Changes in Soil Properties and Carbon Sequestration Potential as a Result of Compost or Mulch Application:
Results of On-farm Sampling

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EXECUTIVE SUMMARY

As part of a Life Cycle Assessment of Organic Materials Diversion Alternatives study being funded by the CIWMB, research was conducted to quantify the benefits from applying compost to agricultural soils in California. An earlier study, prepared by the Recycled Organics Unit (ROU) of the University of New South Wales, was used as a blue print for this work. In that study, a survey of the literature was conducted to estimate potential benefits related to compost use in agriculture. For this study, farm sites with a history of compost or mulch use was conducted. Soil cores and other soil samples were taken at these sites and submitted to a lab for analysis. The parameters that we measured included a subset of those used by the ROU that were possible to analyze within our allocated time and budget. The results were compared to the results of the ROU study to see if the quantification of the benefits associated with land application of organics as defined in the ROU study were applicable to soils in California.

The project sought to investigate the impact of applying compost produced using feedstocks generated by municipalities (i.e., yard trimmings and food scraps) to agricultural soils from greenhouse gas and life cycle perspectives (i.e., are there greenhouse-gas-reducing benefits or other benefits that have value in a life cycle assessment) that accrue by adding compost to agricultural soils.). The following areas were investigated:

- Total organic carbon
- Microbial activity
- Water holding capacity
- Water infiltration rate
- Bulk density
- Nutrient availability.

The results for all of these measures (excluding nutrient availability and water infiltration rate) summarized across all samping sites are shown in Figure ES-1

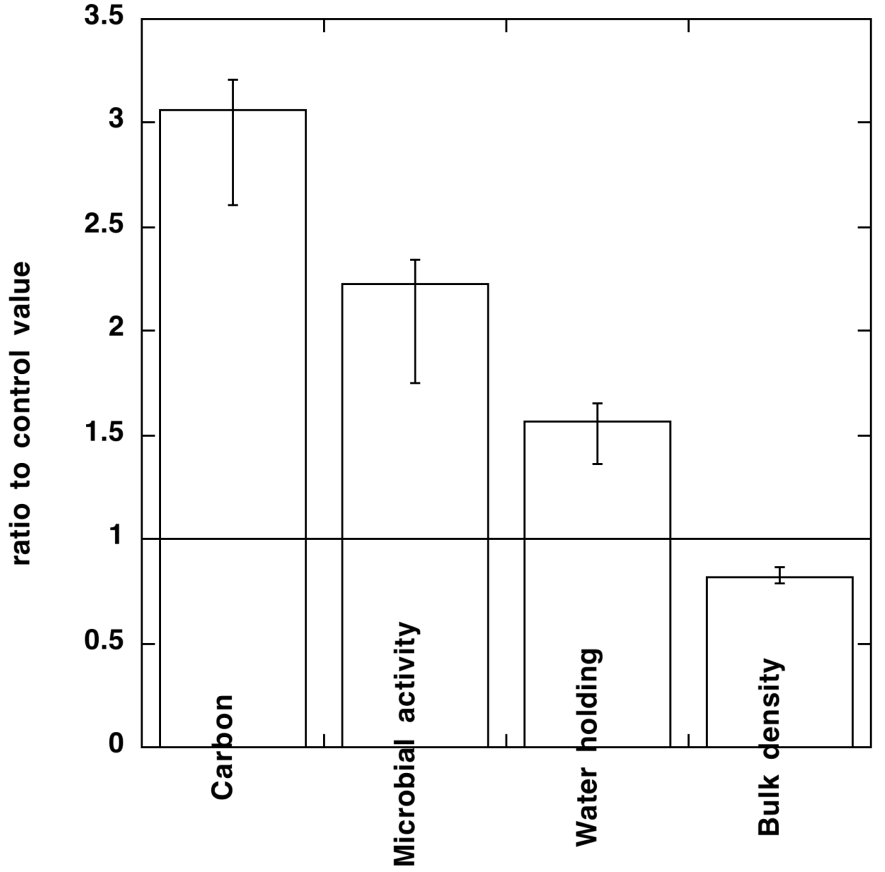

Figure ES-1. The ratio of soil organic carbon, microbial activity, water holding capacity and bulk density in compost-amended soils in comparison to control soils. A value greater or less than 1 indicates a response to compost amendment.

