2 and N_2O, which is a potent greenhouse gas currently considered the most important substance contributing to stratospheric ozone depletion (Charles et al., 2017; Ravishankara et al., 2009).

A field study was conducted on fresh-market tomato grown in open-field in two locations in Florida to examine the potential implications of ASD for both the soil-plant system and the environment. The objectives were to evaluate the effects of ASD and the most common CSF practices on soil temperature, moisture, pH, redox potential, nutrient content, and soil N_2O emissions; to evaluate effects on plant growth and nutrient accumulation, and estimate the residual fertility and the potential risk of nutrient loss at the end of the crop season.

2. Materials and methods

2.1. Experimental sites and treatments

Two field experiments were conducted on fresh-market tomato during the spring season of 2015 in southwestern (Immokalee) and north-central Florida (Citra). Conventional CSF was compared with two ASD treatments, which consisted of amending the soil with 22 Mg ha^{-1} of CPL and two rates of molasses [13.9 (ASD1) and 27.7 m^3 ha^{-1} (ASD2)] as the C source. The first experiment was established on 2 Feb. 2015 at the University of Florida (UF) – Institute of Food and Agriculture Sciences – Southwest Florida Research and Education Center (SWFREC) in Immokalee, FL. The second experiment was established on 25 Mar. 2015, at the UF Plant Science Research and Education Unit (PSREU). Weather conditions and treatment effects on fruit yield and quality, weed and root-knot nematode control, and cumulative soil anaerobicity (mV h) were reported previously by Di Gioia et al. (2016).

The three treatments, CSF, ASD1 and ASD2, were the same at both sites and were arranged in a randomized complete block design with four replications. The two sites differed in soil type. In Immokalee, the soil was a Spodosol classified as Immokalee fine sand (sandy, siliceous, hyperthermic Arenic Haplaquods) and in Citra the soil was a Gainesville loamy sand (hyperthermic, coated typic quartzipsamments). In addition, there were minor differences in the way beds were established. In Immokalee, each of the four blocks consisted of one raised bed, 0.90 m wide, 0.20 m high and 60 m long and treatments were applied to 15-m long sections of the bed, leaving a 3-m space between plots. In Citra, each of the four blocks consisted of three beds 0.90 m wide and 15-m long. Prior to treatment application, the soil was rototilled and a starter fertilizer mix including N, P and potassium (K) was applied based on the specific requirement of each site. Nitrogen, P and K were applied at the rate of 34, 49 and 37 kg ha^{-1} at the Immokalee site, and 56, 22 and 42 kg ha^{-1} in Citra, respectively. The starter fertilizer mix was broadcast applied to the soil surface in 60 cm wide bands at both sites. Rounded false beds were formed by hilling the soil from a depth of 10 cm. ASD beds were amended with CPL at the rate of 22 Mg ha^{-1} in combination with a 1:1 (v:v) water dilution of sugarcane molasses (Agricultural Carbon Source, TerraFeed, LLC, Plant City, FL, USA). Molasses had a density of 1420 kg m^{-3}, 22% water content, and a pH of 4.9–5.2. The molasses-water mix was applied to ASD1 and ASD2 plots at the rate of 27.7 and 55.4 m^3 ha^{-1}. Table 1 shows the mean macro- and micronutrient content of both CPL and molasses, and the total amounts of nutrients incorporated in the soil with the ASD1 and ASD2 treatment application.

After CPL and molasses application, the soil was tilled to a depth of 15 cm with a rotary cultivator, beds were formed and covered with a 0.03-mm black/white VaporSafe® TIF (Raven Industries Inc., Sioux Falls, SD, USA) polyethylene mulch containing an ethylene vinyl alcohol (EVOH) barrier layer. Simultaneously, two drip irrigation lines [20 cm emitter spacing, 0.98 L h^{-1} emitter rate (Jain Irrigation Inc., Haines City, FL, USA)] were installed under the mulch in each bed, approximately 2.54 cm below the soil surface and 20 cm apart from the center of the bed. ASD plots were then irrigated with 5 cm of water (based on raised-bed area only) to saturate air-filled pore space in the top 10 cm of the bed and enhance the development of anaerobic conditions (Butler et al., 2012a).

On the same day, the control plots were fumigated by shank injection. The fumigant applied at each location was the most commonly used product for vegetable production in that region. In Immokalee, fumigation was with Pic-Clor 60 (Soil Chemical Corporation, Hollister, CA, USA) containing a mixture of 1,3-dichloropropene (39.0%) and chloropicrin (59.6%) at the rate of 224 kg ha^{-1}. In Citra, the fumigant was Paladin™ (Arkema Inc., King of Prussia, PA, USA) composed of dimethyl-disulfide (DMDS, 79%) and chloropicrin (21%) at the rate of 496 L ha^{-1}. Fumigated plots were mulched immediately following CSF injection at both sites using the same material as for the ASD plots.

2.2. Crop transplanting and growing conditions

Tomato varieties were selected based on regional grower preferences. The varieties were cv. 'Skyway 687' (Enza Zaden, Salinas, CA, USA) in Immokalee and cv. 'Tribute' (Sakata, Morgan Hill, CA, USA) in Citra. Both are large, round fresh-market commercial tomato varieties. They were transplanted at the third true leaf stage, three weeks after treatment application, 24 Feb. and 17 Apr. 2015 in Immokalee and Citra, respectively. Tomatoes were transplanted in single rows at a distance of 0.45 m within the row and 1.8 m between rows, establishing a density of 12,000 plants ha^{-1} at each site. Each of the twelve plots in the experiment contained 34 plants. Plants were trellised using the stake and weave method at both sites.

Irrigation and fertigation differed by site. A hybrid seepage-drip irrigation system was used in Immokalee, while in Citra, the crop was watered by drip irrigation as described by Di Gioia et al. (2016). Fertigation started three weeks after planting (WAP) following UF/IFAS fertilizer recommendations (FDACS, 2005). At the Immokalee site, N and K were applied twice a week by fertigation using