Compost carryover: nitrogen, phosphorus and FT-IR analysis of soil organic matter

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Abstract

Compost plays a central role in organic soil fertility plans but is bulky and costly to apply. Determining compost carryover is therefore important for cost-effective soil fertility planning. This study investigated two aspects of nutritive carryover (nitrogen and phosphorus (P)), and an indicator of non-nutritive carryover (soil organic matter (SOM)) to determine the residual effect of a one-time compost application applied at four rates in a corn-squash rotation. Crop yield was measured as an integrated carryover indicator of nutritive and non-nutritive effects. Functional groups of compost and SOM were investigated using FT-IR spectroscopy and soil organic carbon (SOC). While year to year variability was great, compost had a persistent positive effect on crop yields, evident three years after application with no reduction in magnitude over time. Soil nitrate was low, and additions of compost at any rate generally did not increase levels beyond the year of application, with the exception of year four. Olsen P was also low, yet was higher in amended soils than in non-amended soils three years after application. Pronounced polysaccharide peaks, evident in compost spectra and absent in control soil, were apparent in compost-amended soils three years after compost treatment and SOC was greater two years afterwards. Compost carryover was most pronounced in year four following the incorporation of a nitrogen-fixing cover crop. These results show that compost can influence nutritive and non-nutritive soil properties many years after incorporation, thereby reinforcing the importance of including compost in organic fertility plans despite the unpredictability of year-to-year response.

Key Words: compost carryover, residual compost effects, organic farming, FT-IR spectroscopy

Introduction

Organic farming poses unique challenges for soil fertility management. Organic producers utilize a more diverse range of inputs to meet fertility goals, which complicates efforts to match nutrient availability with crop demand. In addition, organic growers must operate within a paradigm which mandates responsible management of soil and water resources. Organic farmers rely on intuition and observation, advice from vendors, conventional soil tests, and their own experience to make decisions about the quantity and types of soil amendments to apply. As a result, there is tremendous variability in both the quantities of nutrients applied and the resulting soil fertility status on organically managed farms (Wander et al. 2011).

Composts and manures are commonly used on organic and low input farms to maintain or improve soil fertility. Used primarily for their within-season fertilizing contribution, composts and manures also play an important role in soil organic matter (SOM) accumulation and long-term improvements in soil quality. These long-term effects provide a residual nutritive benefit which is frequently overlooked in fertility planning. Whereas inorganic fertilizers are available immediately, compost decomposes gradually, mineralizing nutrients over many years at decreasing rates. Compost also contains a wide range of plant nutrients in addition to nitrogen (N), which are slowly released into the soil, further complicating fertility planning. Typically the N/P ratio of manures and composts is less than that of plants, so growers who base their application rates to achieve an N target often apply P in excess of crop needs (Eghball and Power 1999). Excess P can become an environmental pollutant if it is carried into surface or ground waters where it can cause eutrophication and contamination (Daniel et al. 1994). Excess concentrations of Cu and Zn may also accumulate in soils (Wander et al. 2011).

In addition, compost influences a range of soil physical and chemical properties which provide many crop benefits that are non-nutritive in nature (Chen et al. 1998; Pinamonti 1998; Seiter and Horwath 2004; Rivero et al. 2004; Weil and Magdoff 2004). Following an initial application, these nutritive and non-nutritive benefits carryover from year-to-year. Soil fertility in a given year therefore becomes a function of the total compost applied, plus a proportion of previous years' applications that are carried over into the current year (Endelman et al. 2010). Understanding compost carryover is therefore the first step in redefining fertility management in farming systems where compost/manure forms an important part of total farm inputs.

The residual effect of compost is predominantly a result of the physical and chemical composition of the compost itself. During composting, easily degradable plant compounds such as carbohydrates and proteins become decomposed, and more recalcitrant plant compounds, such as lignin, together with microbial products and non-identifiable humic substances are relatively enriched (Leifeld et al. 2002). Most of the easily mineralizable N and C is lost, leaving only more stable and recalcitrant forms of N and C (Eghball et al. 1997). The finished product has a higher degree of humification and chemical stabilization than the original raw materials, and exhibits a higher aliphatic character and polysaccharide content than native soil (Soler Rovira et al. 2003).

Many infrared wavelengths are known to induce bonding vibrations in a wide range of functional groups, and can therefore be used to characterize organic and inorganic molecules (Stevenson 1994). Fourier transform infrared spectroscopy (FT-IR) has been widely used to study aspects of compost and SOM. Compost stability and maturity have been well described (Chen 2003; Niemeyer et al. 1992; Inbar et al. 1989) and many studies report changes in SOM resulting from agricultural activity or amendment (Sohi et al. 2005; Ellerbrock et al. 1999ab). Ellerbrock et al. (1999b) found that FT-IR analysis of soils was useful in detecting changes in functional groups, in particular carboxylic groups, in response to manure treatments. Although FT-IR has been used successfully to study various compositional aspects of compost and SOM and may be a more sensitive tool to detect changes in SOM pools than gross total organic C measurements. To our knowledge, no studies have investigated compost persistence in soil following a one-time application, on certified organic land.

The goal of this study was to investigate compost carryover on both nutritive and non-nutritive soil properties as a first step towards improving organic nutrient management plans. We hypothesized that soil N and P concentrations can be used to measure nutritive aspects of compost carryover and that FT-IR can be used to identify functional groups displaying residual carryover arising from a one-time application of compost. Finally we hypothesized that crop yield would be the best integrated indicator of carryover of both nutritive and non-nutritive effects.

Materials and Methods

In the spring of 2008, an experiment designed to assess compost carryover under organically managed conditions was established at the Greenville research farm of Utah State University in North Logan, UT. The soil was a Millville silt loam (coarse-silty, carbonatic, mesic Typic Haploxeroll) and had been leveled in the past (last time in early 1990s) with a 0.5% slope to the south west to facilitate flood irrigation. Baseline soil properties are shown in Table 1 and were measured according to recommended soil testing methods for the Western region (Gavlak et al.

2003). Total C and N were determined by dry combustion (LECO TruSpec C/N). Nitrate-N and ammonium-N were measured in 5:1 extracts (1M KCl) by automated colorimetry cadmium reduction and salicylate methods respectively (Lachat QuickChem AE). Electrical Conductivity (EC) and pH were measured in 1:1 soil/water extracts while P and K were determined from $NaHCO_3$ extracts according to the Olsen method. The site had been managed organically since 2005 and had been planted with various summer and winter cover crops prior to the trial period.