The results of the field analysis were then compared with data presented in a recent Life Cycle Analysis of Windrow Composting (See Table ES1) (ROU 2006). This study was much broader than our field sampling in that it used all available literature to quantify benefits associated with compost use in Australia. The current sampling was conducted to determine whether the findings of the ROU study were suitable for use in California. In general, the current sampling found comparable but slightly larger benefits associated with compost use. The results of our comparison, as well as benefits recommended by the ROU study that were outside of our sampling, are shown below.

Table ES1 A comparison of sampling results from this study with ROU Life Cycle data. Results presented in this summary are from a subsample of the sites in the full survey. The ROU study (2006) quantified potential benefits of compost use for row crops and orchard crops for soils in New South Wales using an extensive literature review to develop values. The results of our sampling are compared to the results of the ROU study and default value recommendations are suggested

	ROU	CA tilled	CA- surface	CA- mulch	Recommended Default Value
		per dry metric ton compost (unless otherwise specified)			
Fertilizer (NPK kg CO_{2eq})	11.8-31.3*	56	56	0	56- based on NP(as P_2O_5)K of 9, 9.5 and 10 kg per Mg of compost Use specific compost analysis when possible
Organic carbon	256 kg CO_2	291 kg CO_2	382 kg CO_2	0	256 kg CO_2 for tilled sites, 300-325 Mg for no till or orchard sites
Water efficiency (% increase)	0.125	1.1	0.5	0.44	0.125
Soil structure-bulk density (% decrease)	2% decrease per 12 Mg compost for incorporated	2.9% decrease per 12 Mg	0.7% decrease per 12 Mg	0.7% decrease per 12 Mg	2% per 12 Mg incorporated, 0.5% per 12 Mg for surface application
Water infiltration rates	1.2% reduction in tilled crops, complete reduction for mulch applications	Infiltration rate 4% as long as control	Infiltration rate 24% longer than control- results specific to site on a sandy soil	Infiltration rate 4% as long as control	We saw an overall average improvement in water infiltration rate of 33% across all sites that received compost or mulch. This can be used as an indicator of reduced erosion potential. Use ROU default values

Herbicide kg CO_{2eq}	30 kg CO_{2eq} per kg herbicide				60 kg CO_{2eq} per ha in orchard crops based on 2 herbicide sprays per season
Saline/sodic	Gypsum replacement				California specific studies recommended
Plant yield	1-2% yield increase per Mg compost				1-2% yield increase per Mg compost
Soil Tilth- using carbon and microbial activity (as CO_2 evolved through microbial respiration) as indicators	Degradation of soils has a cost of $4484 per ha	146% increase in CO_2 emissions/ increase in carbon from 0.7 to 1.1%	Overall 33% increase in CO_2 emissions/ overall increase in carbon from 0.7% to 1.27%	164% increase in CO_2 emissions/ no increase in soil carbon	ROU notes soil with organic C> 2% has improved tilth. Use of compost over time has the potential to improve soil tilth and result in quantifiable $ savings per ha

* The ROU study was done using standard units. The standard unit for land is a hectare. One hectare measures 100 x 100 m2 and is equivalent to 2.47 acres. The standard unit for mass is a metric ton that is equivalent to 1000 kg or 1,000,000 g (Mg). Compost applied at 1 US ton per acre is the same as compost applied at 2.24 metric tons per ha.

Parameter	Unit	ROU	CA tilled	CA- surface	CA- mulch	Recommended Default Value
			per dry metric ton compost (unless otherwise specified)			
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Organic carbon	kg CO_2	256 kg CO_2	291 kg CO_2	382 kg CO_2	0	256 kg CO_2 for tilled sites, 300-325 M or orchard sites
Water efficiency	% increase	0.125	1.1	0.5	0.44	0.125
Soil structure-bulk density	% decrease	2% decrease per 12 Mg compost for incorporated	2.9% decrease per 12 Mg	0.7% decrease per 12 Mg	0.7% decrease per 12 Mg	2% per 12 Mg incorporated, 0.5% per surface application
Water infiltration rates	% decrease	1.2% reduction in tilled crops, complete reduction for mulch applications	96% decrease overall 1% decrease per Mg	24% increase overall 0.005% increase per Mg	96% decrease overall 0.4% decrease per Mg	We saw an overall average improveme infiltration rate of 33% across all sites received compost or mulch. This can b an indicator of reduced erosion potenti per Mg compost
Herbicide	kg CO2eq	30 kg CO_{2eq} per kg herbicide				60 kg CO_{2eq} per ha/compost applicatio orchard crops based on 2 herbicide spr season
Saline/sodic		Gypsum replacement				California specific studies recommend

