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REGULAR ARTICLE

Anaerobic Soil Disinfestation (ASD) Combined with Soil Solarization as a Methyl Bromide Alternative: Vegetable Crop Performance and Soil Nutrient Dynamics

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Abstract
Background and Aims Soil treatment by anaerobic soil disinfestation (ASD) combined with soil solarization can effectively control soilborne plant pathogens and plant-parasitic nematodes in specialty crop production systems. At the same time, research is limited on the impact of soil treatment by ASD+solarization on soil fertility, crop performance and plant nutrition. Our objectives were to evaluate the response of 1) soil nutrients and 2) vegetable crop performance to ASD+solarization with differing levels of irrigation, molasses amendment, and partially-composted poultry litter amendment (CPL) compared to an untreated control and a methyl bromide (MeBr)+chloropicrin-fumigated control.
Methods A 2-year field study was established in 2008 at the USDA-ARS U.S. Horticultural Research Lab in Fort Pierce, Florida, USA to determine the effectiveness of ASD as an alternative to MeBr fumigation for a bell pepper (*Capsicum annum* L.)-eggplant (*Solanum melongena* L.) double crop system. A complete factorial combination of treatments in a split-split plot was established to evaluate three levels of initial irrigation [10, 5, or 0 cm], two levels of CPL (amended or unamended), and two levels of molasses (amended or unamended) in combination with solarization. Untreated and MeBr controls were established for comparison to ASD treatments.
Conclusions Results suggest that ASD treatment using molasses as the carbon source paired with solarization can be an effective strategy to maintain crop yields in the absence of soil fumigants. For both bell pepper and eggplant crops, ASD treatments with molasses as the carbon source had equivalent or greater marketable yields than the MeBr control. The application of organic amendments in ASD treatment (molasses or molasses+CPL) caused differences in soil nutrients and plant nutrition compared to the MeBr control that must be effectively managed in order to implement ASD on a commercial scale as a MeBr replacement.

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Keywords Soil disinfestation · Methyl bromide alternatives · Molasses · Organic amendments · Bell pepper · Eggplant · Solarization · Vegetable nutrition

Abbreviations

ASD	Anaerobic soil disinfestation
CPL	Composted poultry litter
MeBr	Methyl bromide
UTC	Untreated control

Introduction

Production of vegetables, small fruits, and cut flowers can be severely limited by soilborne plant pathogens, plant-parasitic nematodes, and weeds. In recent history, commercial growers have utilized soil fumigants such as mixtures of methyl bromide (MeBr) and chloropicrin to manage pests and improve yields, primarily in plasticulture production systems with limited crop rotation. The global phase-out of MeBr, as part of the Montreal Protocol on Substances that Deplete the Ozone Layer, has created a situation in which many growers are limited in chemical fumigant options due to high costs of alternative fumigants, buffer-zone restrictions, increasing concerns for environmental and human safety, or lack of broad-spectrum efficacy against pests as compared to MeBr. Given these concerns, there is a need for broad-spectrum, non-fumigant soil disinfestation options that are adaptable to grower needs, site conditions, and existing production systems.

One promising non-chemical alternative to soil fumigation is anaerobic soil disinfestation (ASD). This treatment utilizes methods of pre-plant soil disinfestation developed independently in Japan and the Netherlands (Blok et al. 2000; Goud et al. 2004; Messiha et al. 2007; Momma 2008; Momma et al. 2006; Momma et al. 2010) and more recently adapted to production systems in California (Shennan et al. 2011), Florida (Butler et al. 2012a; Butler et al. 2012b), and Tennessee (McCarty et al. 2012) in the USA. Briefly, ASD treatment as described here is characterized by incorporation of easily-decomposable organic soil amendments (e.g., wheat or rice bran, fresh plant residues, molasses, ethanol), irrigation-to-saturation of the topsoil, and covering with polyethylene mulch for a period of approximately 3 weeks. Through the provision of labile carbon (C), the soil amendments encourage rapid soil microbial growth and respiration, leading to depletion of available soil oxygen and the creation of reduced (anaerobic) soil conditions. Control of plant pathogens and parasitic nematodes is achieved, at least in part, through the production of volatile fatty acids (e.g. acetate, butyrate) and other compounds created through anaerobic decomposition of the labile C source, likely by a diverse community of soil microbes including those in the class *Clostridia* (Momma 2008; Momma et al. 2006; Mowlick et al. 2012a, 2012b). The presence of reduced ions of Fe and Mn (Fe^{2+}, Mn^{2+}) has also been reported as a potential control mechanism during ASD treatment (Momma et al. 2011), as well as proliferation of biological control agents (Thaning and Gerhardson 2001). This soil treatment process has also been termed "biological soil disinfestation" (Blok et al. 2000; Goud et al. 2004) or "soil reductive sterilization" (Shinmura 2004), but our preference has been for "ASD" (Butler et al. 2012a; Butler et al. 2012b).

It is expected that soil treatment by ASD+solarization could have an impact on crop performance caused by mechanisms other than the removal of pest and disease pressure, such as changes in soil nutrient availability due to added organic amendments, periods of reduced (anaerobic) conditions and mineralization of nutrients due to the heating action of soil solarization. As such, it is imperative to evaluate ASD treatments through a whole systems approach to capture all impacts of this soil disinfestation practice on system properties. System changes induced by these soil disinfestation practices must be understood to adequately implement ASD treatments or to evaluate the impact of ASD treatments on crop yields or development of plant disease at the field-scale. Research examining crop performance and soil fertility responses to ASD have generally been limited. Published studies from Japan, the Netherlands, and Argentina do offer a great deal of information on pathogen control and mechanisms, but these studies were conducted at the pot or small plot-scale with a focus on plant pathogens (Blok et al. 2000; Goud et al. 2004; Messiha et al. 2007; Momma 2008; Momma et al. 2006; Mowlick et al. 2012a, 2012b; Shinmura 2004; Yossen et al. 2008). At the pot-scale, Butler et al. (2012b) reported on the impact of ASD treatment with C sources of molasses or warm-season cover crops on both soil nutrients and crop performance. Differences among treatments primarily were related to differences in C-source input properties (e.g. C:N ratio, C rate, N rate), but differences were limited, perhaps due to the restricted nature of the pot conditions and use of a dwarf crop variety. Given that limited information is available on the effects of ASD practices on crop yields, soil fertility or effectiveness over multiple cropping seasons from studies conducted at the field scale or for vegetable production, the objectives of this study were to determine the responses of 1) soil nutrients and 2) vegetable crop performance (plant nutrition and yield) to solarization paired with ASD treatments with differing levels of treatment irrigation, molasses amendment, and partially-composted poultry litter amendment (CPL) compared to an untreated control and a MeBr+chloropicrin fumigated control.

Materials and methods

Plot layout and treatment establishment

A field experiment was established at the USDA-ARS, U.S. Horticultural Research Laboratory in Fort Pierce, Florida, USA to examine the impact of initial treatment irrigation, amendment with partially-composted poultry litter, and amendment with molasses on the effectiveness of ASD paired with soil solarization for raised-bed vegetable production. Treatment impacts on pathogen and nematode control in this field study, as well as accumulated anaerobic conditions, were reported by Butler et al. (2012a). Molasses was chosen as the labile C source to facilitate rapid microbial growth leading to anaerobic soil conditions, and is locally-available in Florida as a by-product of the sugar cane industry. Partially-composted poultry litter amendment was evaluated as a complimentary ASD amendment due to its reported potential to improve ASD treatment through increased water holding capacity of the sandy soils in this region (e.g., Evanylo et al. 2008; Haynes and Naidu 1998), as well as its potential to increase soil microbial diversity (e.g., Acosta-Martínez and Harmel 2006; Pérez-Piqueres et al. 2006) and improve pest control (Gamliel et al. 2000). Experimental establishment was described by Butler et al. (2012a), and is summarized here. The experiment was established as a complete factorial combination of treatments with three levels of initial irrigation (10, 5, 0 cm), two levels of partially-composted poultry litter (CPL; amended, unamended), and two levels of molasses (amended, unamended). Treatments without labile C source (i.e., molasses) amendment are not considered as ASD treatments (i.e., solarization only, solarization+CPL). The soil is classified in the Oldsmar series (sandy, siliceous, hyperthermic Alfic Arenic Alaquod) and had been cropped with various vegetables in previous years, although fallow for the year preceding the start of this experiment. In each of four blocks, four raised beds 60 m long were formed (approximately 0.9 m wide and 1.5-m on center). Experimental plots were arranged in a split-split plot design; level of initial (treatment) irrigation was the main plot factor, CPL application was the sub-plot factor, and molasses application was the sub-sub-plot factor. Accordingly, each treatment combination occupied a bed length of 15-m. Experimental factors of each variable (initial irrigation, CPL application, and molasses application) were randomly assigned to be applied within each of the main-plots, sub-plots, and sub-sub-plots, respectively. In each block, the remaining bed (i.e. a 60-m main plot) was divided in half and one half was randomly assigned as the untreated check (UTC) and one half assigned as the MeBr control. Experiments began in August 2008 and were repeated on the same plot locations beginning in August 2009.