Four levels of compost (10, 20, 30, 40 Mg DM ha^{-1}) were applied in each of three years (2008, 2009, and 2010) to three randomly assigned replicate plots per rate. A further four plots served as control plots and received no compost in any year. Plots received compost for the first time each year and received compost only once over the course of the experiment. The experiment therefore consisted of 40 plots, 36 of which (3 years × 4 treatment levels × 3 replicates) received a one-time compost application and four received no compost. The 40 plots were arranged in 2 strips if 20 plots each. Each plot was 4.6 m x 4.6 m in dimension.

Although originally designed as a three year experiment, a further year was added (2011) because of a poor treatment response observed in the third year (2010). In 2011 the experimental design did not allow for the addition of compost to the plots but could still be used to assess compost carryover.

Compost

Compost was purchased in bulk from Miller's in Hyrum, UT. Miller's 'Premium Organic Compost' brand was used in 2008, while 'Millers Steer Compost' was used in both 2009 and 2010. Both composts were made from the same feedstocks (steer manure, stomach contents and non-treated woodchips), however the Premium Organic mix also contained humic acids from a mined source. Chemical analyses of the composts are shown in Table 2. Total C and N were determined by dry combustion (LECO TruSpec C/N). Nitrate- N and ammonium-N were measured in 5:1 extracts (1M KCl) by automated colorimetry cadmium reduction and salicylate methods respectively (Lachat QuickChem AE). Electrical Conductivity (EC) and pH were measured in 1:1 compost/water extracts while total P and K were determined by HNO_3/H_2O_2 digestion. Olsen P and K were measured instead of total P and K in 2008 (Olsen et al. 1954).

Plots were treated with one of four rates of compost (10, 20, 30, 40 Mg DM ha^{-1}). Treatment rates were calculated on a volume basis using compost bulk density. Compost was spread evenly over the plots with a rake and incorporated with a rototiller. No other additional amendments or fertilizers were used and Supplemental Table 1 provides the compost incorporation dates for each year.

Crops

Two crops were grown in rotation, summer squash and silage corn. The crops were chosen to reflect a high and moderate nutrient demand and not necessarily a standard crop rotation (although in Utah silage or sweet corn are commonly grown in combination with a vegetable such as onions or melons in addition to wheat or alfalfa). Certified organic summer squash (*Cucurbita pepo L.*) hybrid ('Golden Zucchini') was used in 2008, and 2010. In 2008 plants were started in the USU Research Greenhouse on May 28th and in 2010 plants were started in 50-cell flats in the greenhouses on May 13th. In 2008 the potting mix contained Miller Premium Organic Compost, vermiculite, perlite, and blood meal. In 2010 the potting mix was comprised of peat moss (0.22m^3), perlite (0.11m^3) and vermiculite (0.11m^3) with the addition of 5.7L of fertilizer comprised of 15 parts bone meal, 10 parts blood meal, 10 parts kelp meal, and 5 parts dolomite. No synthetic fertilizers or amendments were used.

Three sheets of black plastic mulch (1.2m wide) were laid down the full length of the plot area (91.4m) at a spacing of 1.5m in early June. Seedlings were transplanted into the mulch at a spacing of 0.61m between plants within a row with 2 rows spaced 0.61m apart. Thus each sheet of mulch contained two rows of plants in a staggered pattern. Plant density was 21,500 plants ha^{-1}. See Supplemental Table 1 for the transplant dates of each year. A severe windstorm occurred on June 13, 2010 and the majority of the squash crop was lost. On June 15, 2010 a replacement crop was direct seeded into the plastic mulch and the damaged plants removed. Weeds were controlled between mulch rows with a walk behind stirrup hoe and 0.46m rototiller. Overhead sprinklers on 1.82m risers were used in all years. Plots were irrigated once per week for four hours duration at a rate of 0.414cm hr^{-1} for a total 1.66cm $week^{-1}$. No signs of water stress were observed.

Squash fruit were picked twice per week for four weeks. See Supplemental Table 1 for the first harvest date of each year. All fruit larger than 15cm in length were harvested and fresh weights were recorded from 6 plants within the center row of each plot to minimize potential boundary effects. The average cumulative harvest weight per plant was calculated and then this number was scaled to a 1 hectare basis using the density of 21,500 plants ha^{-1}.

The second crop was a certified organic field corn (*Zea mays L.*) hybrid (Dahlco 2146). Seeds were drilled 91.4m long, with rows spaced 0.76m apart for a total of 6 rows per plot. See Supplemental Table 1 for seeding dates for each year. The crop was not systematically thinned and emerged with an average density of 100,000 plants ha^{-1}. Weeds were controlled within row by hand, and between row by a combination of rototiller and walk-behind wheel hoe.

Corn plants were harvested by hand at approximately 30% dry matter. Data were collected from the two center plant rows of each plot (1.5m × 1.5m area). Corn ears were removed and fresh weights recorded for both corn stalks and ears. See Supplemental Table 1 for harvest dates for each year. Ears and stalks were dried at 50°C for a minimum of 14 days and ears shelled. Dry weights were recorded for both stalks and grain. The average grain and silage yield per plot was calculated and then scaled to a 1 hectare basis using the density of 100,000 plants ha^{-1}.

Cover Crop

A hard red winter wheat (*Triticum aestivium*) cover crop was seeded at a rate of 28 kg ha^{-1} on all plots in September 28 2007, September 24 2008 and September 29 2009. The cover crop was allowed to over-winter before being tilled under in the following spring. In 2010 hairy vetch (*Vicia villosa*) was planted in combination with winter wheat and seeded at a rate of 30 kg ha^{-1} for vetch and 28 kg ha^{-1} for wheat on September 30. Cover crops were first mowed and then incorporated using a rototiller on May 15 2008, May 20 in 2009, May 27 in 2010, and May 27 in 2011.

Soil Analysis

In 2009, 2010, and 2011 bulk soil samples were collected from both corn and squash plots at a time corresponding to 30 days of corn growth. This 30-day mark is widely used by corn growers to assess early-season soil-N and apply a side-dress fertilizer if required. In each year, five subsamples of 0-30 cm depth were collected from the center of each plot and combined into one representative sample per plot. Soils were passed through a 2-mm sieve and stored at 4°C until analysis. Sub-samples were oven dried for 24 hrs at 105°C and gravimetric moisture content determined. Nitrate (NO_3^-) and ammonium (NH_4^+) content was determined by automated colorimetry using the cadmium reduction and salicylate methods respectively (Lachat QuickChem AE) in 5:1 extracts (1M KCl). Electrical Conductivity (EC) and pH were measured in 1:1 soil/water extracts while P was determined in 1:20 soil/$NaHCO_3$ extracts according to the Olsen method in 2011 only (Olsen et al. 1954). All measurements were made according to recommended testing methods for the Western region (Gavlak et al. 2003).