Plant yield	% increase	1-2% yield increase per Mg compost				1-2% yield increase per Mg compost
Soil Tilth- using carbon and microbial activity (as CO_2 evolved through microbial respiration) as indicators		Degradation of soils has a cost of $64.00 Australian per ha	146% increase in CO_2 emissions/ increase in carbon from 0.7 to 1.1%	Overall 33% increase in CO_2 emissions/ overall increase in carbon from 0.7% to 1.27%	164% increase in CO_2 emissions/ no increase in soil carbon	ROU notes soil with organic C> 2% ha improved tilth. Use of compost over tir potential to improve soil tilth and resul quantifiable $ savings per ha

From a GHG perspective, there is an estimated savings of 316 kg of CO_2 per metric ton of compost used as a low-fertility mulch and 277 kg of CO_2 per metric ton of compost tilled into soils as a soil conditioner, according to the ROU estimates (Table ES2). This is based on soil carbon sequestration, avoided use of synthetic fertilizers, herbicides and pesticides. Based on the results from oursampling, this savings increases to approximately 508 kg of CO_2 per metric ton of compost when applied as a surface mulch in organic orchards, and to 357 kg of CO_2 per metric ton of compost when used as a soil conditioner on tilled sites. In addition to the benefits regarding GHG emissions, benefits were observed for water infiltration in finer soils and water holding capacity (particularly in coarser textured soils). The benefits regarding water were slightly higher than those in the ROU study. A conservative estimate of a 0.125% increase in water efficiency per metric ton of compost is recommended.

Table ES2. Greenhouse gas savings associated with the use of compost for surface application (mulch) and tilled into soils (till). Results presented include savings calculated in the Recycled Organics Unit [ROU]LCA and from samples collected at an organic orchard and tilled row crop site in CA.

	Mulch		**Till**	
	ROU	CA	ROU	CA
	kg CO_2 per dry Mg Compost			
Fertilizer		66	21	66
Herbicide	60*	60		
Soil Carbon	256	382	256	291
Total GHG benefits	**316**	**508**	**277**	**357**

* This credit must be distributed based on the application rate of compost and refers to a per hectare credit and not a per Mg credit

Introduction

Organic materials (leaves, grass, food scraps, etc,) comprise a significant category of recyclable wastes still being disposed in California landfills. A statewide waste characterization study (CIWMB 2004) identified that seven of the top ten materials disposed in California landfills were organic. Diverting organic materials from landfills is a key aspect of achieving and maintaining California's 50 percent recycling goal set by AB 939. With the passage of AB 32, the Global Warming Solutions Act, diverting organics also has the potential to reduce greenhouse gas emissions and provide compost for use as a soil amendment. In the emerging effort to reduce greenhouse gasses, landfill diversion of organics has primarily been understood as a means to reduce methane emissions into the atmosphere (USEPA 2006, 2007a, 2007b, Pipatti et al., 2006, Clean Development Mechanism, 2008; Chicago Climate Exchange, 2009). The Clean Development Mechanism has established a protocol that gives carbon credits for landfill diversion of organics to compost facilities (Clean Development Mechanism, 2008). Carbon credits are based on the methane gas that would have been released after the organics were placed into the landfill and prior to the initiation of gas collection. The benefits are given on a per ton basis for feedstocks diverted from landfills. No credits are provided for use of composts. For materials that are composted, the composting process results in significant volume reduction of 40-80% due to decomposition (i.e. a single US ton of organics that qualifies for methane avoidance credits through diversion to a compost facility yields as little as 200 kg compost). Greenhouse gas benefits associated with use of compost would potentially result from soil carbon sequestration and herbicide and/or fertilizer avoidance. In comparison with methane avoidance that has a CO_2 equivalence of 21 times, compost-use benefits would be based on CO_2 and so are likely to be significantly lower than benefits associated with methane avoidance. related to diversion from a landfill.

