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Soil Quality After Eight Years Under High Tunnels

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***Abstract*. The sustainability of soil quality under high tunnels will influence management of high tunnels currently in use and grower decisions regarding design and management of new high tunnels to be constructed. Soil quality was quantified using measures of soil pH, salinity, total carbon, and particulate organic matter (POM) carbon in a silt loam soil that had been in vegetable production under high tunnels at the research station in Olathe, KS, for eight years. Soil under high tunnels was compared with that in adjacent fields in both a conventional and an organic management system. The eight-year presence of high tunnels under the conventional management system resulted in increased soil pH and salinity but did not affect soil carbon. In the organic management system, high tunnels did not affect soil pH, increased soil salinity, and influenced soil carbon (C) pools with an increase in POM carbon. The increases in soil salinity were not enough to be detrimental to crops. These results indicate that soil quality was not adversely affected by eight years under stationary high tunnels managed with conventionally or organically produced vegetable crops.**

High tunnels (sometimes called hoophouses) in their simplest form are constructed with a framework tall enough to walk under and are covered by clear plastic film, heated by solar radiation, and cooled by passive ventilation. Construction design, materials, and other features vary. High tunnels are used to modify the crop environment allowing season extension (early or late), some exclusion of rain, wind, and insects as well as enhanced crop quality and yield (Lamont, 2005). Protected agriculture under plastic film structures began in the 1950s and has since continued to expand worldwide. There was a 50% increase in the area under high tunnels around the Mediterranean between 1985 and 1995 (Baudoin, 1999). Also during this time, there was a growing interest in high tunnel use in the United States. Although plastic-covered tunnels are widely used for overwintering in the nursery industry in the United States, it is only more recently that the possibility of their use began to be realized by vegetable and small fruit producers (Lamont, 2009). In the early 1990s, research and extension professionals in the Northeast began reporting the potential that high tunnels hold for vegetable producers in the United States (Wells and Loy, 1993). It is estimated that of the 800,000 ha under high tunnels worldwide (Enoch and Enoch, 1999), only ≈5000 ha are in the United States (Carey et al., 2009). Increased high tunnel use in the United States is sure to continue as high tunnels were reported in 45 states in 2007 with ongoing research and demonstration projects underway in 36 states (Carey et al., 2009).

High tunnel crops and soils are often more intensively managed than field crops. Intensified production may increase soil nutrient removal, tillage, and traffic. The effect that this may have on soil quality is uncertain. In a 2006 survey of vegetable, fruit, and flower growers using high tunnels in the central Great Plains, 14% of growers were of the opinion that they had soil quality problems in their high tunnels compared with adjacent fields (Knewtson et al., 2010b). There is concern that covering a soil year-round will result in a buildup of insect pests, soil pathogens, and excess nutrient salt levels (Coleman, 1999). Coleman (1999) discusses soil revitalization options that include soil sterilization, soil removal and replacement, removal of the plastic covering for part of the year, and moving the high tunnel to a new location. Publications circulated among vegetable growers such as *Small Farm Today* have stated that imbalances occur where soil is covered and that movable tunnels allow “wind, rain, and sun to improve soil health and pest management” (La Mar, 2010). However, the decline of soil quality under high tunnels has not been confirmed by research. University research and extension studies have mainly focused on crop production methods (Carey et al., 2009). Also, most research done under high tunnels in the United States is still fairly new. The question of sustainability of soil quality under high tunnels becomes more important as existing tunnels age and growers ponder whether to maintain structures in their current location or construct new high tunnels at different locations or as growers plan to use high tunnels on a larger scale where frequent structure shifting is less feasible.

It is the objective of this research to determine if the presence of a high tunnel affects soil quality in a silt loam soil after eight years. Because of the design and management of the experimental plots, we were able to investigate soil quality under high tunnels compared with adjacent fields under both conventional and organic management. Measures of soil quality were: pH, salinity, total soil C, and POM C.

Chemical indicators of soil quality include pH and salinization. pH is closely correlated to base saturation and may be used as an indicator of nutritive quality (Singh and Goma, 1995). Exclusion of rainfall that allows leaching makes high tunnels suspect for salinization, so it is advisable to monitor high tunnel salinity (Knewtson et al., 2010b).

Because organic matter influences soil structure, nutrient storage, water-holding capacity, biological activity, tilth, water and air infiltration, erosion, and even efficacy of chemical amendments made to soil (Dumanski and Pieri, 2000), it is commonly used as a biological indicator of soil quality. Soil organic C is used to estimate organic matter (Nelson and Sommers, 1996), and in non-calcareous soils organic C is equivalent to total soil carbon (Loeppert and Suarez, 1996). In this study total soil C was used to indicate soil quality.