FT-IR Spectroscopy and SOC

Only the high rate (40Mg DM ha^{-1}) compost, and control treatments were selected for FT-IR and soil organic carbon (SOC) analysis. Soils (0-10cm) were sampled in September 2011 in plots which had received 40Mg ha^{-1} compost in 2008, 2009, and 2010. Additionally, soils were sampled from plots which had received no compost over the course of the study. Each replicate was comprised of six soil subsamples, collected from the center of each plot and then combined to make one representative sample. Soils were sieved through a 2-mm screen and air-dried before being ground with a mortar and pestle. Soil organic C (OC) and inorganic C (IC) was measured using a Skalar Primacts SLC Analyzer model CS22 (Breda, Netherlands) using the two temperature method of Chechester and Chaisen (1992). Compost was also analyzed by FT-IR spectroscopy. A sample from each of the three composts applied during the experiment was air dried and ground. Two replicates from each year were scanned, adjusted for background, and their spectra averaged to depict a representative spectrum for each compost.

Individual FT-IR spectra were composed of 333 scans with a resolution of 4cm^{-1} (Thermo Scientific Nicolet 6700). For each treatment year, including zero rate control, two samples were selected and spectra determined for two reps of each sample, for a total of 4 spectra for each sample year, and 4 spectra for control. Each group of 4 spectra was corrected against the spectrum for background before being averaged to make one final spectrum representative of each treatment year as well as control. The operating range was 550-3500cm^{-1}. FT-IR spectra were corrected for mineral component by mathematical subtraction based on the FT-IR spectra of the ash from the same sample, as described below.

Organic matter was oxidized in a 1:10 soil/sodium hypochlorite extract. Sodium hypochlorite (6% NaOCl) was adjusted to pH 9.50. Soils were first allowed to react with the NaOCl in pyrex centrifuge tubes for 9 hrs at room temperature (25°C) before being placed in a digestor set at 90°C. Soils were digested for 20 minutes and were agitated every 5 minutes with a vortex mixer. Soils were then allowed to cool to room temperature before being centrifuged for 10 minutes at 2,310 x g. The supernatant was discarded. Heat treatment and centrifuge steps were repeated 4 times until supernatant was transparent.

Soils were then washed in a 1:10 soil/$CaCO_3$ solution (15mM) before being shaken on an end-to-end shaker for 10 minutes and then centrifuged for 10 minutes at 2,310 x g. Supernatant was discarded and the process repeated for a total of three wash treatments. Soils were then dried at room temperature (25°C) for 12 hrs.

Compost spectra were interpreted based on the characteristic FT-IR absorption bands for composted manure described by Carballo et al. (2008). Carballo et al. (2008) defined these as; 2960 – 2850cm^{-1} (C-H stretch of aliphatic structures), 1620 – 1660cm^{-1} (C=O vibrations of ketones, quinnone, carboxylic acids and esters, as well as C=C vibrations of aromatic components), 1430 – 1455cm^{-1} (O-H in-plane bend of carboxylic acids, CO_2 stretch of carboxylates and aliphatic CH_2 alkanes, and also C-O stretch vibration of carbonates), 1030 – 1150cm^{-1} (polysaccharides), 1504cm^{-1} (weak peak), and 1595cm^{-1} (vibration of the aromatic skeleton of lignin).

Statistical Analysis

Crop yield, Soil N, Soil P. Analysis of variance and regression diagnostics for the influence of compost on crop yield, Soil N, and Soil P were conducted in R using the function lm from the stats package (R Development Core Team, 2014). Stepwise model selection was conducted using the stepAIC function from the MASS package (Venables and Ripley, 2002). Spatial covariates for “strip” (1-2) and “range” (1-20) were included as potential variables in the stepwise regression (experiment had 2 x 20 physical layout, with a gap between the strips). Contrasts were estimated using the glht function in R package multcomp (Hothorn et al., 2008).

FT-IR Spectroscopy and SOC. Statistical analysis of polysaccharide peak area was conducted. Integration under the peaks was achieved using OMNIC software (Omnic 8.0, Fisher Thermo Scientific Inc.) for all 16 spectra in the range 800-1300cm^{-1}. Analysis of variance of peak area and SOC was determined using PROC GLIMMIX (SAS version 3.1) in a single factor design where year of compost addition was the only factor. All model assumptions were met.

Results

Crop Yield

A one-time application of compost was made at rates of 10, 20, 30, and 40 Mg DM ha^{-1} in 2008, 2009, and 2010. In addition, four plots never received compost during the three years. Figure 1 shows the yield response to compost for the season in which it was applied. Due to a slight slope (0.5%), water (and presumably nutrients) moved toward one end of the field. This may partially explain the unusually high yield at 30 Mg ha^{-1} in 2008, which was at the lowest point of the field (plot 121). Analysis of variance revealed that field position along the slope was a significant covariate in 2008 ($p = 0.003$). Even with this covariate in the model, plot 121 had large influence (Cook's distance = 0.67 for 16 observations), and thus this data point was omitted for a more robust linear analysis.

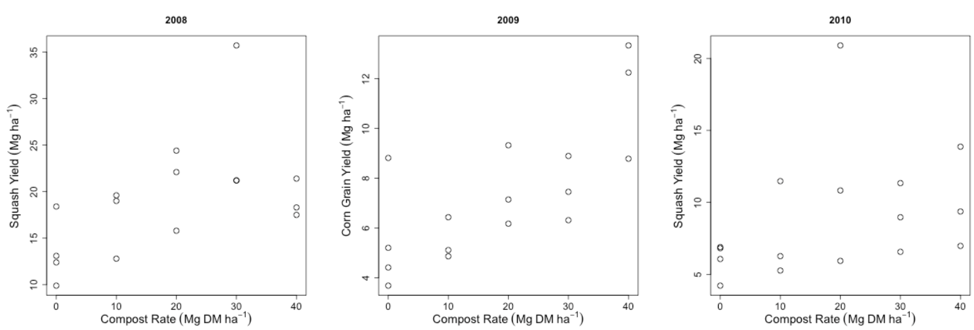

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Figure 1. Yield response to compost during season of application.

As might be expected from visual inspection of Figure 1, ANOVA indicated that the addition of compost (ignoring rate) led to a significant yield increase in 2008 ($p = 0.002$) and 2009 ($p = 0.04$), but not in 2010 ($p = 0.6$). In 2010 an extreme weather event destroyed most of the squash transplants two weeks after planting. The field was replanted, but this disruption may explain the apparent lack of a yield response in 2010. From Figure 1 it was clear that either a quadratic or linear-plateau model was needed to model the yield response to compost rate in 2008. The former was chosen because it is amenable to fitting by multiple linear regression. Stepwise regression was used to build the regression model with the lowest AIC. In 2008 both Rate and $Rate^2$ were included in the final model, while in 2009 the final model included only $Rate^2$. The regression coefficients and their standard errors are shown in Supplemental Table 2.