There is growing recognition of the benefits associated with using organic amendments on soils. These are based both on smaller, yet significant, GHG benefits as well as increased soil health in cases where organic amendments are regularly applied. A large number of studies have shown increased soil carbon concentrations when manures, composts or municipal biosolids are land applied (Albaladejo et al., 2008; Favoino and Hogg, 2008; Kong et al., 2005; Schroder et al., 2008; Smith et al., 2007). Increasing soil carbon is a cost effective means to sequester carbon that provides a range of ancillary benefits. These potential benefits include increased water holding capacity, increased water infiltration rates, reduced bulk density, improved soil tilth (i.e., health and workability of soil), reduced erosion potential, decreased need for herbicides and pesticides, decreased salinization, reduced fertilizer requirements, and improved yields and/or crop quality (eg. Cogger et al., 2008; Favoino and Hogg, 2008; Recycled Organics Unit, 2006). Each of these can have an enormous financial impact on high value agriculture. In combination, these benefits can result in increased profitability and competitiveness for agriculture.

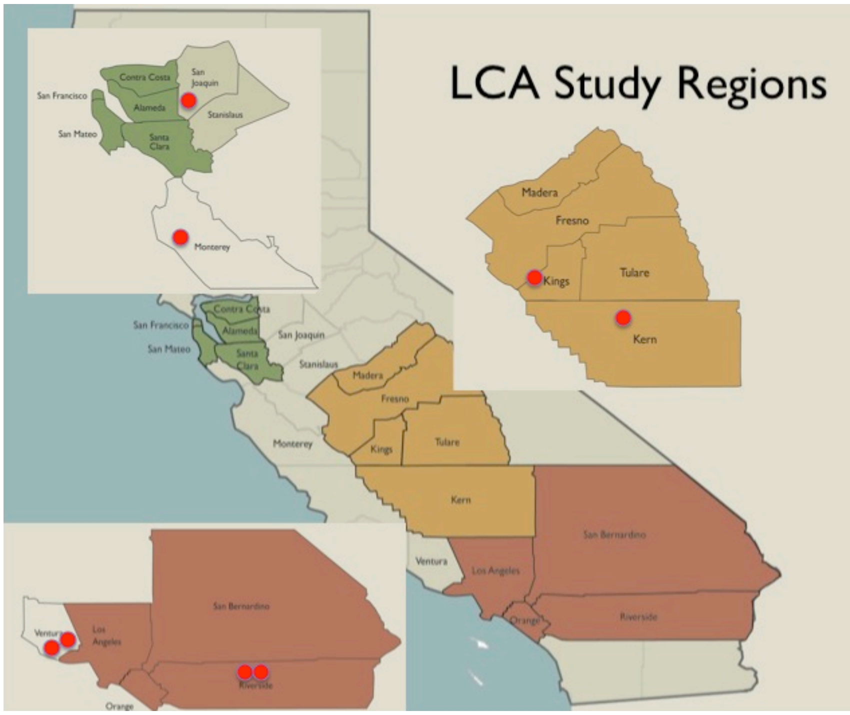
Soil sustainability is increasingly being recognized as important. (Lal, 2007; Mann, 2008). It may be critical to both controlling and adapting to climate change. As the value of soil is understood, the negative impacts of intensive agriculture and urbanization on soil are also being recognized (Lal, 2007). Organic amendments, such as composts, are a means to restore the health and productivity of soils (Smith et al., 2007, Favoino and Hogg, 2008; Recycled Organics Unit, 2006). The Recycled Organics Unit of the University of New South Wales (ROU) (2006) quantified benefits of organics use by conducting a thorough literature review of reported benefits over a broad range of soil and plant characteristics. These were then used to estimate potential benefits for compost use in New South Wales for two applications: as a low-fertility, surface-applied mulch and tilled into soil as a soil conditioner. Both cases were modeled on high value crops. The study did not consider use of compost for agronomic crops. High value agriculture is a major industry in California. It is also the primary user of potable water in California. Water and soil quality have been degraded through conventional agricultural practices. These factors suggest that quantification of the benefits of compost use in California is important. Although the most significant greenhouse gas reductions associated with landfill diversion of organics may be related to methane avoidance, the benefits associated with compost use are likely to be appreciated from a broader perspective.