Application rates of CPL were calculated based on University of Florida Extension recommendations for commercial growers (Olson et al. 2010). To meet this recommendation of 224 kg N ha^{-1}, 26 Mg dry matter ha^{-1} of CPL (pH 8.7, 2.7 mg C g^{-1} soil, 364 kg P ha^{-1}, 624 kg K ha^{-1}, 587 kg Ca ha^{-1}, 134 kg Mg ha^{-1}) was applied in 2008 and 16 Mg dry matter ha^{-1} (pH 8.6, 1.9 mg C g^{-1} soil, 384 kg P ha^{-1}, 640 kg K ha^{-1}, 558 kg Ca ha^{-1}, 112 kg Mg ha^{-1}) in 2009 (Butler et al. 2012a). Application rates were determined following initial sample analysis for total N colorimetrically following a Kjeldahl digestion (USEPA 1993). Rates were adjusted according to an estimate of 50 % availability of applied total N in CPL during the bell pepper growing season (Ritz and Merka 2004). Applied CPL was incorporated into beds only (not the alleyways between beds) with a rotary cultivator to a 15 to 20-cm depth and the beds were reshaped. Treatment beds amended with blackstrap molasses were sprayed with a 1:1 dilution of blackstrap molasses (Westway Feed Products/U.S. Sugar Corporation, Clewiston, Florida, USA) mixed with water. Molasses was applied to beds at a rate of 20 Mg ha^{-1} (wet basis; 8.2 Mg ha^{-1} dry matter basis, pH 4.8, 1.1 mg C g^{-1} soil, 83 kg N ha^{-1}, 7 kg P ha^{-1}, 336 kg K ha^{-1}, 66 kg Ca ha^{-1}, 20 kg Mg ha^{-1}) in both years. Carbon to nitrogen ratios of applied amendments for each treatment combination ranged from a low of 11.1 for treatments with CPL only in 2009 to a high of 34.8 for treatments with molasses only (Table 1). Given that soil amendments were applied to the raised bed area only, field application rates would be approximately half of the rates given above as the alleyways between beds did not receive amendments.

Two drip irrigation lines (30.5-cm emitter spacing, 0.91 L h^{-1} emitter rate, Jain Irrigation Inc., Haines City, Florida, USA) were placed in raised beds at approximately 2 cm below the soil surface and transparent polyethylene solarization mulch film (15 μm; Polydak,

Table 1 Soil amendment carbon (C) and nitrogen (N) application rates and C:N ratios at 2008 and 2009 soil treatments

	Total C		Total N		C:N ratio	
	2008 kg ha^{-1}	2009	2008	2009	2008 Ratio	2009
Solarization only	0	0	0	0	N/A	N/A
Solarization+molasses	2,890	2,890	83	83	34.8	34.8
Solarization+CPL	7,020	4,960	448	448	15.7	11.1
Solarization+mol. + CPL	9,910	7,850	531	531	18.7	14.8
Untreated control	0	0	0	0	N/A	N/A
MeBr control	0	0	0	0	N/A	N/A

Ginegar Plastic Products, Ginegar, Israel) was applied on all beds simultaneously (except the MeBr and UTC treatments) and buried at the edges. Irrigation was then applied to each solarized treatment at the assigned rate of 10, 5, or 0 cm (approximately 8 h of irrigation time was required to apply 5 cm). The MeBr treatment was fumigated with 225 kg ha^{-1} of a MeBr (67 %)/ Chloropicrin (33 %) mixture via shank injection and covered with a metalized plastic film (32 µm, silver on white, Canslit Inc., Montreal, Quebec, Canada). The UTC treatment was covered with the same metalized film material.

Vegetable crop management and crop performance evaluation

In order to stop soil heating in solarized treatments prior to planting bell peppers, metalized plastic film was applied over the transparent mulch at the end of the 3-week treatment period. In order to evaluate treatment impacts on crop performance and soil nutrient dynamics, a bell pepper–eggplant double crop system was implemented. Bell pepper (cv. Seminis 83–02, Seminis Vegetable Seeds, Inc., Saint Louis, Missouri, USA) transplants were planted with a 30-cm within row spacing on two rows within each bed in September 2008 (5 days after treatment termination). Eggplant (cv. Night Shadow, Seminis Vegetable Seeds, Inc., Saint Louis, Missouri, USA) was double-cropped, i.e. planted into the same beds, following bell pepper crop termination. Eggplant transplants were planted in a single row with a 45-cm within row spacing in February of 2009. As previously described, the experiment was repeated beginning in August 2009 with treatments re-applied to the same plot locations. Bell peppers were transplanted in the second season in September 2009 (1 day after treatment termination) and eggplants planted in February 2010. In plots without CPL, a water-soluble fertilizer (20 % N, 10 % P_2O_5, 20 % K_2O, 0.05 % Mg, 0.02 % B, 0.05 % Cu, 0.1 % Fe, 0.05 % Mn, 0.01 % Mo, and 0.05 % Zn) was used to fertigate the crop according to standard grower practice for the region and University of Florida Extension recommendations (Olson et al. 2010). CPL-amended plots were fertigated only during eggplant production. Fertigation rates were calculated to provide the recommended rate of 224 kg N ha^{-1}, 49 kg P ha^{-1}, and 186 kg K ha^{-1} throughout the growing season (Olson et al. 2010).

Yields were determined by harvesting three representative sections of 12 bell pepper plants and two representative sections of six eggplant plants in each plot. This represented 5.4-m of bed length for each crop and a total of 36 bell pepper plants and 12 eggplant plants for each plot. Bell peppers were harvested three times in each season (2008, 2009) and eggplants were harvested five times in each season (2009, 2010). Fruit were graded according to USDA standards (USDA-AMS 2005, 2013) for size and appearance, and the number and weight of fruit in each category (Fancy, U.S. 1, U.S. 2, and cull) were recorded. Fruit graded as Fancy, U.S. 1 and U.S. 2 were summed to obtain a measure of marketable yield, and marketable yield and culled fruit yield were summed to obtain a total yield measure. Yields from harvested bed length (5.4 m) were extrapolated to a per hectare basis based on an estimate of 6,667 m of bed length per hectare on a commercial scale.

At first harvest, crop leaf tissue was sampled by collecting recently matured leaves from five randomly selected bell pepper plants and three randomly selected eggplant plants in each plot. Leaf tissue was rinsed in sequence with deionized water, 0.1 N HCl/0.01 % detergent (Tween™ 80) and deionized water again to remove any surface contamination. Leaf tissue was dried in a forced-air oven at 80 °C and then ground. Plant leaf tissue was analyzed for total N content by combustion (NC Soil Flash EA1112, CE Elantech Inc., Lakewod, New Jersey, USA). Plant leaf tissue was also digested utilizing a closed-vessel microwave-assisted digestion (MARS Express, CEM Corp., Matthews, North Carolina, USA) according to U.S. EPA method 3052 (USEPA 1997). Digestates were then analyzed by inductively coupled plasma atomic emissions spectrometry (ICP-AES; iCAP 6500, Thermo Scientific, Waltham, Massachusetts, USA) for concentrations of P, K, Ca, and Mg.