Having characterized the first-year yield response to compost, we then examined the carryover effect. Figure 2a compares the 2009 corn grain yield for plots that received compost in 2008, those that received compost in 2009, and the four control plots that never received compost. Analysis of variance revealed no significant difference between the 2008 compost treatment and the control treatment ($p = 0.7$). Thus, although the 2008 compost application had a clear effect on the 2008 squash crop, we were unable to detect a carryover effect on the 2009 corn crop yield. Figure 2b compares the corn grain yield in 2011 between plots that received compost in 2008, 2009, or 2010. From the figure it appears there was a detectable carryover effect relative to the control plots, and the magnitude of this carryover effect did not diminish over time. Analysis of variance confirmed there was no significant effect of the year of compost application on the 2011 yield ($p > 0.9$), and the mean yield of the plots that had received compost was 2.3 Mg ha^{-1} greater than the control plots ($p = 0.04$, one-sided). Stepwise regression selected a model with a quadratic dependence on rate, and the results of this analysis (Supplemental Table 2) indicates the rate of compost application was detectable in the carryover effect in 2011.

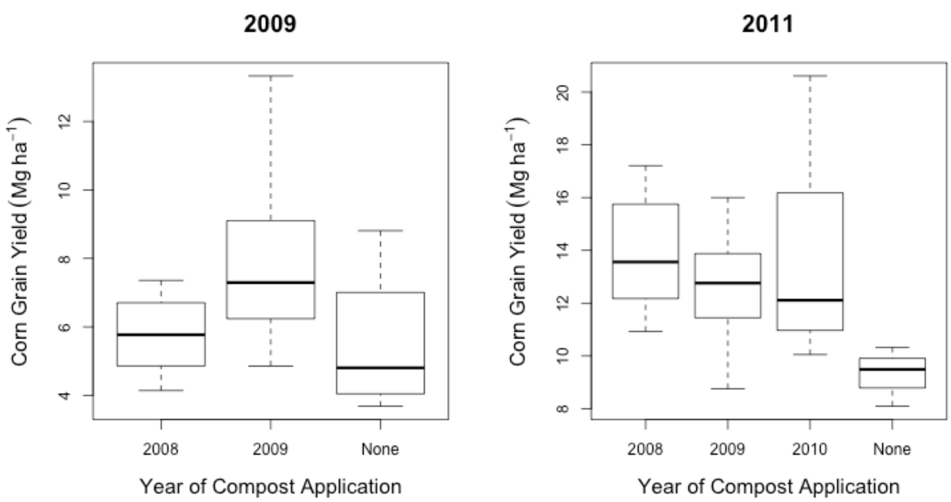

Figure 2. Carryover effect of compost on corn yield.

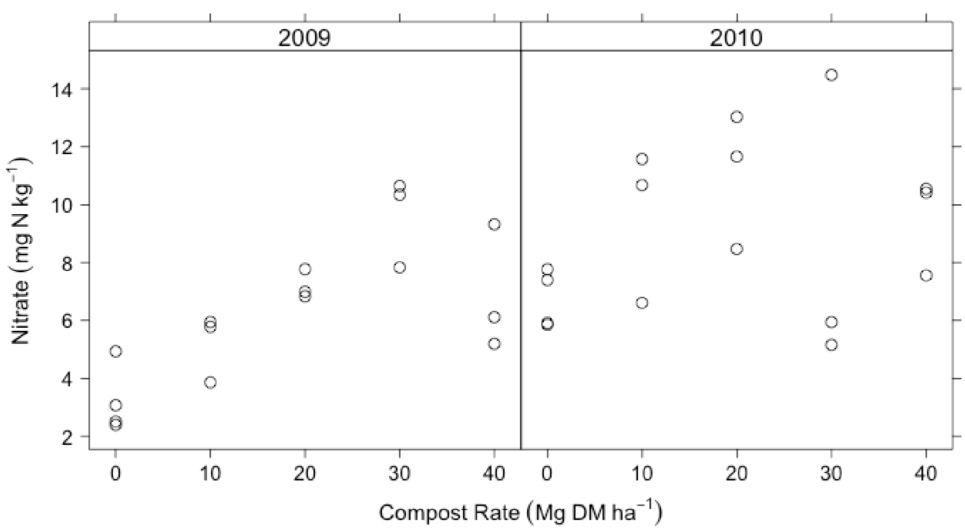

Figure 3. Influence of compost rate on soil nitrate.

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Soil Nitrate and Available Phosphorus

Soil samples were analyzed for nitrate at day 30 of crop growth in 2009, 2010, and 2011. Figure 3 shows soil nitrate concentration in 2009 and 2010 as a function of compost rate, for plots that were amended in that same year. From the figure it appears that nitrate was affected by compost rate in 2009 but not in 2010, which was confirmed by regression analysis. Stepwise regression for the 2009 nitrate data resulted in a quadratic model, with regression coefficients of 0.37 (SE 0.09, $p = 0.002$) mg N kg^{-1} ha (Mg DM compost)$^{-1}$ for Rate and -0.006 (SE 0.002, $p = 0.02$) mg N kg^{-1} ha^2 (Mg DM compost)$^{-2}$ for $Rate^2$. Although rate was not significant in 2010, on average the plots that received compost in 2010 contained 2.9 mg more nitrate-N kg^{-1} than the control treatment ($p = 0.04$, one-sided, Table 3). Table 3, which presents the mean nitrate level across all compost rates, shows no carryover effect was observed for nitrate levels in 2009 and 2010. In 2011 a carryover effect was detected, and stepwise regression resulted in a linear rate model, with nitrate increasing by 0.07 (SE 0.02, $p = 0.008$) mg N kg^{-1} for every Mg DM ha^{-1} of compost, regardless of its year of application.

The Olsen P results, which were only measured in 2011, are shown by year of application in Table 4 and by application rate in Table 5. Although there was no consistent effect of year, regression analysis confirmed that rate was significant: as 1 Mg DM ha^{-1} of compost increased Olsen P by 0.03 (SE 0.01) mg P kg^{-1} ($p = 0.007$).

Finally, we investigated the relationship between crop yield and the soil nutrient measurements. As shown in Figure 4, there was a positive relationship between soil nitrate and yield ($R^2 = 0.41$, $p < 10^{-4}$), but no significant correlation with Olsen P was observed ($p = 0.6$).