A soil survey/sampling was conducted to quantify the benefits associated with compost use in California. The variables tested in the sampling included total soil organic carbon and nitrogen, available nutrients, bulk density, soil microbial activity, water holding capacity, water infiltration rate and soil texture. These variables were selected as they reflected benefits observed from compost use in other studies and were feasible to measure in the time frame and budget allotted for this work. The study done by the ROU (2006) was used as a basis of comparison for our results. If the results of our limited survey generally agree with the results based on the extensive literature search done by the ROU(2006), there is the potential to directly apply those findings to California agriculture and other potential applications. The survey sites were determined by working with the farming contacts of large-scale composting operations in a number of counties. These sites are representative of operating farms, rather than replicated experimental field plots that are customarily used for research. Using actual working field sites can lack the scientific data and precision offered in replicated trials. Higher variability is also anticipated when working with actual farms in comparison to replicated field trials. However, working directly with farmers presents an opportunity to get a ‘real world’ view of current compost use and its’ associated benefits in California across a wide range of sites, soils, and crops.

Materials and Methods

Site selection

Site selection was done collaboratively with compost producers in different counties (Riverside, Ventura, Kern, Stanislaus, and Monterey). Sites used in this study are listed in Table 2 and were selected to be representative of agricultural regions and types of crops that use compost that is generated by residuals produced in the regions identified by the CIWMB for the LCA. A map of the study sites in relation to the regions identified for study in the CIWMB’s LCA is shown below.



Map of sampling sites for the current study

In most cases, sites were selected through discussions with compost producers and the growers that use their material. In a few cases, the compost facilities were located on the farms. Generally the farmer or a representative of the farmer met us at the site. In other cases, the compost producers were familiar with the farm and were able to provide information on the history of compost use and the rate applied. For almost all cases, precise application histories were not available. Compost was applied on a wet weight basis and percent solids for each material applied wasn't known. We assumed a solids content of 50% based on discussion with the compost producers. In most cases, compost was applied as a band under the trees. Here the width covered by the spreader was not known and again, an application rate was estimated based on the width of the work row in comparison to the orchard crop. The work row is the area in between the crop row that is used to gain access to the crop by workers as well as any equipment such as compost spreaders. The crop row for all sites covered about 50% of the total land area. Generally, it was assumed that compost was applied to about 50% of the soil surface. Based on these assumptions, an application of 24 wet Mg ha was taken to be 12 dry Mg ha. Applied to 50% of the soil surface gives a total application to the treated area of 24 dry Mg ha. Reported rates throughout the remainder of the report represent dry loading rates. Total rates presented here should be considered more as general approximations rather than precise loading figures. Concentrations of N, P, and K for all composts used on the farms that we sampled are shown in Table 1.

Table 1. Total nitrogen, phosphorus (as P_2O_5) and potassium of composts used by growers included in the sampling trip.

N	P_2O_5	K
	lbs per dry ton	

Cal Biomass	18	19	20
Agromin	28	12.6	20
Grover	32	54	14.4
Z-Best	22	8.2	14.6

A list of the properties visited with short descriptions of each site follows.

Site descriptions

Riverside County

Two farms were sampled in Riverside County; Rucker and HMS. Both have a history of use of compost produced by California Biomass. California Biomass produces compost using different green wastes as well as food processing wastes.

The Rucker farm is an organic orchard established on a Myoma fine sand. Compost is applied under trees as a mulch. Compost is the sole source of fertilizer on the farm. Soil samples were collected from a grape and a lemon orchard with control samples collected from the work rows in each orchard. Compost had been applied to the site at 24 Mg ha for 10 years

The second farm sampled in Riverside County, HMS Agriculural was located on a Cochella fine sand soil. The farm was managed as an organic orchard with compost surface applied under the trees. Compost had been applied for a minimum of 5 years with a single application of approximately 18-24 dry Mg ha. A mixture of compost from California Biomass and composted chicken manure was used to provide sufficient fertility to the site. The nutrient content of the chicken manure was not known. The quantity of chicken manure in relation to the compost produced by Cal biomass was also not known. In general, chicken manure has a high nitrogen content and is applied at significantly lower rates than compost. The primary reason for compost use at this site is to provide fertilizers to the trees. Secondary reasons for using compost include reduced water stress on trees, increased water holding capacity in soils and increased soil health. Control samples for this site were collected from the work row

Ventura County

Two farms that had received mulch applications were sampled in Ventura County. The mulch consisted of coarsely (>5 cm) ground green waste from Material Recovery Facilities in Los Angeles. Organic Ag Inc served as an intermediary between the MRFs and the growers. The mulch was processed (i.e., chipped) but not composted. The first site that was sampled had received a single 20 cm surface application of mulch under mango trees. The soil series at this site was an Azule gravelly loam. The primary reason for mulch application was erosion control. The control samples for this site were taken from the work row. A second mulch site was also sampled. Here, a single application, of a similar depth was made to a Mineola orchard. Control samples were taken from a nearby field which was planted in mature avocado trees. The soil in the area that had received mulch was classified as a Mocho loam. The soil in the control farm was a Metz loamy fine sand. Both sites were on the same farm and a history for each field was provided by the farmer. At the second mulch site, the control was located directly across a farm road from the treated site. Distance between the two sites was approximately 100 m.

