Title
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Journal
Acta Horticulturae, 1044(1044)

ISSN
0567-7572

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Publication Date
2014-07-01

DOI
10.17660/actahortic.2014.1044.33

Peer reviewed

Integrated Rotation Systems for Soilborne Disease, Weed and Fertility Management in Strawberry/Vegetable Production

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Keywords: *Verticillium dahliae*, organic farming, crop rotation, mustard seed meal, anaerobic soil disinfestation, biological alternative to fumigant, broccoli rotation

Abstract

Organic strawberry/vegetable producers in coastal California face soilborne disease, nutrient, and weed management challenges. In conventional systems, stringent regulations and air quality concerns make the sustainability of fumigant-dependent systems uncertain. To evaluate efficacy of anaerobic soil disinfestation (ASD), mustard cake (MC) application and broccoli residue incorporation, we initiated trials at an organic farm (Org) and a conventional farm (Conv) with crop rotation (broccoli (*Brassica oleracea* L. *italica*) – strawberries (*Fragaria ananassa*), cauliflower (*Brassica oleracea* L. *botrytis*) – strawberries, or fallow – strawberries) as main plot in June 2011. Sub plots (ASD, MC, ASD+MC, untreated control (UTC), and fumigant (Pic-Clor 60. Conv only)) were applied prior to strawberry in October 2011. Cover crop and lettuce (*Lactuca sativa*) were grown after strawberries at Org only. Marketable fruit yield, weed density, and disease level were monitored during the strawberry season and soil inorganic N dynamics for the entire period. ASD+MC and ASD produced similar fruit yields as fumigant at the Conv site. ASD+MC produced greater fruit yield than UTC and MC at both sites and ASD at the Org site. ASD and ASD+MC produced high inorganic N in the soil 2 to 3 months after application at both sites. This caused salt damage on strawberry during early growth especially at Conv which may have reduced fruit yields in both treatments. *Verticillium dahliae* population in soil at strawberry transplanting was less than 1 microsclerotia/g soil at both sites. However, *V. dahliae* infection on strawberry plants at the end of the harvest season in Org was reduced by ASD and ASD+MC suggesting that the mechanisms of yield increase by ASD involved disease suppression. Weed suppression by ASD and MC was limited. The effect of broccoli rotation in *V. dahliae* and weed suppression was also limited and no synergistic effect of broccoli rotation with ASD and MC was observed.

INTRODUCTION

Management of soilborne disease, weed, and fertility are some of the greatest

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challenges in both conventional and organic strawberry production systems. In conventional systems, stringent regulations and air quality concerns make the sustainability of fumigant-dependent systems uncertain. To manage plant diseases one of the oldest cultural practices in agriculture is perhaps crop rotation (Cook, 1991). Subbarao et al. (2007) demonstrated that rotation with broccoli followed by incorporation of the residues reduced the number of *Verticillium dahliae* microsclerotia in soil possibly due to hydrolysis of glucosinolates, which releases compounds with pesticidal activity (Brown and Morra, 1995). Mustard seed cake (MC), a residue product of the seed oil extraction process, is also high in glucosinolates and can provide disease control and weed suppression as well as supplemental nutrients (Handiseni et al., 2011). Anaerobic soil disinfestation (ASD), a biological alternative to fumigation, has shown a wide spectrum of efficacy against many soilborne pathogens and nematodes in different locations (Momma, 2008; Butler et al., 2012; Blok et al., 2000). ASD is based upon the addition of a carbon source material followed by irrigation to create anaerobic conditions for a period of time, during which by-products of anaerobic respiration, changes in soil Eh, pH and microbial community composition are all thought to contribute to disease suppression (Momma et al., 2013).

In this study we evaluated the efficacy of ASD, MC, and broccoli residue incorporation, alone or in combination, on Verticillium wilt on strawberries, weed density, and soil inorganic N dynamics on two farms in coastal California.

MATERIAL AND METHODS

Two field trials were established: one at a 35-year-old organic farm in Santa Cruz, CA (Org) and the other on a conventional farm in Salinas CA (Conv). These trials were designed as 4 replicate randomized block split-plot experiments with crop rotation (broccoli-strawberry, cauliflower-strawberry, or fallow-strawberry) as the main plots and ASD, MC (*Brassica juncea*:*Sinapis alba* = 1:1 by weight), ASD plus MC, and untreated control (UTC) as sub plots. At the Org site, after strawberries, legume/cereal mix winter cover crop and then summer lettuce were grown at all plots. At the Conv site, fumigation (Pic-Clor60 bed application) sub plots were also established. Each sub-plot plot was 14 m^2 at Org, and 15 m^2 at Conv.