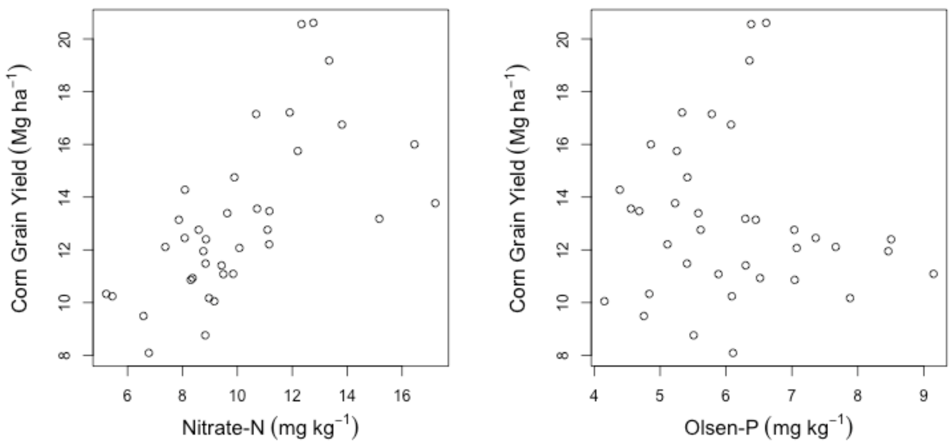

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Figure 4. Relationship between 2011 grain yield and soil measurements of nitrate (left panel) and Olsen P (right panel).

FT-IR Spectroscopy and SOC

Absorption spectra for compost and control soil were very different (Figure 5). The sharp peak recorded at 1027cm^{-1} (polysaccharides) was only weakly apparent in the bulk soil spectra. A broad peak recorded at 1432cm^{-1} (O-H in-plane bend of carboxylic acids, CO_2 stretch of carboxylates and aliphatic CH_2 alkanes, and C-O stretch vibration of carbonates) in the compost spectra was also absent in the control soil. Relative absorption of the band in the region 1640cm^{-1} (C=O vibration of ketones, quinones, carboxylic acids and esters, as well as C=C vibrations of aromatic components) was more pronounced in the compost than in the control soil. A weak peak in the region 1508cm^{-1} (vibration of the aromatic skeleton of lignin) was evident in the compost and largely absent in the control soil. The broad absorption band 3200-

3500cm^{-1} (O-H stretching vibrations) displayed a higher relative absorption intensity in the compost compared with the control soil. Two peaks superimposed as a shoulder of the broad O-H band at 2848cm^{-1} and 2917cm^{-1} (C-H stretch of aliphatic structures) were both absent in the control spectra.

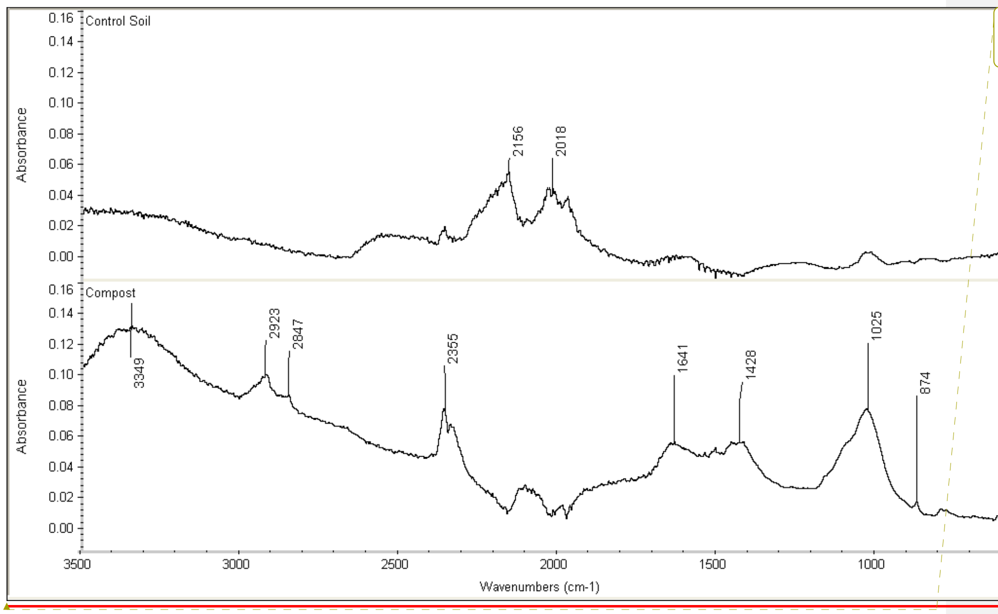

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Figure 5 FT-IR absorbance spectra of compost and control soil. Compost (blue, top) and control (red, bottom) spectra are shown on a common scale and peaks are labeled with their respective wavelengths for clarity

Absorption peaks typical of the compost spectra were evident in compost-treated soils, even 3 years after initial application (Figure 6). The pronounced compost polysaccharide peak at 1027cm^{-1} was evident in all compost-treated soils and showed reduced intensity as time elapsed since treatment increased. The 2010 treated soil recorded a stronger polysaccharide absorption intensity than both 2009 and 2008-treated soils, which recorded weaker but very similar intensities. Absorption in the region of 1440cm^{-1} (carboxylic and carbonyl groups) was weaker than compost in the treatment soils, with 2010 and 2008-treated soils showing stronger absorption than both 2009 and control soils. The two sharp peaks seen in the region 2900cm^{-1} (C-H stretch of aliphatic structures) in the compost spectra, were absent in all treated soils.

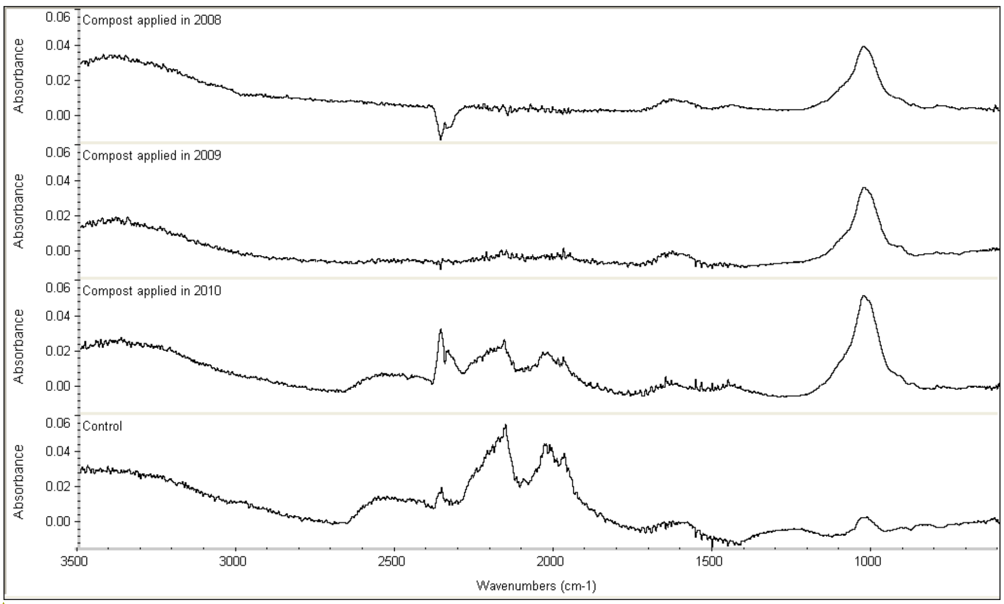

Figure 6 FT-IR absorbance spectra of treatment and control soils. Soils were amended with 40 Mg DM ha^{-1} compost in 2010, 2009 and 2008. Spectra are shown on a common scale