Soil samples were also collected from the Limoneira Company. Agromin operates a compost facility adjacent to the Limoneira Company orchard sites and provided compost for the site. At Limoneira, compost had been added to lemon trees as a mulch at 67 wet Mg ha for 3-4 years. Soil at the site was classified as a Mocho clay loam. Application was banded directly under the trees. The primary reason for compost application was to improve quality of the fruit. Control samples were collected directly under the trees of a different lemon orchard where synthetic fertilizers had been used on the same farm and were from a very similar soil series, Mocho loam.

Kern County

Soil samples were collected from a conventionally managed grape orchard called the Grapery. Originally when it wasn't possible to purchase large quantities of compost, compost for this farm was produced by the farmer. Currently the farmer purchases compost from Community Recycling and Resource Recovery in Arvin, CA. Community Recycling composts green material from the Central Valley and Los Angeles areas as well as food scraps collected from grocery stores. The Grapery currently applies about 6.7 Mg ha banded on the grapes as a mulch. Compost has been applied annually to the soil since 1991 with the exception of two years of missed applications. Compost is applied to improve fruit quality, to maintain healthy vines, and to reduce water and fertilizer use. Control samples from this site were collected from the work rows. The soil at this site was classified as a McFarland silty loam.

Kings County

Kochergan Farms is another location where the compost facility is surrounded by orchards. Green material is collected from the surrounding Fresno County area (the facility is just over the Kings County border with Fresno County). Soil samples were collected from an almond orchard that was in the process of becoming certified organic. Compost had been surface applied to the soil (Lethent clay loam) under the trees in two previous applications of 22 dry Mg ha and a single application of 6.5 dry Mg ha over a 3 year period. Compost is applied to meet the fertilizer needs of the trees. Control soils were collected from the work rows.

Stanislaus County

In Stanislaus County representatives from the Grover Environmental compost facility provided access to growers who used their compost. Grover makes compost from green material and food residuals primarily from the San Francisco Bay Area. Soil samples were collected from under the trees in an organic apricot orchard. Compost had been applied under the trees as a mulch to supply the nutrients for the fruit at a rate of 9 dry Mg ha for a minimum of 5 years. Soil at this site is classified as a Zacharias clay loam. Control samples were collected from another apricot orchard that was managed conventionally. The soil series for the control was a Vernalis clay loam

Monterey County

In Monterey County three fields were sampled all of which were owned by Tanimura & Antle (T&A). T&A purchases compost from the Z-Best Composting Facility in Santa Clara County. Most of Z-Best's compost is made from green material that comes primarily from collection programs in the City of San Jose. Soils were sampled from high production, tilled row crop soils. Three sites were sampled here. Two of the fields had a single owner who leased the land.

Compost use was a requirement of the lease. One of these fields was certified organic and compost had been applied at 11.2 dry MG ha for 9+ years. The other was managed conventionally and had had compost applied at 5.6 dry Mg ha for 10+ years. The control soils for this series were sampled from a field across the road that was also used for row crop production, was managed conventionally, and was the same soil series, Pico fine sandy loam.

Table 2. Sample sites for soil collection.

Compost/mulch application rate and total application rates are approximate values based on the best recollection of the compost supplier and or the farmer. .