In June to September 2011, broccoli 'Gypsy' (Org) and 'Patron' (Conv), and cauliflower 'Snow crown' (Org) and 'Absolute' (Conv) were grown as main plots and head yield (Org only) and biomass (both sites) were measured. Split plot treatments were established in fall 2011 before planting strawberries. For ASD plots, 20 t ha^{-1} of rice bran was applied to the bed surface and rototilled to 15 cm depth. For MC plots 3.4 t ha^{-1} MC was incorporated. For ASD+MC plots, 16.9 t ha^{-1} of rice bran and 3.4 t ha^{-1} of MC were applied and incorporated in the same manner. ASD and ASD+MC plots were drip irrigated first to saturate bed soil and then to maintain water content above the field capacity for 3 weeks using 108 mm of water. Strawberry plants 'Albion' were transplanted in November 2011. A harvest station of 20 selected plants was marked in each plot and strawberry yield was monitored at the stations twice weekly from April to September 2012. At the Org site, 336 kg ha^{-1} of legume/cereal cover crop (45% bell beans (*Vicia faba*), 45% vetch (*Vicia sativa*), 10% rye (*Secale cereale*) 'AGS104') was planted in all plots in the fall 2012 and grown until the following spring at which time they were mowed and incorporated into the soil. Then Romaine lettuce 'Salvius' was grown in the summer 2013.

To monitor soil inorganic-N dynamics, soil samples from 0-15 and 15-30 cm depths were taken monthly and at crop harvest and pre- and post-ASD treatment. *V. dahliae* population in 0-15 cm of soil was tested using a modified Anderson sampler and NP10 selective medium (Koike et al., 1994) before and after each crop, and pre- and post-ASD treatment. *V. dahliae* infection on strawberry plants was evaluated at the end of the growing season for four plants per plot. Weed density at each plot was determined at a clear plastic window (0.5 m^2) created in each plot five times throughout the growing season of strawberries in 2012. A split plot ANOVA was used for statistical analysis.

RESULTS

Organic Site

In the summer 2011, broccoli and cauliflower head yield (*P*=0.80) and residue biomass (stems and leaves fresh weight; *P*=0.29) showed no difference between sub plots. Cumulative marketable fruit yield of strawberries was greatest in ASD+MC (averaged 862 g plant^{-1}), followed by ASD (781 g plant^{-1}), MC (646 g plant^{-1}), and lowest for UTC (618 g plant^{-1}) (*P*=0.0001***; Fig. 1a). There was no difference in fruit yield between main plots (*P*=0.58). In the summer 2013, lettuce head yield showed no significant differences between main plots (*P*=0.18) or sub plots (*P*=0.93) with values ranging between 1.6 to 1.9 t ha^{-1}.

Inorganic N dynamics throughout the experiment are shown in Figure 2a. As crop residues were incorporated in September 2011 and rice bran and MC applied, soil inorganic N in the topsoil rapidly increased and peaked in November to December reaching to 60-120 and 10-30 mg kg^{-1} for NO_3-N and NH_4-N, respectively. The NO_3-N peak in December for sub plots was highest in ASD+MC, followed by ASD, MC and UTC (*P*<0.0001***). Soil inorganic N concentration gradually decreased at all plots regardless of treatment during strawberry growth. No significant difference was found in inorganic N at either depth after cover crops were planted in the fall 2012.

Viable *V. dahliae* microsclerotia in topsoil prior to the strawberry planting were rather low: averaging 1.5 ms g^{-1} soil pre-ASD/MC application. Post-ASD/MC application, viable *V. dahliae* microsclerotia were not detected in ASD and ASD+MC plots whereas microsclerotia counts were 0.3 to 0.5 ms g^{-1} soil in MC and UTC, respectively (*P*=0.15). However, at the end of the growing season, strawberry plants from UTC had higher *V. dahliae* infection rates than ASD and ASD+MC (*P*=0.006**; Fig. 3).

Total weed densities in cauliflower plots were less than broccoli and fallow plots (*P*=0.046), but no difference was found between subplots (*P*=0.17).