Analysis of variance of polysaccharide peak areas determined that the control treatment had a significantly reduced polysaccharide peak area than all treatment plots, regardless of which year those treatments had been applied (p<0.05) (Supplemental Figure 1). There was no difference in peak area between treatment plots, regardless of year applied (p>0.05). Soil

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organic C was also slightly but significantly increased by the addition of compost although the difference between compost applied in 2008 and the control was not significant (2008 application 1.14 vs 0.93%, $p>0.05$; 2009 application 1.08 vs 0.93%, $p< 0.05$; 2010 application 1.27 vs 0.93%, $p< 0.01$).

Discussion

The original goal of the study was to precisely determine compost carryover in terms of compost equivalents as described by Endelman et al (2010). However, high experimental error prevented the precise determination of the carryover terms (Olsen 2012). Nevertheless, regression analysis clearly showed a persistent carryover effect present on yield, soil nitrate and Olsen P three years after application, with no evidence of any lessoning of this effect with time (Figures 1, 2, and Tables 5 and 6). While the carryover effect on yield and soil nitrate was inconsistent in the short term, a clear carryover effect for all years of application emerged in the fourth year of the study after the incorporation of hairy vetch into the winter cover crop mix. This suggests that both corn and squash were N limited regardless of rate, and that supplying extra nitrogen to the rotation in the form of hairy vetch revealed long-term non-nutritive compost effects or carryover effects of other nutrients such as P.

Yield Response

Year-to-year variability was great, possibly due to temperature and moisture variations across years as well as differences in compost composition (Tables 2 and 8). In season rate responses for both soil nitrate and yield was observed in 2009 but not 2010. Even at the high treatment rate (40 Mg DM ha^{-1}) maximum yield was not reached for corn, based on county averages. Cache County yield averages for corn silage are in the range 18-21 Mg DM ha^{-1} (Griggs et al.

2005, 2006; Griggs and Israelsen 2007). Typical yields of summer squash (zucchini) range from 20.4 Mg ha^{-1} to 37.7 Mg ha^{-1} (Goldy and Wendzel 2009; Gordon et al. 2008). In this study, the maximum average yield for corn silage across all compost levels was 13.7 Mg ha^{-1} recorded in 2008, and the maximum average across all compost levels for squash was 17.2 Mg ha^{-1} achieved in 2008. The apparent yield plateau at levels below county averages is somewhat surprising as a linear yield response to compost might have been expected. Lower soil N was observed at the highest compost rate in 2009 and 2010 also, suggesting that the additional C applied might have caused immobilization of soil N not seen at lower rates. A linear soil nitrate - N response was seen in 2011 (Table 3), bolstering this hypothesis. Alternatively, high rates could have been toxic to plant growth, perhaps through the addition of salts or organic breakdown products. Regardless, compost applied at these rates was insufficient to maximize yields in the given crop rotation.

In the fall of 2010 it was decided to extend the experiment an additional year, and to plant a hairy vetch cover crop (*Vicia villosa*) to overwinter and boost fertility in the spring. A well nodulated hairy vetch crop can contribute 67-134 kg ha^{-1} N. Vetch biomass was not recorded in 2011 so it is unclear how much N was added to the system upon incorporation. However, cover crop biomass collected in 2009 and 2010 showed a linear response to compost rate (data not shown), so it is likely that the vetch responded to treatment similarly and therefore fixed more N in plots which had previously received higher rates of compost. The 2011 season showed a marked improvement in corn yields similar to the high yields seen in 2008.

Available Soil N

Compost at the rates applied did not result in sufficient NO_3^- mineralization for maximum yields to be realized. Over the course of the study, soil NO_3^- levels were low, and additions of compost at any rate did not increase NO_3^- levels beyond the year of application. In 2011 after incorporation of hairy vetch, NO_3^- levels were higher than those of 2009 or 2010 and showed a rate response (Table 3). However, these levels were still below what is typically deemed adequate for corn and squash crops. For corn it is generally recommended to apply fertilizer if pre-sidedress soil tests show NO_3^- levels below 25 mg kg^{-1} (Heckman et al. 1995; Zebarth et al. 2001). Average NO_3^- levels in our corn plots peaked in 2011 at only 9.98mg kg^{-1}. Given these levels, a conventional grower would certainly apply N. Davis and Westfall (2009) suggest a fertilizer application rate of 151kg ha^{-1} for soil NO_3^- in this range (7-12mg kg^{-1} NO_3^- and 1.1-2.0% OM).

Nitrogen mineralization may have also been influenced, to some degree, by the maturity and composition of the compost each year, as well as spring-time temperatures and moisture. Though the composts used each year were purchased from the same facility, they varied somewhat in their chemical composition and degree of maturity (Table 2). The 2010 compost in particular was lower in total N and much lower in NO_3^- than the composts of 2008 and 2009 and had an NH_4^+ content which was considerably higher. These factors may have influenced early spring N-mineralization. The cold spring of 2010 (Supplemental Table 3) may have slowed nitrification, retaining N in NH_4^+ form. Brady and Weil (2002) note that ammonia volatilization is more pronounced at high pH and where there are high levels of NH_4^+ in the system, and as a result ammonium losses from calcareous soils can be quite large. It is also likely that the particularly wet 2010 spring resulted in a significant proportion of soil NO_3^-

leaching and/or undergoing denitrification, and being lost from the soil as NO, N_2O, and N_2 gasses. Whatever the cause, it is clear that the crop grown in 2010 was N-deficient.

Available Soil P

Phosphorus carryover could explain some of the yield response which occurred in the absence of N-carryover. Compost is a significant source of P and composts used in this study contained 1000 mg Olsen P, and 1900 and 4400mg kg^{-1} total-P for the years 2008, 2009 and 2010 respectively (Table 2). Depending on compost rate, P applied per hectare was 10-40kg in 2008, 19-76 kg in 2009 and 44-176kg in 2010 (note estimated P application for 2008 is likely low as Olsen P was measured as opposed to total P). Baseline soil P levels measured in 2007 were very low (averaging 5.90 mg kg^{-1} (±0.22), 10 mg kg^{-1} is generally considered adequate soil test P in calcareous soils), so it seems likely that additional P to the system would have produced a yield response. Nevertheless unlike with nitrate-N there was no relationship between available soil P and crop yield suggesting the system was predominantly N limited (Figure 4). Available soil P clearly responded to compost additions, however, with the effect of rate more evident than year of application. As with nitrogen, differences in compost composition applied each year seems to have affected availability of P.