Soil redox potential and soil nutrient analyses

Prior to initiating treatments, six soil cores (1.75-cm internal diameter) were taken from each 15-m section of bed to a 30-cm depth. Soil cores were divided into two depths (0 to 15 cm and 15 to 30 cm) and composited for each plot by depth. Soils were again sampled by the same methods immediately after treatment termination (before pepper planting), at pepper mid-season, at pepper harvest, at eggplant planting, and at eggplant harvest. Soil samples were sealed in plastic bags, placed in a cooler, and immediately taken to the lab for inorganic N extraction. Briefly, approximately 5 g of soil (dry weight equivalent) was shaken for 30-min with 40 mL of 1-M KCl. Samples were filtered (Whatman 42, Whatman Ltd., Kent, UK) and filtrate analyzed by the Analytical Research Laboratory at the University of Florida, Gainesville, Florida, USA using the phenol-hypochlorite method for NH_4–N (USEPA 1983a) and the cadmium reduction method for NO_2+NO_3-N (USEPA 1983b). Gravimetric soil moisture content (105 °C) was used to calculate soil inorganic N on a dry-weight basis. Moist soils were also analyzed for pH (1:1 in deionized water) using a pH electrode. Remaining soil in each sample was air-dried, then sieved (<2 mm). One 5-g sample was analyzed for Extractable P, K, Ca, and Mg using methods described by Mehlich (1984). Concentrations of P, K, Ca, and Mg, in extracts were determined by ICP-AES analysis as described for plant tissue digestates.

Two oxidation-reduction potential electrodes (ORP; Pt combination electrodes, Ag/AgCl reference) were placed at a 15-cm depth in each plot in three of the four blocks prior to treatment irrigation. The electrodes were used to monitor the presence of anaerobic conditions during the 3-week treatment period, as indicated by redox potential (Eh) below a calculated critical redox potential considered to be indicative of anaerobic conditions (Butler et al. 2012a; Fiedler et al. 2007; Rabenhorst and Castenson 2005). An automatic data logging system (CR-1000 with AM 16/32 multiplexers, Campbell Scientific, Logan, Utah, USA) was used to monitor electrodes continuously during the treatment period.

Statistical analysis

The mixed model procedure in SAS 9.2 was used to perform analysis of variance according to the split-split plot design (SAS Institute 2007). When main effects or interactions were significant ($p<0.05$), adjusted means were separated using the LSMEANS (least squares means) procedure with the pdiff option ($p<0.05$). A series of linear contrasts was used in the general linear model (GLM) procedure in SAS 9.2 to determine differences between experimental treatments and the UTC or MeBr control.

Results

Soil redox potential

Butler et al. (2012a) reported treatment impacts on accumulation of anaerobic conditions and reported no significant impact of applied initial irrigation on anaerobic conditions. The accumulation of anaerobic conditions is calculated as a summation of the difference between measured redox potential and a calculated critical redox potential mV (approximately+ 200 mV, but differing slightly with soil pH) considered to signify anaerobic conditions. Here, we present data on average trends in soil redox potential (Eh) over the time of soil treatment to allow for comparison of soil nutrient and crop performance data to treatment impacts on reduced soil conditions (Figs. 1 and 2). Averaged across initial irrigation in 2008, only treatments with both applied molasses and CPL averaged time with Eh below +200 mV (Fig. 1). Similar trends were observed in 2009, although conditions were generally more anaerobic than in 2008 (Fig. 2).

Soil inorganic N

Immediately following soil treatments in both 2008 and 2009, soil NH_4-N and NO_2+NO_3-N were significantly increased by the application of CPL at 0 to 15-cm and 15 to 30-cm depths (data not shown). A significant main effect of molasses application was also observed on soil NO_2+NO_3-N at 0 to 15 cm following 2008 treatments and both NH_4-N and NO_2+NO_3-N at the 15 to 30-cm depth in 2009. Because treatment irrigation did not

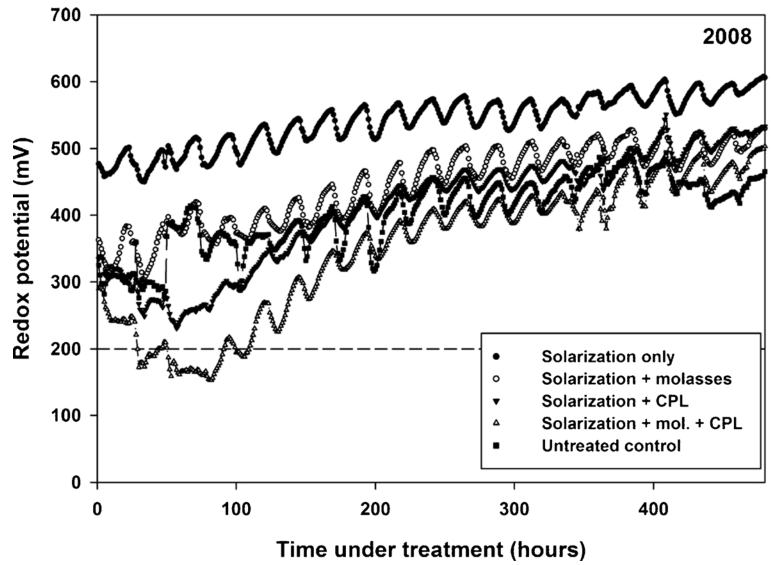

Fig. 1 Mean hourly soil redox potential (Eh) as affected by soil treatment in 2008. *CPL* composted poultry litter, *mol.* molasses. *Dashed line* at 200 mV represents division between conditions typically considered aerobic (>200 mV) and anaerobic (<200 mV)

affect soil NH_4-N and NO_2+NO_3-N, response to application of CPL and molasses were averaged across irrigation treatments (Fig. 3). In treatments with applied CPL, mean soil NH_4-N at the 0 to 15-cm depth was very high post treatment (>143 mg N kg^{-1} soil in 2008 and >68 mg N kg^{-1} soil in 2009) and at least three times that of soil NO_2+NO_3-N (>10 mg N kg^{-1} soil in 2008 >20 mg N kg^{-1} soil in 2009). In treatments without applied CPL (including the UTC and MeBr controls), soil NH_4-N and NO_2+NO_3-N were generally below 10 mg N kg^{-1} soil at both sampling depths. At sampling times and depths where a main effect of molasses application was observed, there was generally a reduction in soil inorganic N when molasses was applied. This was most notable at the 15 to 30-cm sampling depth in 2009, where lower soil NH_4-N and NO_2+NO_3-N were observed at post treatment when CPL was applied with molasses as compared to application of CPL without molasses (Fig. 3).