Conventional Site

In the summer 2011, fresh biomass of broccoli and cauliflower was 36.3 t ha^{-1} for both crops. Strawberry harvest yield data collection began in May and ended in July due to a labor shortage. Cumulative marketable fruit yields of strawberries in ASD+MC and ASD treatments were similar to Pic-Clor, and ASD+MC and Pic-Clor had a significantly higher yield than UTC and MC (*P*=0.01*; Fig. 1b). No difference in marketable yield was found between main plots (*P*=0.58).

Although it followed a similar pattern as Org, the overall inorganic N concentration was much higher at Conv due to the pre-plant chemical fertilizer application (Fig. 2b). NO_3-N concentration peaked in November at 70-150 mg kg^{-1} in 0-15 cm depth in the clayloam soil. Significant differences in both main plots (*P*<0.05) and subplots (*P*<0.001) were observed in November, indicating N mineralization from crop residues, rice bran and MC were greatest about 2-3 months after incorporation, whereas Pic-Clor appears to have slowed down the nitrification in the topsoil. Strawberries experienced severe salt burn damage in December to January due to the dry and warm winter resulting in the high soil EC. Damage was especially severe in ASD and ASD+MC plots where soil EC exceeded the threshold for salt sensitive crops such as strawberries.

Generally weed density in Conv was about 1/10 of the Org site. Pic-Clor had a significantly lower weed density compared to all other sub plots (*P*=0.002). Main plot treatments did not have any effect on weed density (*P*=0.22).

DISCUSSION

Overall, ASD+MC and ASD produced similar fruit yields as Pic-Clor at the Conv site and ASD+MC produced greater fruit yield than UTC and MC at both sites and ASD at the Org site. The yield of ASD and ASD+MC in the Conv site, however, may have been reduced by the salt damage at early growth. ASD, MC, and ASD+MC application provide large amounts of N (ASD plot: ~400 kg-N ha^{-1}, MC plot; ~200 kg-N ha^{-1}, ASD+MC plot; ~530 kg-N ha^{-1}) which affected soil inorganic N levels. Pre-plant N input reduction to account for nutrients from the carbon source used for ASD warrant further study. At both sites, when strawberries were transplanted, *V. dahliae* population in the soil was not as high as expected. However, *V. dahliae* infection on strawberry plants at the end of the harvest season in the Org site was reduced by ASD and ASD+MC (Fig. 3) suggesting that the yield increase from ASD involved disease suppression. Weed suppression by ASD and MC appears to be limited. In contrast to previous work the effect of broccoli rotation and MC application on *V. dahliae* and weed suppression was limited in this study. No synergistic effect of broccoli rotation with ASD and MC was observed. This may be partially due to the unexpectedly low initial *V. dahliae* populations at the trial sites.

ACKNOWLEDGEMENTS

We thank Gary Tanimura and Glenn Noma of Tanimura and Antle Fresh Foods Inc., Elizabeth Milazzo, Darryl Wong, Andrew Webster, and Damian Parr of UCSC, and student workers of the Shennan lab for their collaboration and assistance. This project was partially funded by the Western Sustainable Agriculture Research and Education Program SW11-116 and Organic Farming Research Foundation.