FT-IR Spectroscopy and SOC

In addition to nutrient carryover, non-nutritive carryover could also contribute to the yield response (Figures 5 and 6). Yield increases ranging from 5 to 25% have been attributed to non-N sources (Magdoff and Amadon 1980; Schroder and Dilz 1987). Non-nutritive carryover is profoundly influenced by SOM. It is clear that despite comprising less than 5% of a typical soil (1% or less in this case), SOM exerts a disproportionally large influence on soil properties

(Wagner and Wolf 1999). Following compost application, SOM displays enrichment corresponding to the original composition of the compost amendment. This enrichment can be investigated by measuring changes in gross SOC content but can be investigated in more detail using infrared spectroscopy.

Compost spectra displayed a pronounced polysaccharide peak which was evident in soil three years after the year of application. Leifeld et al. (2002) noted that polysaccharides present in compost are primarily of plant and microbial origin. Compost polysaccharides can be categorized as being either structural or storage in terms of their chemical composition, with structural polysaccharides, such as cellulose, being more resistant to decay than storage polysaccharides, such as starch. The composition of polysaccharides in our compost was not tested, however because it was plant derived it is likely that it contained a large proportion of cellulose, and that the more labile polysaccharides were rapidly decomposed within the growing season. While cover crops also contain pollyaccharides, the very small peak in control soils compared to those that received compost indicates that compost contributed most strongly to this peak.

Since polysaccharides are strongly hydrophilic, their presence in the compost amended soils can contribute to the non-nutritive compost carryover effects by enhancing soil-water retention (Lowe 1978). Alternatively polysaccharides may sorb to soil minerals or complex humic fractions, thereby reducing SOM decomposition (Lowe 1978). The carbohydrates can affect nutrient phytoavailability by complexing micronutrients or by stimulating microbial activity to enhance or limit nutrient uptake (Lowe 1978; Ros et al. 2006).

Simon (2007) found that soils amended with farm yard manure compost displayed increased intensity of FT-IR spectra of both aliphatic and aromatic bands compared with the control treatment. FT-IR was used by Gerzabek et al. (1997) to show that peat characteristics could be detected in peat treated soils in their long-term field trial. It is clear that compost persists in soil many years after incorporation, contributing distinct functional groups to SOM. Further work is required, however, to determine where these functional groups are located in the soil matrix and how they influence compost decomposition and carryover.

Compost Carryover and Cropping System Design

A variable yield response to compost is common, with the result that many growers look on compost as a soil conditioner rather than a fertilizer. Applying compost in large quantities on an annual basis is a common strategy of organic specialty crop growers while relying on other quick release N sources such as bat guano and fish emulsion in the short-term. Other growers, particularly those with large acreages of grain crops, question the value of compost, instead relying on cover crops or periods of fallow to supply nutrients (Reeve et al. 2012). This has led to criticisms of soil mining by extensive organic farmers on the one hand and an over application / input substitution approach by specialty crop growers on the other. This study suggests, however, that persistent effects of even low applications of compost are important and can have a real benefit in terms of yield of both vegetable and field crops for many years. Interestingly, the carryover effect was most pronounced in year four of the study after incorporation of a nitrogen fixing cover crop. This suggests that after N limitations were ameliorated, other nutritive and non-nutritive effects of compost on yield were expressed. The synergistic effect of compost and cover crops combined in rotation to influence yield even at low rates of compost application is important and deserves further study.

The literature on manure and compost carryover is sparse, especially for soils with low native soil organic matter. With carryover effects of one to six years typically reported (Ippolito et al. 2010; Nyiraneza et al 2010; McAndrews et al. 2006; Eghball et al. 2004; Mooleki et al 2004; Lund and Doss 1980), there is growing evidence that the residual effects of compost in semi-arid dryland cropping systems is considerably longer (Cogger et al. 2013; Reeve et al. 2012; Brown et al. 2011; Eck 1988). Brown et al. (2011) showed that carryover effects were longer in soils with lower SOM. However, the drawback of many of these studies is that they were conducted at disposal rates of application (+200 Mg ha^{-1}). In this study we measured compost carryover at agronomic rates on a low OM soil for a total of four years, with little evidence of a decrease in yield response over time. Breakdown of SOM is typically attributed to the rate and quality of the inputs, soil temperature and precipitation regimes, soil structural properties and the level of disturbance (Horwath 2007). In arid and semi-arid calcareous soils improvements in the availability of P and trace elements due to compost/manure additions may also play an important role (Reeve et al. 2012; Braschi et al. 2003; Grossl and Inskeep, 1991). It is often assumed that compost will persist in soil longer than raw manure due to the more recalcitrant nature of the material (Leifeld et al. 2002; Eghball et al. 1997). There is a lack of appropriately designed research that adequately tests this hypothesis, and, carryover effects have been reported for manure slurry also (Endelman et al. 2010).

Given the persistent carryover effect, compost applications may not be warranted more than every few years in organic cropping systems that rely on N fixing cover crops for the majority of N requirements (Peoples et al. 2009; Peoples et al. 1995). This would provide necessary P, K, S and micronutrients to the system, building non-N fertility which also carries over in following years. In addition, compost builds SOM, and regular use can lead to greater non-nutritive benefits over time. To rely on green manures and cover crops solely, is to neglect the nutritive as well as the many non-nutritive benefits for SOM arising from compost use. Compost and manure is the most economically viable way to incorporate a wide range of macro and micro nutrients in to the soil, and without it growers run the risk of mining their soils of these nutrients.

In addition, our results clearly show that it is not feasible to grow cash crops in rotation on low organic matter soils such as those in Utah while relying on compost to supply N needs. Ideally, a legume cover crop would be grown each year to fix N and supplement the compost or a fertilizer used that is richer in available N such as manure slurry, fish or bat guano products. Short growing seasons limit winter cover crop growth in much of the Intermountain West, USA. Given that squash requires a shorter growing season than corn, there is opportunity for the grower to gain a real benefit from a post-squash winter cover crop, such as hairy vetch, that fixes N. Concerns over pathogens limit the use of raw manure in crops with short planting to harvest intervals or crops that come in contact with the soil such as vegetables. Other more readily available sources of organic N are prohibitively expensive for application to field crops. In more intensive cropping systems it may be necessary to incorporate a perennial legume or pasture ley phase, relay crop under seeded legumes, or even devote an entire season to cover crop production. In an integrated cropping system in Iowa, Davis et al. (2012) showed that N inputs can be reduced by over 80 % when incorporating legumes and manure into an extended rotation.