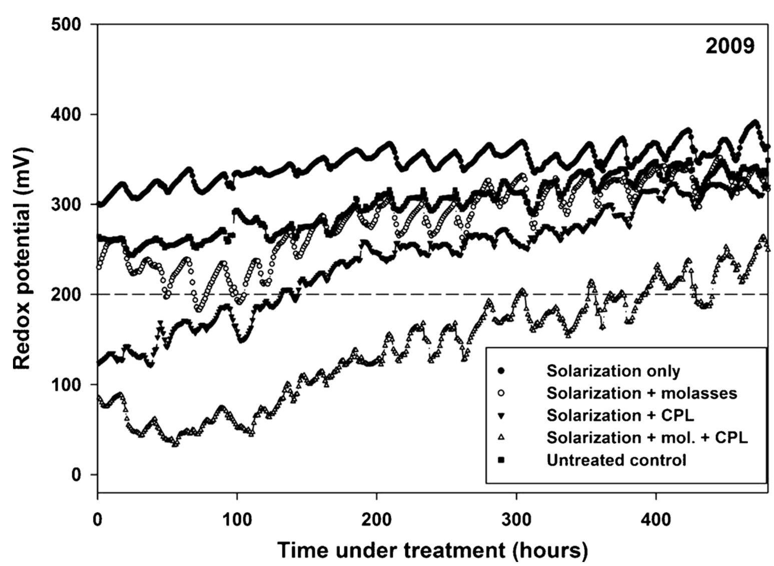

Fig. 2 Mean hourly soil redox potential (Eh) as affected by soil treatment in 2009. *CPL* composted poultry litter, *mol.* molasses. *Dashed line* at 200 mV represents division between conditions typically considered aerobic (>200 mV) and anaerobic (<200 mV)

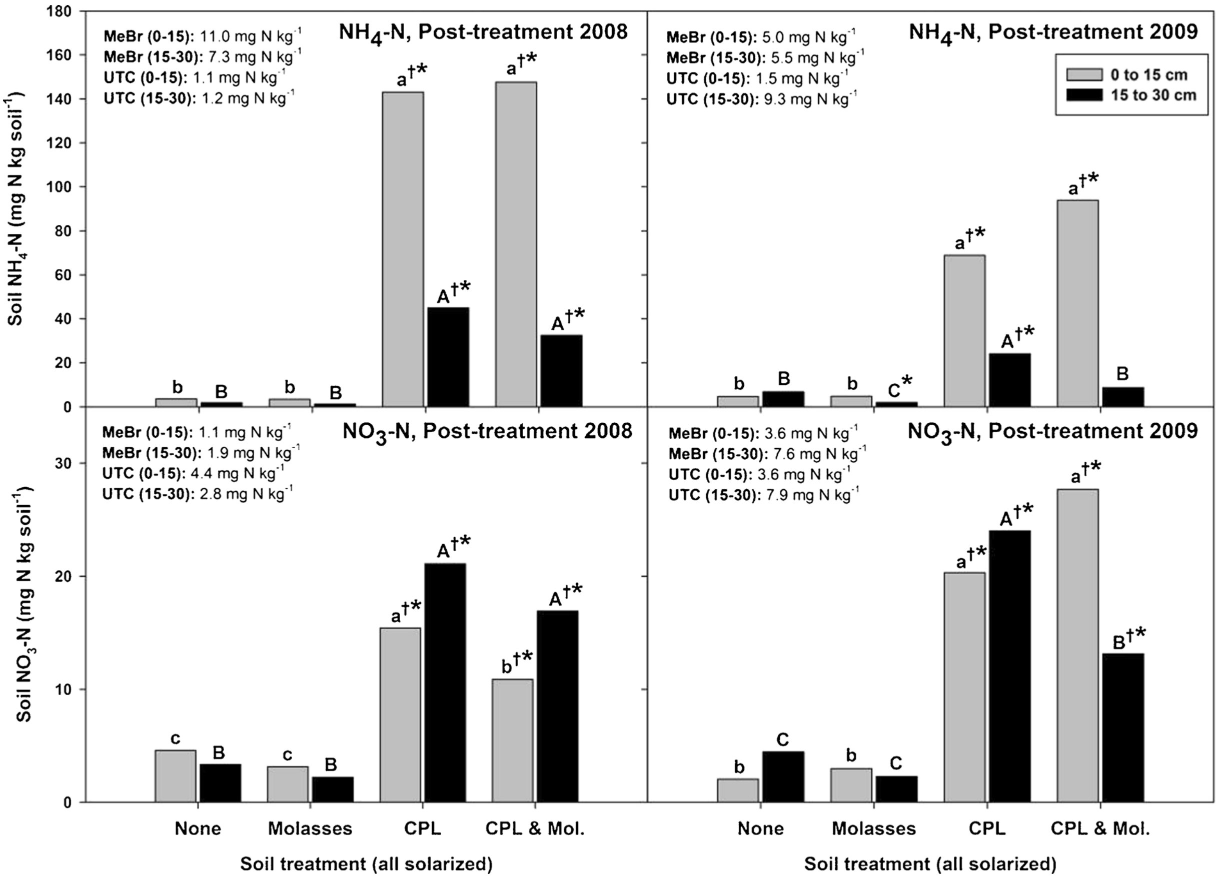

Fig. 3 Total soil ammonium-nitrogen (NH_4-N) and soil nitrite+nitrate-N (NO_2+NO_3-N) as affected by soil treatment. Within year, bars indicated by the same letter are not significantly different, $p>0.05$. *Bars* indicated with a † or * are significantly different from the untreated (UTC) or methyl bromide (MeBr) controls, respectively

In treatments without CPL, total soil inorganic N was below 10 mg N kg^{-1} soil and generally stable across sampling times for both the bell pepper and eggplant growing seasons (Table 2). Likewise, few differences were observed in total soil inorganic N at each sampling time for treatments which did not include CPL. In treatments with CPL, very high levels of inorganic N were observed immediately following soil treatment (>89 mg N kg^{-1} soil). However, at the mid-season soil sampling for the bell pepper crop, soil inorganic N from these treatments was not higher than that observed from treatments without CPL application.

Mehlich-3 extractable soil P

Soil P at the 0 to 15-cm depth averaged 57.8 mg P kg^{-1} soil across all treatments prior to soil treatment application in 2008 (data not shown). Whereas no effect of molasses application or initial irrigation treatment was observed, the application of CPL greatly increased soil P. At the 0 to 15-cm depth, soil P averaged 272 mg P kg^{-1} soil immediately after soil treatment in 2008 for those plots which included the application of CPL. Values of soil P remained high at the 0 to 15 cm depth for these treatments throughout the study period, averaging 263 mg P kg^{-1} soil at eggplant harvest in 2010 at the end of the study. In plots without CPL, soil P at the 0 to 15 cm depth remained at a similar level throughout the experiment, averaging 68.5 mg P kg^{-1} soil at eggplant harvest at the end of the study. At the 15 to 30-cm depth, soil P averaged 56.0 mg P kg^{-1} soil at the start of the experiment (data not shown). In treatments which did not include application of CPL, soil P at a 15 to 30-cm depth at the end of the experiment was slightly higher at 74.7 mg P kg^{-1} soil. However, in treatments which included CPL, soil P at eggplant harvest at the end of the experiment averaged 147.3 mg P kg^{-1} soil at the 15 to 30-cm depth.

Mehlich-3 exchangeable K, Ca, and Mg

Prior to treatment initiation, exchangeable soil K averaged 31.5 mg K kg^{-1} at the 0 to 15-cm depth (data not shown). Immediately following treatments in 2008, there were significant main effects of both molasses and CPL on exchangeable soil K. At this sampling, soil K ranged from an average of 33.6 mg K kg^{-1} soil in treatments without CPL or molasses (solarization only, UTC, and MeBr), 515 mg K kg^{-1} soil in treatments with molasses only, 819 mg K kg^{-1} soil in treatments with CPL only, and 939 mg K kg^{-1} soil in treatments with both molasses and CPL. There was no effect of treatment irrigation. Trends were similar throughout the two seasons of the study, although all treatments averaged less than 205 mg K kg^{-1} soil at eggplant harvest in 2010.

Exchangeable soil Ca averaged 210 mg Ca kg^{-1} soil at the initiation of the study (data not shown). Following the first soil treatment, there was a persistent main effect of CPL application on soil Ca levels throughout the experiment, and less consistent main effects of molasses application. Following the first soil treatment, exchangeable soil Ca was unchanged in treatments that did not include either molasses or CPL, 328 mg Ca kg^{-1} soil in molasses only treatments, and highest in treatments which included CPL (529 mg Ca kg^{-1} soil in CPL only and 497 mg Ca kg^{-1} soil in CPL+molasses treatments). Exchangeable soil Ca levels slowly increased over the course of the experiment, averaging 366 mg Ca kg^{-1} soil at eggplant harvest in 2010 in treatments which did not include CPL or molasses. This did not differ from the 416 mg Ca kg^{-1} soil in treatments with molasses only, but levels were higher in treatments with CPL only (689 mg Ca kg^{-1} soil), and highest in treatments with both CPL and molasses (806 mg Ca kg^{-1} soil).