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Figures

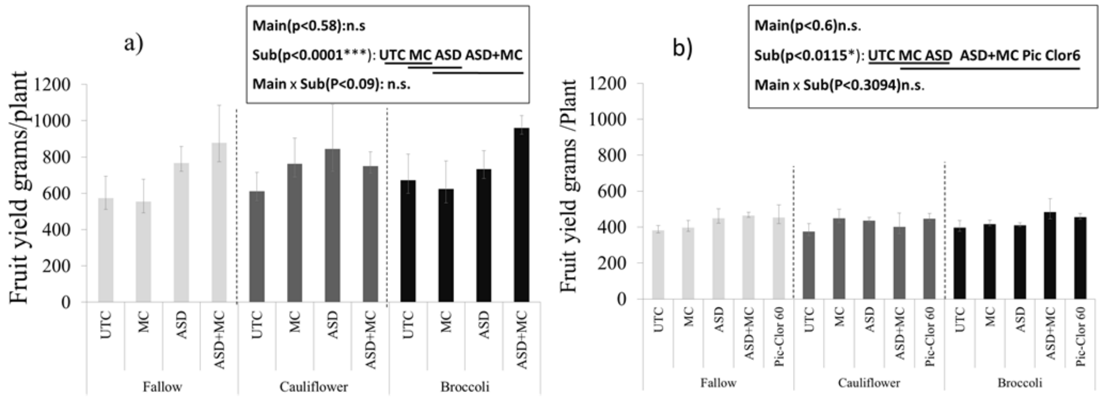

Fig. 1. Cumulative marketable fruit yield at a) organic site and b) conventional site. Each bar indicates mean ± SEM (n=4). Treatment on the same line do not have significant different by Tukey's HSD test (*P*=0.05). UTC: untreated control; MC: mustard cake; ASD: anaerobic soil disinfestation; ASD+MC: anaerobic soil disinfestation and mustard cake.

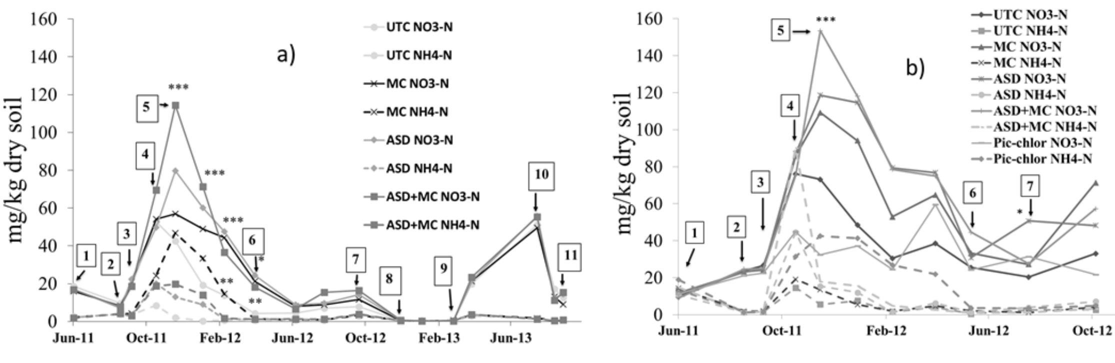

Fig. 2. Inorganic N dynamic at 0-15 cm soil depth at a) the organic site and b) the conventional site. 1: broccoli and cauliflower transplanting, 2: broccoli and cauliflower harvest, 3: pre ASD, MC treatments, 4: post ASD, MC treatments, 5: strawberry planting, 6: first strawberry harvest, 7: last strawberry harvest, 8: cover crop planting, 9: cover crop incorporation, 10: lettuce transplanting, 11: lettuce harvest. UTC: untreated control; MC: mustard cake; ASD: anaerobic soil disinfestation; ASD+MC: anaerobic soil disinfestation and mustard cake.

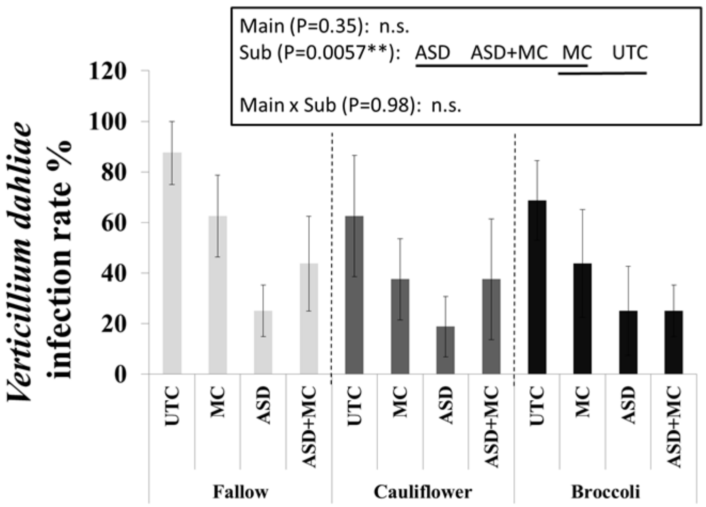

Fig. 3. *Verticillium dahliae* infection rate of strawberry plants at the organic site at the end of the harvest season. Plants were sampled on Sept. 2012. Each bar indicates mean ± SEM (n=4). Infection rate (%) = # of diseased plant/4 plants tested ×100. UTC: untreated control; MC: mustard cake; ASD: anaerobic soil disinfestation; ASD+MC: anaerobic soil disinfestation and mustard cake.