Particulate organic matter as an indicator of soil quality has the advantage of a faster response to environmental change than soil organic matter as a whole (Elliott et al., 1994; Wander, 2004). Particulate organic matter is the labile organic matter of size fraction 53 μm to 2 mm. Gregorich and Janzen (1996) cited four studies that showed greater resolution and sensitivity in measurements of POM change compared with organic matter change. Particulate

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organic matter has been correlated to microbial biomass (Wander and Bidart, 2000), C and nitrogen mineralization (Bremer et al., 1994; Janzen et al., 1992), and soil aggregate formation and stability (Waters and Oades, 1991), demonstrating that increased POM indicates improved soil quality.

Methods

High tunnels were established at the Kansas State University Horticulture Research and Extension Center at Olathe, KS, in 2002, on a Kennebec silt loam soil (fine-silty, mixed, superactive, mesic Cumulic Hapludolls) that was formerly pasture. The six tunnels were constructed with a single layer of 6-mil (0.153-mm thickness) polyethylene sheeting over a metal hoop frame that stands 3.2 m at the center high point. Sidewalls were 1.5 m high and can be manually rolled-up for ventilation. The tunnels and plots measured 9.8 m in length on the east–west axis and 6.1 m in width on the north–south axis. The high tunnels and field plots were kept close together to minimize spatial differences in soil, but the layout had to take into account the wind blocking and shadow effects of the tunnels. Three high tunnels were laid out in a north–south row with 5.6 m between tunnels. A second row of three high tunnels was 5.6 m to the east. The six field plots were laid out in the same configuration with plots in a north–south line with the high tunnels, beginning 10 m to the south of the tunnels. The area between tunnels was mowed grass walkway. High tunnels and field plots were arranged with alternating organic and conventional management. This arrangement attempted to equalize field position, so that position would not become a factor in the design of crop experiments.

Since 2002, soil under the high tunnels and in adjacent field plots has been used for a variety of production-oriented research and extension activities. Soil inputs and crop management have varied with the years. However, the six high tunnels and six field plots have been managed with matching crops and soil amendments in that time. Half of the high tunnels and field plots were managed with conventional amendments and half with organic amendments.

Beds, 9.1 m in length and 0.61 m in width, were made in each high tunnel and field plot for crop demonstration or experiment. Since 2002, each bed, and sometimes subplots within a bed, was managed differently. Tillage, crop, planting date, irrigation, fertilizer, and soil amendments varied from year to year and bed to bed. Crops were replicated across all plots, and soil amendments were replicated in three high tunnels and three field plots, organic or conventional. For example, in Fall 2005, all high tunnels and field plots were planted with the following crops in matching bed sequence: bed 1, collard greens (*Brassica oleracea* L.) with subplots testing a microbial tea additive; bed 2, spinach (*Spinacia oleracea* L.) with subplots planted at different dates; bed 3, different spinach variety with subplots of planting date; bed 4, broccoli (*Brassica oleracea* L. var. *italica* Plenck); bed 5, mixed leafy greens; and bed 6, garlic (*Allium sativum* L.). In general, vegetable crops such as leafy greens were grown in the cooler part of the year and tomato (*Solanum lycopersicum* L.), eggplant (*Solanum melongena* L.), and other warm season crops in the summer. Some years, winter cover crops of rye (*Secale cereale* L.) or spring cover crops of buckwheat (*Eriogonum* Michx.) were planted, but most winters were fallow.

Regardless of plot location (high tunnel or open field), organic matter was added annually or, more frequently, to plots under organic management. Plots under conventional management had organic matter added only in the form of a few cover crops tilled under during the eight-year period. The plots had the same soil organic composition at the beginning of the experiments in 2002. The most commonly used organic fertilizers were Hu-More 1-1-1 (composted cattle manure and alfalfa hay; Humalfa, Inc., Shuttuck, OK), Bradfield Organic fertilizer 3-1-5 (Bradfield Industries, Springfield, MO), and fish emulsion 5-1-1 (Lilly Miller Brands, Clackamas, OR). Fertilizer applications were calculated to apply roughly equivalent amounts of total nitrogen to organic and conventional plots in an experiment.

Irrigation was mainly delivered by drip tape down the rows with a valve for each bed. A row of sprinklers down the center of the plot with heads 0.66 m above the soil were sometimes used to cool leafy green crops. Irrigation water was pumped from a creek.