Exchangeable soil Mg at the beginning of the study averaged 23.1 mg Mg kg^{-1} soil across treatments. Immediately following soil treatment in 2008, soil Mg increased to a mean of 145 mg Mg kg^{-1} soil in treatments which included CPL. Throughout the study, there was a consistent main effect of CPL on exchangeable soil Mg levels, and a main effect of molasses application in the second year of the study. At eggplant harvest in 2010, soil Mg was lowest in treatments without CPL or molasses (22.3 mg Mg kg^{-1} soil), followed by treatments with molasses (51.9 mg Mg kg^{-1} soil), CPL (89.5 mg Mg kg^{-1} soil), and application of both molasses and CPL (127 mg Mg kg^{-1} soil). Initial treatment irrigation did not significantly affect exchangeable soil Mg.

Leaf tissue N and P

During the 2008 season, bell pepper leaf tissue N concentration (at first harvest) was significantly affected by CPL application and not significantly affected by treatment irrigation or molasses application (Table 3). In treatments with CPL amendment in 2008, bell pepper leaf tissue N averaged 40.0 mg N g^{-1}, significantly less the 49.2 mg N g^{-1} observed in solarized treatments without CPL amendment (Fig. 4). In 2009, a similar trend was observed with a mean bell pepper leaf tissue N concentration of 29.4 mg N g^{-1} in treatments with CPL and 43.9 mg N g^{-1} in solarized treatments without CPL. Bell pepper leaf tissue N concentrations in the untreated and MeBr controls were similar to solarized treatments without CPL. During the 2009 eggplant season, there were no significant main effects of irrigation, CPL or molasses amendment on eggplant leaf tissue concentration (Table 4). In 2010, there was a main effect of CPL on eggplant leaf tissue N concentration. In treatments with applied CPL eggplant leaf tissue N concentration averaged 36.3 mg N g^{-1}, significantly less than the 51.4 mg N g^{-1} observed in treatments without CPL.

Bell pepper leaf tissue P concentration was significantly influenced by a main effect of CPL and an interaction between CPL and molasses in 2008 and 2009, with an additional main effect of molasses in 2009 (Table 3). In 2008, of the solarized treatments, bell pepper leaf tissue P concentration was lowest in treatments including application of both CPL and molasses (3.3 mg P g^{-1}), intermediate in treatments with CPL alone (3.5 mg P g^{-1}), and greatest in treatments which did not include CPL application (3.9 mg P g^{-1}). In 2009, mean bell pepper leaf P concentration was highest in treatments with application of CPL alone (4.5 mg P g^{-1}), which was higher than all other treatments (3.2 mg P g^{-1}). Bell pepper leaf tissue P concentrations in the untreated and MeBr controls were similar to solarized treatments without applied CPL. Similar to N concentration for eggplant leaf tissue in 2009, there were no significant main effects on eggplant leaf tissue P concentrations. In 2010, there were significant main effects of both CPL and molasses on eggplant leaf tissue P concentrations. The highest eggplant leaf P

Table 2 Total soil inorganic nitrogen (N) at 0 to 15-cm depth as affected by soil treatment throughout the 2-year study

		Solarization only mg N kg^{-1} soil	Solar. + molasses	Solar.+ CPL	Solar. + mol. + CPL	Untreated control	MeBr control
Pre treatment	02 Sept 08	4.0 ab§	4.2 ab	4.7 a	3.6 b	*4.6*	*3.6*
Post trt/pepper planting	29 Sept 08	8.1 b	6.5 b	158.6 a†*	158.6 a†*	*5.6*	*12.1*
Pepper mid-season	18 Nov 08	12.2 a	8.3 b	6.4 bc	3.6 c†*	*8.9*	*9.0*
Pepper harvest	8 Dec 08	6.6 ab	5.1 b	8.2 ab	11.1 a†	*6.5*	*5.2*
Eggplant planting	10 Feb 09	6.2 c	8.0 bc*	10.4 a†*	9.3 ab*	*6.1*	*4.5*
Eggplant harvest	14 May 09	7.4	6.1	11.5	15.4	*8.0*	*4.0*
Pre treatment	03 Aug 09	6.8 b	5.7 b	4.5 b	12.6 a†*	*4.0*	*5.0*
Post trt/pepper planting	14 Sept 09	6.7 b	7.7 b	89.2 a†*	121.5 a†*	*2.9*	*8.6*
Pepper mid-season	29 Oct 09	3.0 b	3.8 a	3.5 ab	3.7 ab	*3.5*	*3.3*
Pepper harvest	14 Dec 09	1.7	1.8	1.5	1.1	*1.1*	*1.6*
Eggplant planting	2 Feb 09	4.1	4.5	4.4	4.2	*3.7*	*4.1*
Eggplant harvest	20 May 10	1.5	1.8	2.4	1.7	*1.8*	*1.3*

§Within rows, means of solarized treatments (not italicized) indicated by the same letter or no letters are not significantly different, $p>0.05$. Means of solarized treatments indicated by a † or * are significantly different from the untreated or MeBr controls (italicized), respectively

concentrations were observed in treatments receiving only solarization (5.3 mg P g^{-1}) and lowest in treatments amended with both CPL and molasses (4.0 mg P g^{-1}). Treatments amended with either molasses or CPL alone had intermediate levels of eggplant leaf tissue P concentration, which did not differ from each other.

Leaf tissue K, Ca, and Mg

In both 2008 and 2009, significant main effects of CPL and molasses application were observed for bell pepper leaf tissue K concentration (Table 3). In 2008, bell pepper leaf tissue K concentration was highest in treatments which included molasses (56.0 and 53.8 mg K g^{-1} for molasses+CPL and molasses treatments, respectively) and lowest when no amendments were applied (48.6 mg K g^{-1} for solarization only). In 2009, treatments which included molasses again had the highest concentrations of K in bell pepper leaf tissue (51.4 and 54.5 mg K g^{-1} for molasses+CPL and molasses treatments, respectively), but lowest when CPL was applied (43.1 mg K g^{-1}). Main effects of CPL and

Table 3 The mixed procedure analysis of variance for main effects and interactions on bell pepper leaf tissue nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) content

	2008					2009				
	N *p*-value	P	K	Ca	Mg	N *p*-value	P	K	Ca	Mg
Block	NS[a]	0.02	0.06	0.1	NS	NS	0.1	NS	NS	0.04
Irrigation	NS	NS	NS	NS	0.05	NS	NS	NS	NS	NS
CPL	0.001	0.0002	0.02	0.0001	0.0001	0.0001	0.001	0.005	0.0001	0.0001
Irrig. x CPL	NS	NS	0.09	NS	NS	NS	NS	NS	NS	NS
Molasses	NS	NS	0.0001	0.0002	0.0001	NS	0.0006	0.0001	0.0001	0.0001
Irrig. x mol.	NS	NS	NS	NS	0.03	NS	NS	NS	NS	NS
CPL x mol.	NS	0.01	NS	NS	NS	NS	0.009	NS	NS	NS
Irrig. x CPL x mol.	NS	NS	NS	NS	NS	NS	NS	0.008	NS	0.06