Acknowledgements

This research was supported by the Utah Agricultural Experiment Station (UAES) and the Utah State University Vice President for Research Fellowship program. Many thanks to Dr. Dan Drost for advice on crop management and data collection. To Xin Dai for assistance with statistical analysis. And to Jeff Slade for technical field assistance. This article was approved as UAES journal paper # 8729.

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Tables and Supplemental Content

Table 1 Baseline soil properties. Measured (0-30cm) prior to the commencement of the study in 2007

Parameter	Soil test value
Organic Carbon %	1.3
Total Nitrogen %	0.15
Phosphorus mg kg^{-1}	5.9
Potassium mg kg^{-1}	143
pH	8.04
EC μS cm^{-1}	296.7

Table 2 Compost properties. Concentrations reported on a dry weight basis

Property	2008 compost	2009 compost	2010 compost
Dry matter %	58.0	56.6	58.0
Total N %	1.9	2.3	1.6
C:N ratio	11.0	15.6	14.7
Nitrate N (mg kg^{-1})	1900	256	11
Ammonium N (mg kg^{-1})	1000	363	1740
Total P %	-	0.19	0.44
Total K &	-	0.86	1.35
Olsen P (mg kg^{-1})	1000*	-	-
Olsen K (mg kg^{-1})	11,000*	-	-
pH	8.0	7.7	9.3
EC (mS m^{-1})	6.0	6.3	8.7

- Note that available Olsen P and K is an underestimate of total P.

Table 3. Mean nitrate levels (mg N kg^{-1}), as influenced by the year of compost application, with standard errors in parentheses.

Year Compost Applied	Year of Nitrate Measurement 2009	2010	2011
None	3.2 (0.8)	6.7 (1.2)	6.8 (1.3)
2008	3.6 (0.5)	6.5 (0.7)	10.7 (0.8)
2009	7.2 (0.4)	7.2 (0.7)	9.8 (0.7)
2010		9.7 (0.7)	10.5 (0.7)

Table 4. Mean Olsen-P levels in 2011, as influenced by the year of compost application.

Year Compost Applied	Olsen-P (mg P kg^{-1})
None	5.6 (0.6)
2008	6.5 (0.3)
2009	5.7 (0.3)
2010	6.5 (0.3)

Table 5. Mean Olsen -P levels in 2011, as influenced by the rate of compost application.

Compost rate (Mg DM ha^{-1})	Olsen-P (mg P kg^{-1})
0	5.6 (0.6)
10	5.7 (0.4)
20	6.2 (0.4)
30	6.0 (0.4)
40	6.8 (0.4)

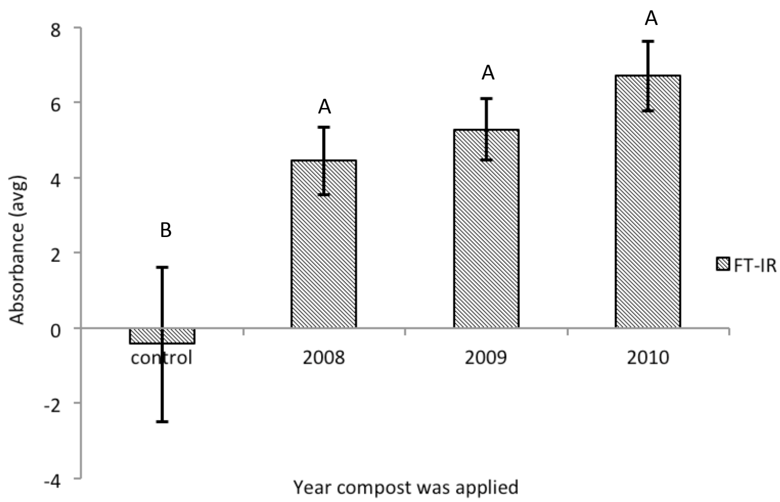

Figure 1S Polysaccharide IR peak area. Areas of FT-IR spectra for 40 Mg DM ha-1 and control treatments. Treatment peak area was significant greater than the control, regardless of which year the compost was applied (p<0.05). Error bars indicate ± standard errors

Table 1S Crop management dates

	2008	2009	2010	2011
Compost Applied	May 15	May 28	May 27	-
Squash Transplant	June 15	-	June 8*	-
Squash First Harvest	July 3	-	Aug 5	-
Corn Planting	-	June 13	-	June 1
Corn Harvest	-	Sept 22	-	Sept 8

*Squash was replanted (direct seeded) on June 15.

Table 2S Regression model for yield response to compost rate

Year	Model term	Estimate (SE)	Units	p-value (estimate = 0)
2008¶	Rate	0.52 (0.17)	Mg squash (Mg DM compost)$^{-1}$	0.01
	Rate^2	-0.010 (0.004)	Mg squash * ha (Mg DM compost)$^{-2}$	0.04
2009¶	Rate^2	3.8 (0.6)	kg grain * ha (Mg DM compost)$^{-2}$	< 10^{-4}
2011‡	Rate^2	1.1 (0.5)	kg grain * ha (Mg DM compost)$^{-2}$	0.04

¶ Models the yield response of the crop to which compost was applied.

‡ Models the carryover effect of the compost, regardless of its year of application.

Table 3S Summary of climate data by month and year. Data sourced from the Utah Climate Center, USU Weather Station. Standard errors (±) for averaged data are reported

Month and Year	Maximum Temp. Average (C)	Minimum Temp. Average (C)	Precipitation Total (cm)	Snow fall Total (cm)
April				
2008	11.0 (±1.1)	-1.7 (±0.7)	2.3	6.6
2009	12.5 (±1.1)	1.6 (±0.6)	7.7	20.3
2010	12.8 (±1.2)	1.5 (±0.8)	6.2	52.3
2011	10.2 (±0.8)	0.3 (±0.5)	11.2	22.8
May				
2008	17.3 (±1.1)	5.0 (±0.7)	6.2	3.8
2009	20.1 (±0.9)	7.1 (±0.7)	4.5	0
2010	14.3 (±0.9)	3.6 (±0.7)	8.2	5.8
2011	14.7(±0.9)	4.4 (±0.5)	13.8	1.3
June				
2008	24.5 (±1.3)	10.2 (±0.8)	2.4	0
2009	22.6 (±0.8)	10.9 (±0.4)	8.6	0
2010	23.5 (±1.0)	10.7 (±0.6)	3.5	0
2011	23.5 (±0.9)	9.8 (±0.7)	2.5	0

Utah State University- Utah Climate Center: http://climate.usurf.usu.edu/#