A storm in the Fall of 2004 removed the plastic cover from all of the high tunnels. This was repaired in the Spring of 2005. The plastic covering was replaced as part of routine tunnel maintenance in the Spring of 2008.

To determine if high tunnels alter soil quality, comparison was made of soil from these matched plots in high tunnels and adjacent fields. Soil samples were collected at a 15-cm depth from five random spots within crop beds (not foot paths) of high tunnels and field plots using a probe of 2 cm diameter in Sept. 2010.

Soil pH was measured in a 1:1 soil and distilled water slurry with a Corning 440 pH meter (Corning Inc., Corning, NY) and a 3 M KCl liquid-filled combination glass electrode (Denver Instrument, Bohemia, NY). Salinity was measured with a Corning Model 441 conductivity meter as electrical conductivity (EC) in liquid extracted from a 1:2 soil and distilled water slurry (Rhoades, 1996).

Samples for soil C measurement (total C or POM C) were oven-dried at 55 °C for at least 24 h. Total soil C was measured after sample combustion with a TruSpec CN 2000 (Leco Corp., St. Joseph, MI).

The POM fraction was separated by moist sieving soil samples dispersed in 5 $g \cdot L^{-1}$ sodium hexametaphosphate solution through a 53-μm sieve cloth (Gregorich and Ellert, 1993). Sieves were rinsed with distilled water to drain out clay and silt size particles. Sand and POM were retained on the sieve. Carbon was measured in POM after combustion with an Elementar Vario MAX CN (Elementar Analysensysteme GmbH, Hanau, Germany).

Measures of soil quality (pH, EC, total C, POM C, and POM C as a fraction of total C) were analyzed as a two-way factorial treatment structure in a completely randomized design with treatment factors location (high tunnel and adjacent field) and management (conventional and organic). All measures were replicated with triplicate plots. Each measure of soil quality was analyzed using the Mixed procedure of SAS (Version 9.2; SAS Institute Inc., 2009). Type III tests of fixed effects (F-tests) were used to determine the significance of the location and management main effects and the location-by-management interaction. Type III tests examine the significance of each partial effect with all the other effects in the statistical model (SAS Institute Inc., 2009). For all measures of soil quality, P values of four tests of normality using the SAS Univariate procedure (Shapiro-Wilk, Kolmogorov-Smirnov, Cramer-von Mises, and Anderson-Darling) were greater than 0.01, implying there was no evidence to conclude that the residuals were not normal. Thus, we conclude that the F-tests are valid. F-tests were also used to evaluate the simple effect comparison of location (high tunnel vs. field) within each management system. The significance level of $\alpha = 0.05$ was used in all statistical tests. Means and SES for the fixed effects were also calculated using the Mixed procedure.

Results and Discussion

The effects of a high tunnel on soil quality were studied within a conventional and within an organic management system. The eight-year presence of a high tunnel significantly affected soil pH and EC ($P = 0.0002$ and $P = 0.0004$, respectively; Table 1). There was a significant interaction effect between location (high tunnel vs. adjacent field) and management (conventional vs. organic) for measures of pH and EC ($P = 0.0021$ and $P = 0.040$, respectively; Table 1). In the conventional management system the mean soil pH was 7.8 in high tunnels and 7.0 in the adjacent field, a significant difference ($P < 0.0001$; Table 2). In the organic management system, the difference between mean soil pH in the high tunnel (pH 7.7) and the adjacent field (pH 7.6) was not significant ($P = 0.22$; Table 2). The significant location-by-management interaction occurred because pH was different between high tunnel and field under conventional management but was not different under organic management. It is not then simply the absence or presence of a high tunnel that caused a shift in pH. However, certain fertilizer regimes may affect soil pH differently under high tunnels compared with open field. It is advisable to monitor soil pH in high tunnel and field and adjust soil amendments as needed.

Elevated salinity was found under high tunnels, particularly with organic management; however, after eight years, the increase in salinity was not enough to be detrimental, even to sensitive crops. Soil is considered

Table 1. Type III tests of fixed effects (F-tests, $\alpha = 0.05$) for the location and management main effects and the location-by-management interaction for soil quality data collected from under conventional and organic management locations at Olathe, KS, in 2010.^{z}

	Main effects				Interaction effect	
	Location		Management		Location × management	
	F-value	*P* value	F-value	*P* value	F-value	*P* value
pH	41	0.0002	11	0.011	20	0.0021
EC	33	0.0004	5.5	0.047	6.0	0.040
Total C	2.51	0.152	21.1	<0.0001	2.32	0.166
POM C	7.36	0.0265	70.1	<0.0001	4.62	0.0638
Total C:POM C	11.1	0.0103	51.8	<0.0001	3.37	0.104

^{z}See the text for a description of Type III tests.