[a] Not significant

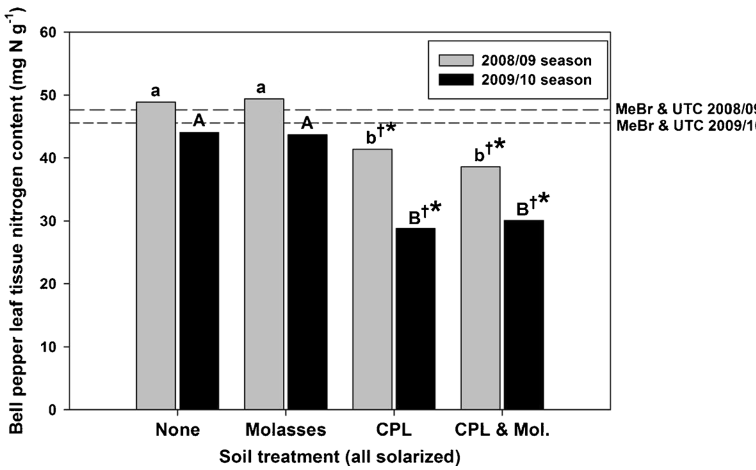

Fig. 4 Bell pepper leaf tissue total nitrogen content as affected by soil treatment. Within year, *bars* indicated by the same letter are not significantly different, $p>0.05$. *Bars* indicated with a † or * are significantly different from the untreated (UTC) or methyl bromide (MeBr) controls, respectively

molasses application were observed for K concentration in eggplant leaf tissue in 2009, but only for CPL in 2010. In 2009, the highest eggplant leaf K concentration was observed from treatments which included both CPL and molasses (51.0 mg K g^{-1}) and lowest in treatments without amendments (i.e. solarization only; 41.2 mg K g^{-1}). In 2010, eggplant leaf tissue K was higher in treatments which did not include CPL (mean 33.2 mg K g^{-1}) than in those with CPL (28.2 mg K g^{-1}).

Main effects of CPL and molasses application were evident for concentration of Ca in bell pepper leaf tissue in both 2008 and 2009 (Table 3). In 2008 and 2009, the highest level of Ca in bell pepper leaf tissue was observed in treatments without amendments (solarization only; 28.6 and 43.3 mg Ca g^{-1} in 2008 and 2009, respectively) and the lowest in treatments with CPL and molasses (17.5 and 30.2 mg Ca g^{-1} in 2008 and 2009, respectively). No main effects of irrigation, CPL or molasses were observed for Ca concentration in eggplant leaf tissue in 2009. In 2010, a main effect of CPL was observed where treatments with application of CPL had much greater Ca concentrations (41.7 mg Ca g^{-1}) than treatments without CPL (25.6 mg Ca g^{-1}).

Main effects of CPL and molasses application were evident for concentration of Mg in bell pepper leaf tissue in both 2008 and 2009. In both seasons, the highest level of Mg in bell pepper leaf tissue was observed in treatments with CPL alone (9.6 and 10.0 mg Mg g^{-1} in 2008 and 2009, respectively) and the lowest in treatments with molasses only (6.4 and 5.6 mg Mg g^{-1} in 2008

Table 4 The mixed procedure analysis of variance for main effects and interactions on eggplant leaf tissue nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) content

	2009					2010				
	N *p*-value	P	K	Ca	Mg	N *p*-value	P	K	Ca	Mg
Block	NS[a]	NS	NS	0.03	NS	NS	NS	NS	NS	NS
Irrigation	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CPL	NS	NS	0.02	NS	0.02	0.0004	0.006	0.0004	0.0001	0.0001
Irrig. x CPL	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Molasses	NS	NS	0.0003	NS	0.0001	NS	0.002	NS	NS	0.05
Irrig. x mol.	NS	NS	NS	NS	0.1	NS	NS	NS	NS	NS
CPL x mol.	0.03	0.05	NS	NS	0.007	NS	NS	NS	NS	NS
Irrig. x CPL x mol.	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a] Not significant

and 2009, respectively). Main effects of CPL and molasses were also evident for eggplant leaf Mg concentration in both seasons, as well as a significant interaction in 2009. In 2009, the highest level of Mg in eggplant leaf tissue was observed in treatments without molasses (7.1 mg Mg g^{-1}) and the lowest in treatments with molasses only (5.3 mg Mg g^{-1}). In 2010, treatments without CPL amendment had the lowest mean Mg concentrations (4.5 mg Mg g^{-1}) and treatments with CPL only had the highest level of Mg in eggplant leaf tissue (6.4 mg Mg g^{-1}).

Bell pepper yield

There was a persistent main effect of molasses application across classes of bell pepper yield during both 2008 and 2009 seasons (Table 5). A main effect of CPL application was present for weight of fancy grade bell pepper in both years, but less consistent for other classes. An interaction between molasses and CPL was present for marketable, fancy, and total yields in 2009. During the 2008 season, the highest marketable bell pepper yield was observed from the plots receiving solarization only (35.4 Mg ha^{-1}), which did not differ from the MeBr control (Fig. 5). This was followed by solarized treatments with molasses application (31.3 Mg ha^{-1}), solarized treatments with CPL application (28.3 Mg ha^{-1}), and solarized treatments receiving both CPL and molasses amendment (24.3 Mg ha^{-1}). All solarized treatments resulted in greater marketable yields than the untreated control. Similar trends were observed for total yield, fancy yield, and culled fruit yields (Table 6). Yield of fancy grade bell peppers exceeded the MeBr control in 2008 in treatments including solarization only.

In 2009, a different pattern emerged for marketable bell pepper yields in that the solarization only treatments resulted in the lowest marketable fruit yields, equivalent to the untreated control (Fig. 5). The highest marketable yields were observed from treatments including solarization and molasses application, which were higher than the MeBr control. Yields from treatments with CPL only or CPL+molasses were statistically equivalent to treatments amended with molasses only and the MeBr control. Trends were similar for total and fancy-grade yields, but no differences were observed in weights of culled fruit (Table 6).

Eggplant yield

In 2009, a clear main effect of CPL application was observed on fancy grade, marketable grade, and total yield of eggplant (Table 7). The main effect of molasses was also significant at the $p<0.1$ level. Marketable eggplant yield was lowest in treatments with solarization only, which did not differ from yields in the untreated control (Fig. 6). Yields were slightly increased in solarized treatments with molasses amendment, with yields similar to the MeBr control. The highest yields were observed from treatments including the application of CPL, which were higher than the MeBr control. Trends were similar for yields of fancy-grade eggplant

Table 5 The mixed procedure analysis of variance for main effects and interactions on fancy grade, marketable, total, and culled bell pepper yield

	2008				2009			
	Fancy *p*- value	Marketable	Total	Culled	Fancy *p*-value	Marketable	Total	Culled
Block	NS[a]	NS	NS	NS	0.02	0.03	0.04	NS
Irrigation	NS	NS	NS	NS	NS	NS	NS	NS
CPL	0.01	0.004	0.003	NS	0.03	0.08	NS	NS
Irrig. x CPL	NS	NS	NS	0.09	NS	NS	NS	NS
Molasses	0.001	0.003	0.0001	0.002	0.0004	0.0002	0.0008	NS
Irrig. x mol.	NS	NS	NS	NS	NS	NS	NS	0.08
CPL x mol.	NS	NS	NS	NS	0.002	0.002	0.002	NS
Irrig. x CPL x mol.	NS	NS	NS	NS	NS	NS	NS	NS

[a] Not significant

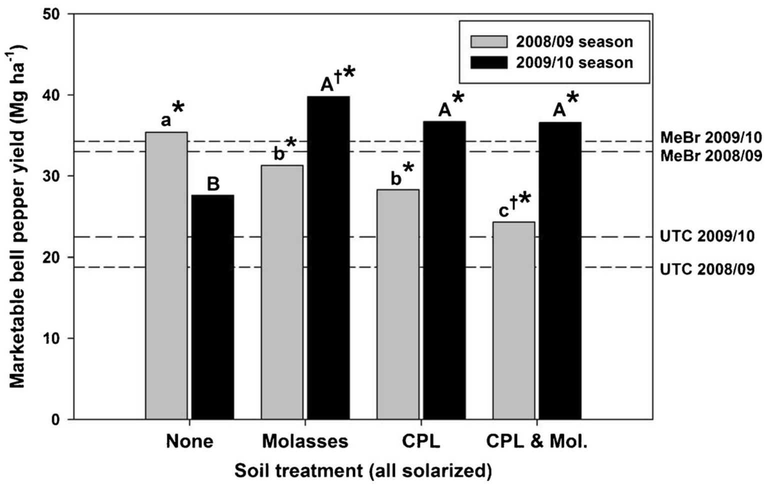

Fig. 5 Total marketable bell pepper yield as affected by soil treatment. Within year, bars indicated by the same letter are not significantly different, $p>0.05$. *Bars* indicated with a † or * are significantly different from the untreated (UTC) or methyl bromide (MeBr) controls, respectively

and total yield (Table 8). No differences were observed in yield of culled eggplant across treatments.