EC = electrical conductivity; C = carbon; POM = particulate organic matter.

Table 2. Measures of soil quality in eight-year-old high tunnels (HT) and adjacent fields at Olathe, KS, in 2010 and *P* values produced by statistical comparison of high tunnels and adjacent fields within conventional and organic management systems.

	Conventional management			Organic management		
Measures of soil quality	HT	Field	*P* value^{z}	HT	Field	*P* value^{z}
pH	7.8^{y}	7.0	<0.0001	7.7	7.6	0.22
EC, $dS\cdot m^{-1}$	0.16^{y}	0.065	0.047	0.30	0.059	0.0004
Total C, $g\cdot kg^{-1}$ soil	17.5^{y}	19.3	0.0591	22.4	22.4	0.967
POM C, $g\cdot kg^{-1}$ soil	1.65^{y}	1.51	0.701	4.20	3.02	0.0088
POM C:total C	0.0941	0.0784	0.320	0.188	0.134	0.0065

^{z}*P* value of F-tests comparing high tunnel and adjacent field, 8 df.

^{y}Treatment mean, n = 3.

EC = electrical conductivity; C = carbon; POM = particulate organic matter.

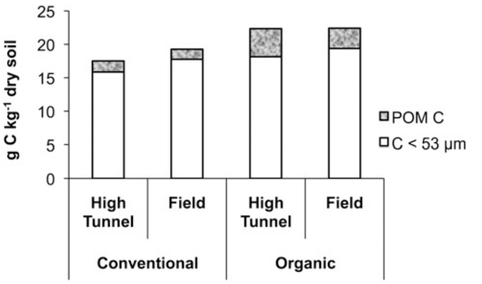

Fig. 1. Carbon in the upper 15 cm of soil in high tunnels and adjacent fields, under conventional and organic management, at Olathe, KS, in 2010. Total carbon (C) is indicated by total column height and particulate organic matter (POM) C by the shaded cap at the top of the column.

saline when the EC is 4 $dS\cdot m^{-1}$ (Brady and Weil, 1999). Only certain sensitive crops such as bean (*Phaseolus* L.), carrot (*Daucus carata* L.), and tomato are affected at EC 2 $dS\cdot m^{-1}$ (Bernstein, 1964). Soil salinity was significantly higher in high tunnels compared with adjacent fields ($P = 0.0004$; Table 1), but was not at a level detrimental to crops (Table 2). In the conventional management system, the high tunnels had a mean EC of 0.16 $dS\cdot m^{-1}$ compared with 0.065 $dS\cdot m^{-1}$ in the adjacent fields ($P = 0.047$; Table 2). In the organic management system, high tunnels had a mean EC of 0.30 $dS\cdot m^{-1}$ compared with 0.059 $dS\cdot m^{-1}$ in the adjacent field ($P = 0.0004$; Table 2). High tunnel salinity was two and a half times higher than adjacent fields in the conventional system compared with five times higher in the organic system. The difference between high tunnel and adjacent field was more pronounced under organic management; thus, there was the significant location-by-management effect ($P = 0.040$; Table 1).

In soil under the high tunnels and in the field, there were significant differences in soil total C ($P < 0.0001$) and POM C ($P < 0.0001$) between the conventional management and the organic management after eight years of organic treatment (Table 1). This is not stated to compare the organic and conventional systems. Most growers using organic amendments in our geographic region use a combination of organic and conventional soil amendments (Knewtson et al., 2010a). Rather it is stated to point out that high tunnel effects on soil quality will vary depending on management. Our study found that measurements of soil quality were affected by the presence of a high tunnel and by organic compared with conventional management (Table 1). There can also be interaction effects between tunnel presence and management (Table 1). By showing results for a conventional and organic system, our conclusions may be of more use to others.

Under the conventional management system, total soil C under high tunnels was 17.5 $g\cdot kg^{-1}$ soil and in the field plots 19.3 $g\cdot kg^{-1}$ soil compared with 22.4 $g\cdot kg^{-1}$ soil in organically managed high tunnels and field plots. Total soil C was not significantly affected by the eight-year presence of a high tunnel ($P = 0.152$; Table 1). Organic soil amendments in the organic management system caused a significantly higher total soil C content ($P < 0.0001$; Table 1). The soil C of size fraction less than 0.53 µm was less affected by organic management (Fig. 1, open bar). Much of organic additions consist of organic particles larger than 53 µm diameter, thus of the POM C size. After eight years of organic soil amendments, the amount of POM C doubled in the organic system as compared with the conventional system in both field and high tunnel (Table 2). In organic field plots, mean POM C was 3.02 g POM C/kg soil compared with 1.51 g POM C/kg soil in the conventional fields (Table 2). The difference was even more in the high tunnels (Table 2) with 1.65 g POM C/kg soil in conventionally managed high tunnels compared with 4.20 g POM C/kg soil under organic management. In the organically managed system, POM C then made up a larger portion of the total soil carbon pool (Fig. 1; Table 2).

Particulate organic matter is considered the more labile fraction of organic matter, and it was in this POM C fraction that the effect of high tunnel presence became evident ($P = 0.0265$; Table 1). In the organic system, the amount of soil POM C was significantly higher ($P = 0.0088$; Table 2) in the high tunnels (4.20 g POM C/kg soil) than the adjacent fields (3.02 g POM C/kg soil). Because the high tunnels and adjacent field plots were portioned off from the same pasture and then subjected to the same soil amendments within a conventional or organic system, the differences after eight years seem to indicate that POM C decomposed less rapidly in the high tunnels than in the adjacent fields. This was more evident in the organic management system with its larger additions of organic matter than in the conventional management system. In the conventional management system, soil POM C was not significantly higher in high tunnels compared with adjacent fields ($P = 0.701$; Table 2).

Decreased POM C decomposition in high tunnels was also reflected by POM C as a fraction of the total soil C (Fig. 1). In the conventional management system, the POM C:total C fraction did not significantly differ between the high tunnels (0.0941) and adjacent fields (0.0784) (Table 2). It was under the organic system that the presence of high tunnels caused a significant shift in the POM C:total C ratio ($P = 0.0065$; Table 2). In the organic management system, the high tunnels had a POM C:total C ratio of 0.188 compared with a POM C:total C ratio of 0.134 in the adjacent field. Over time the presence of a high tunnel affected the soil C pool toward a larger POM C fraction. Higher POM C has been correlated with improved soil quality (Wander and Bidart, 2000; Waters and Oades, 1991), so our measures of POM show that the presence of a high tunnel was not detrimental to soil quality.

We are not the first to report soil C differences between high tunnel and field. Ge et al. (2011) found greater amounts of total organic C and soil respiration, determined from CO_2 evolution, in organically managed high tunnels in humid subtropical China than in nearby organically managed open fields. When comparing two systems with matching organic inputs and an advanced time line, higher soil respiration such as found in the high tunnels of Ge et al. (2011) may indicate that organic residue decomposition has not progressed as far and there is more organic residue remaining to support microbial populations compared with a system with lower respiration (Brady and Weil, 1999). It may be that high tunnels affect long-term organic decomposition.

We observed less decomposition of POM C in organic high tunnels compared with organic fields adjacent to those high tunnels. This may be the result of soil moisture differences. It is likely that fallow periods without irrigation reduced soil microbial activity under the precipitation-sheltered high tunnels at Olathe, KS. The high tunnels are irrigated only when a crop is in production (spring through fall). In the winter, the high tunnels are not irrigated and the soil under them does not receive winter rains and snow. Microbial activity in this dry soil would be much reduced compared with open fields so that, although high tunnel soils have more hours with elevated temperatures (Both et al., 2007), an accelerator of microbial activity, at our research location, is outweighed by the reduced organic decomposition in high tunnels during winter months when moisture is the limiting factor.

Conclusions

The high tunnels at Olathe, KS, demonstrated that the presence of a high tunnel affected measures of soil quality. Soil pH, salinity, and particulate organic matter were influenced, but not unfavorably, by the presence of high tunnels. In a conventional management system, the eight-year presence of a high tunnel resulted in an increase in soil pH and salinity but did not affect soil C. In an organic management system, high tunnels did not affect soil pH, increased soil salinity, and affected soil carbon pools with an increase in POM C. For both the conventional and organic management systems, the increase in salinity was not enough to be detrimental to even sensitive crops. We conclude that soil quality was not adversely affected by eight years under stationary high tunnels managed with conventionally or organically produced vegetable crops. How much a high tunnel will influence soil quality may vary depending on soil crop management and soil inputs.

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