Main effects of CPL and molasses application were observed for yields of fancy grade, marketable grade, and total eggplant in 2010 (Table 7). While marketable yield trends between treatments were similar to 2009, yields were much lower in 2010 than in 2009 (Fig. 6). The highest marketable yield was observed from treatments which were amended with both CPL and molasses, with slightly lower yields from treatments amended with CPL only. Lowest marketable yields were observed from the MeBr and untreated controls and solarized treatments without amendment or with molasses only. In both years, treatments amended with CPL had marketable yields which were greater than the MeBr control. Similar trends were observed for fancy grade and total yields of eggplant in 2010, with yields from treatments including CPL far out-yielding all other treatments (Table 8).

Discussion

In a previous published manuscript from this field study, we reported that molasses+CPL amendment combined with solarization was effective at increasing accumulation of anaerobic soil conditions, compared to the unamended treatments (solarization only; Butler et al. 2012a). At the same time, mortality of introduced inoculum of *Phytophthora capsici* was equivalent to the MeBr control and better than the untreated control in all solarized treatments. Mortality of introduced

Table 6 Soil treatment impacts on bell pepper total yield, fancy grade yield, and culled fruit yield

	Total		Fancy		Culled	
	2008–09 Mg ha^{-1}	2009–10	2008–09	2009–10	2008–09	2009–10
Solarization only	39.1 a§†	29.7 b*	13.1 a†*	13.8 c*	3.7 a	2.2
Solarization+molasses	33.8 b†	41.2 a†	10.5 b†	21.0 a†	2.5 bc	1.4
Solarization+CPL	31.6 b†	39.0 a†	9.7 b†	17.3 bc†	3.3 ab	2.3
Solarization+mol. + CPL	26.7 c*	38.7 a†	7.6 c†	18.5 ab†	2.4 c	2.2
Untreated control	22.2	26.9	4.4	11.6	3.4	1.3
MeBr control	36.3	36.3	9.6	18.9	3.3	2.1

§Within columns, means of solarized treatments indicated by the same letter or no letters are not significantly different, $p>0.05$. Means of solarized treatments indicated by a † or * are significantly different from the untreated or MeBr controls, respectively

Table 7 The mixed procedure analysis of variance for main effects and interactions on fancy grade, marketable, total, and culled eggplant yield

	2009				2010			
	Fancy *p*-value	Marketable	Total	Culled	Fancy *p*-value	Marketable	Total	Culled
Block	NS[a]	NS	NS	NS	NS	NS	NS	NS
Irrigation	NS	NS	NS	NS	NS	NS	NS	NS
CPL	0.0001	0.0001	0.0001	NS	0.001	0.0002	0.0002	0.0003
Irrig. × CPL	0.06	NS	NS	0.05	NS	NS	NS	NS
Molasses	0.01	0.1	0.1	NS	0.03	0.03	0.03	NS
Irrig. × mol.	0.05	0.02	0.02	NS	0.03	NS	NS	NS
CPL×mol.	0.02	0.02	0.03	0.05	NS	NS	NS	NS
Irrig. × CPL x mol.	NS	NS	NS	NS	0.1	NS	NS	NS

[a] Not significant

inoculum of *Fusarium oxysporum* was improved over the untreated control in all solarized treatments, but most effective and equivalent to the MeBr control when soils were amended with molasses. Control of endemic populations of plant parasitic nematodes (*Meloidogyne* spp.) was most effective (and equivalent to the MeBr control) when soils were amended with molasses and/or CPL and irrigated with 5 or 10-cm of water at treatment (Butler et al. 2012a). These results suggest that ASD paired with soil solarization can be an effective strategy for control of soilborne diseases in raised bed vegetable production, but treatment impacts on soil properties and crop performance have not been reported.

Here, we report that very high concentrations of NH_4-N in comparison to NO_2+NO_3-N were typical of treatments which included CPL application in both years of the study. This suggests that, even with the moderate anaerobic conditions (average above 0 mV; Figs. 1 and 2), the oxygen-limited soil conditions may be limiting the activity of nitrifying (i.e., ammonia-oxidizing) soil bacteria, which are obligate aerobes (Bodelier et al. 1996; Kowalchuk and Stephen 2001). At the same time, it has been reported that the high soil temperatures achieved with solarization can have a detrimental impact on nitrifying bacteria in the short-term, which may lead to an accumulation of NH_4-N as observed in our study (Chen et al. 1991; Chen and Katan 1980; Hasson et al. 1987; Stapleton et al. 1985). Similarly, the effect of soil fumigation with mixtures of chloropicrin and MeBr has a well-documented

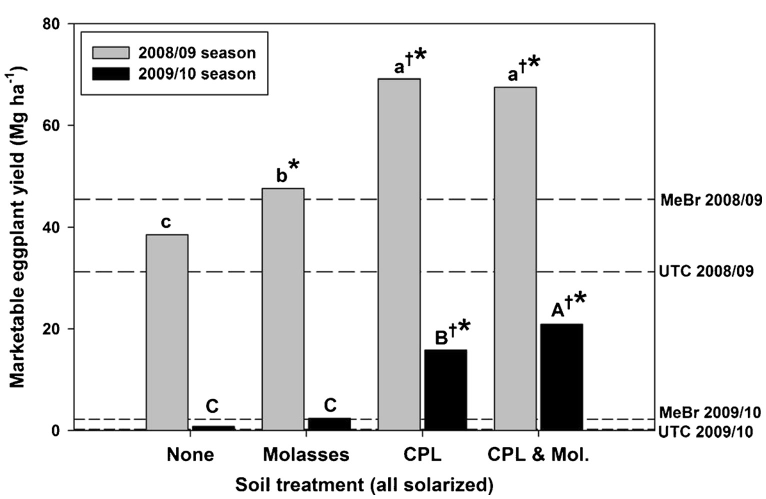

Fig. 6 Total marketable eggplant yield as affected by soil treatment. Within year, bars indicated by the same letter are not significantly different, $p>0.05$. *Bars* indicated with a † or * are significantly different from the untreated (UTC) or methyl bromide (MeBr) controls, respectively

Table 8 Soil treatment impacts on eggplant total yield, fancy grade yield, and culled fruit yield

	Total		Fancy		Culled	
	2008–09 Mg ha^{-1}	2009–10	2008–09	2009–10	2008–09	2009–10
Solarization only	39.6c§	1.0c	20.0c*	0.2c	1.1	0.1
Solarization+molasses	48.2b	2.9c	28.3b†	0.8c	0.6	0.5
Solarization+CPL	69.9a†*	18.3b†*	37.9a†*	4.6b†*	0.9	2.4†*
Solarization+mol. + CPL	68.6a†*	23.3a†*	38.5a†*	7.5a†*	1.1	2.4†*
Untreated control	32.4	0.3	18.6	0.3	1.2	0.0
MeBr control	46.1	2.5	28.2	0.4	0.5	0.3

§Within columns, means of solarized treatments indicated by the same letter are not significantly different, $p>0.05$. Means of solarized treatments indicated by a † or * are significantly different from the untreated or MeBr controls, respectively

detrimental impact on nitrifying soil bacteria (Chen et al. 1991; Rovira 1976), a trend that we observed in 2008, but not 2009 (Fig. 3).

While the application of molasses did reduce the amount of both NH_4-N and NO_2+NO_3-N observed at the 15 to 30-cm soil depth immediately following treatments which included CPL application in 2009, the trend of lower soil inorganic N in treatments with molasses was not significant at most sampling times. This contrasts with the observed N deficiency symptoms seen in the weeks following bell pepper transplanting in treatments which included only molasses application. It is likely that this C-input-induced N limitation was not observed in soil samples as the brief period of N limitation was corrected by supplemental N through fertigation prior to mid-season soil samplings in the molasses only treatments. Likewise, reduced bell pepper leaf tissue N from treatments which included CPL as compared to solarization only was observed in both seasons, but related reductions in soil inorganic N was observed only in soil samples at mid-season in 2008. This may be in part related to the slightly earlier maturity of fruit from treatments that included CPL due to the very high availability of N earlier in the production cycle. The N deficiency induced by application of molasses (or other C source with a high C:N ratio) for ASD treatment is an important consideration for crop management. The use of plant tissue testing to alter soil fertigation rates will likely be necessary for growers until they are more familiar with crop needs following ASD treatment.

In the absence of added CPL, inorganic N present in soils following solarization only treatments did not differ from that observed in the untreated or MeBr control treatments. While increases in inorganic soil N following solarization have been reported (Chen et al. 1991; Chen and Katan 1980; Stapleton et al. 1985), the very low soil organic matter in our study (5.7 g total C kg^{-1} soil) likely prevented such observations. As our study was not designed around this question, we cannot draw conclusions on the impact of solarization on the mineralization of N from applied CPL due to the lack of treatments with CPL amendment but without solarization. Likewise, the dynamics of Mehlich 3 extractable soil P and exchangeable soil K, Ca, and Mg were most related to the application of significant amounts of these mineral elements in either CPL (i.e., P, K, Ca and Mg) or molasses (i.e., K, Ca and Mg). While some past work has indicated an increase in these mineral elements with solarization (e.g., Chen and Katan 1980), other studies have shown variable results (Chen et al. 1991; Stapleton et al. 1985) which were likely related to soil properties in those studies such as organic matter content and soil mineralogy.

A potential impact of the soil pH changes and anaerobic conditions associated with these treatments as described by Butler et al. (2012a) and here (Figs. 1 and 2) on soil P status was also not discernible. In the case of CPL amendment, this was likely due to the overriding impact of amendment nutrient applications, limiting observation of the effect of the more basic soil pH present immediately after soil treatments on soil P status as compared to the solarization only treatments. In the case of molasses amendment, there was no impact of the more acidic soil pH of these treatments versus solarization alone (Butler et al. 2012a) on soil P status. As soil samples were taken at the end of the 3-week treatment period when soils were no longer anaerobic, we were unable to discern impacts of the anaerobic conditions on soil P status. This is consistent with data reported by Vadas and Sims (1998), who demonstrated that soil P status following reoxidation of poultry litter-amended coastal plain soils in Delaware, USA was similar to that observed prior to soil reduction.

The use of CPL in ASD to potentially improve soil water holding capacity and to improve soil microbial diversity in low organic matter soils with a history of soil fumigation could be environmentally problematic with repeated soil treatment due to the potential of high soil P status, as observed following 2 years of treatment in this study. Future work to reduce the amount of CPL used during treatment or to examine the use of composts lower in P content could improve the sustainability of soil treatment by ASD using molasses and composted organic amendments combined with solarization. Given the high level of soilborne pathogen control (Butler et al. 2012a) observed with ASD treatments with molasses amendment+solarization and equivalent yields to the MeBr-fumigated control reported here, the additional organic amendment may not be needed at all, or at least not in all treatment applications. In that case, all required fertility amendments could be applied post treatment, such as through drip fertigation.

Due to the high levels of N and other nutrients applied in CPL-amended treatments, application of supplemental N in these treatments did not begin until the eggplant phase of the double crop system. As such, there was a clear trend of lower leaf tissue N concentrations in bell pepper plants from treatments with applied CPL in both seasons. As described previously, the large release of N during soil treatment was not well-timed to crop needs, leading to N limitation during the latter stages of the bell pepper production cycle. This large release of inorganic N following treatment could also be environmentally problematic if lost from the production system through leaching or denitrification, rather than plant uptake or immobilization within soil microbial biomass. Alteration of the overall C:N ratio of amendments to allow for simplified grower management and reduced risk of adverse environmental impact will help to facilitate the adoption of ASD by growers currently using soil fumigants. Alternatively, the use of amendments with very high C:N ratios could be practical if supplemental N can be applied based on plant tissue testing during the growing season, as discussed previously.

The increase in total bell pepper yield in the second year is consistent with the increase in accumulated anaerobic conditions that was observed that year (Butler et al. 2012a), which may indicate a relationship to improved bell pepper plant health in the second season. Whereas treatments which included an organic amendment (molasses or CPL) with solarization showed improved yields in the second season, treatments with solarization only showed reduced bell pepper yields in the second season. This is consistent with slightly increased root galling by *Meloidogyne* spp. (root knot nematodes) observed in solarization only treatments in the second season (Butler et al. 2012a). Galling by *Meloidogyne* spp. was the only significant disease observed in the study, with higher levels on both pepper and eggplant generally observed in the second season of the study in solarization only treatments versus the MeBr control and treatments with organic amendments and solarization (Butler et al. 2012a). Due to the repeated production of crops in the Solanaceae in this field trial, this may indicate that the pairing of solarization with ASD (or organic amendments) may be an effective strategy to combat yield decline (reduced yields in limited crop rotation in the apparent absence of disease) when crop rotation is limited due to logistical constraints (Bailey and Lazarovits 2003; Bennett et al. 2012). The trends in bell pepper yield do not appear to be directly related to residual N in the CPL-amended plots, as the crop yield in the solarization+molasses plots was equivalent in the second season to those treatments receiving CPL.

The improvement in eggplant yields (greater than the MeBr control) with the application of CPL in both seasons may be due to general improvements in soil properties (e.g., potentially increased water and nutrient holding capacity) associated with added organic materials rather than control of plant pathogens which was typically similar or improved in molasses-amended versus CPL-amended treatments for those pathogens evaluated (Butler et al. 2012a). There was also a general lack of visible eggplant disease during the study (other than limited galling by *Meloidogyne* spp.; Butler et al. 2012a). While the eggplant yield followed a similar trend in both years, the impact of wind-blown weeds from adjacent fields (i.e. after soil treatment), particularly dogfennel (*Eupatorium capillifolium*; Rosskopf et al., unpublished data) in the 2009 to 2010 season likely had a detrimental impact on overall eggplant yield (all treatments) in the second season. While no differences in either bell pepper or eggplant yield were observed with initial treatment irrigation, this may be partly due to the generally low level of disease (Butler et al. 2012a) and relatively low endemic weed pressure observed in solarized plots (with the exception of the final eggplant season; Rosskopf et al., unpublished). Compared to 10-year average yields for commercial production in the state of Florida, bell pepper yields observed for the MeBr control in both years of our study were in general similar to the average of 33 Mg ha^{-1} reported by Maynard and Santos (2007). Eggplant yields in our study were higher than the state average (28 Mg ha^{-1}) for all treatments in 2009 and lower than the state average for all treatments in 2010.

While the potential of ASD (or BSD) treatment to control soilborne plant pathogens in specialty crop production is well-documented, there is limited information on the impact of soil treatment by ASD on crop yield, soil nutrients, and vegetable crop nutrition derived from field-scale research. Our results suggest that solarization combined with ASD treatment using molasses or molasses+CPL amendments has the potential to improve crop yields compared to an untreated control to levels comparable to a MeBr+chloropicrin fumigated control through a number of mechanisms, including control of plant pathogens (Butler et al. 2012a) and changes in chemical, physical, and biological soil properties. The organic amendments used to facilitate ASD treatments in our study can to lead to chemical soil property changes that necessitate changes in growers' soil fertility management to simultaneously maintain yields and protect environmental quality. Researchers and practitioners must continue to refine selection of amendments and amendment mixtures for ASD treatments with the ultimate goal of providing producers with research-based guidance on appropriate amendment rates and amendment properties to balance pest control, soil fertility, crop performance, and environmental protection.

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