Farm	County	Crop	Till	Control	Soil series	Compost/mulch application rate	Years of application	Total application
						Mg ha		dry Mg ha
Bruce Rucker	Riverside	grapes lemons	no	on site	Myoma fine sand	24	10+	448
HMS	Riverside	Mango	no	on site	Cochella fine sand	18-24	5+	168
Organic Ag.	Ventura	Mango	no	on site	Azule gravelly loam	20 cm depth	1	273
Organic Ag.	Ventura	Mineola	no	off site	Mocho loam	20 cm depth	1	269
		Avocado	no		Metz loamy fine sand			
Limoneira	Ventura	Lemon	no	on site	Mocho clay loam	34	4-Mar	224
The Grapery	Kern	Grapes	no	on site	McFarland silty loam	6.72	15	100
Kochergan	Kings	Almonds	no	on site	Lethent clay loam	25	2	100
Grover	Stanislaus	Apricots	no	off site	Zacharias clay loam	9	5+	45
					Vernalis clay loam			

Peter	Stanislaus	row crop	yes	off site	Hillmar loamy sand	-		
					Dinuba sandy loam			
T&A	Monterey	row crop	yes	on site	Pico fine sandy loam	11.2	9	100
						5.7	10+	56

Soil sample collection (a) water infiltration ring, (b) bulk density core and intact core used for water holding capacity and microbial activity, and (c) collecting cores for soil chemical analysis including total C and N and available nutrients

Soil sample collection

For compost- amended areas, complete sets of soil samples were collected from three separate locations within the compost amended area. These were directly under the crops for orchard sites and randomly within the treated areas for row crops. Control samples were collected either from the work row of the compost amended sites or from nearby orchards (Deurer et al., 2008). For each site, the reported values for compost amended soils represent the mean of the three complete sets of soil samples. For the control soils, the reported values represent the mean of the 2-3 complete sets of soil samples taken from each site. Each set of soil samples included a sample for total C and N at 0-15 and 15-30 cm, micronutrients, bulk density, soil water holding capacity and microbial activity

Soil samples were collected as follows. For total carbon, nitrogen analysis, soil cores were collected at the 0-15 cm and 15-30 cm depths. A minimum of 4 cores, collected from random locations, were composited for each sample. Available nutrients (Cu, Fe, Mn, Mg, P, and Zn) were also measured on the 0-15 cm samples collected for total carbon and nitrogen analysis. Bulk density samples were collected using a hammer-driven core sampler that collected a 3 cm deep x 5.4 cm core (Grossman and Reinsch, 2002). One bulk density core was collected from each sampling site. Two to three bulk density measures were averaged to produce a mean value for each site. Water infiltration was measured using a single ring falling-head procedure (Soil Quality Institute, 1999). Infiltration rates were measured 2 times per sampling site. The second measure was used for all sites for analysis as at the time of this second measure, both irrigated and control soils had reached similar saturation levels. Water holding capacity and soil microbial function were measured on intact cores collected using a 15 cm long x 5 cm diameter pipe section that was hammer driven into the soil. As with the other measures, 2-3 intact cores were collected and analyzed for each compost amended or control site.

Soil analysis

All soil analysis was conducted at Soil Control Labs in Watsonville, CA. Total carbon and nitrogen were measured by combustion. Inorganic and organic carbon was accounted for by a two-stage combustion. Intact samples were analyzed for total carbon. Acid was then added to the soil to volatilize any carbon associated with carbonates. The remaining soil was re-analyzed for total carbon. The % carbon in the second combustion was taken as the organic carbon content of the soil. Available nutrients were analyzed using the Mehlich III extract (Mehlich, 1984). Soil water holding capacity was measured at 1 bar soil moisture tension on intact cores. Soil microbial activity as CO_2 evolution was measured as follows: a soil core maintained at 1 barr moisture tension was incubated at 27° C for 48 hr. The soil core was then placed in a 1liter jar and incubated for 24 hour. CO_2 evolved after 24 hr was measured using an IR detector

Data analysis

Data was analyzed using SPSS version 16 (SPSS, 2005). Statistics for all main effects were compared using analysis of variance (Anova) with $p < 0.05$. Compost and mulch amended sites were analyzed separately except for water infiltration rates. Means were separated using the Duncan Waller procedure following a significant ANOVA. Variables measured included soil organic carbon, bulk density, microbial activity, water holding capacity, total nitrogen, water infiltration rate, and MIII extractable nutrients. The significance of each of these variables as a function of treatment, site and treatment x site were examined. Site, treatment and treatment x site were generally significant at $p < 0.05$. In order to be able to assess the effect of treatment across all sites, the data was transformed to create a more normal distribution. A ratio variable was created that measured the response of each parameter at a site in the treated soils to the average value of that parameter in the control samples for that site (Brown et al., 2004). Use of the ratio variables enabled comparison of response to compost addition across a wide range of soil series. Ratio variables were used for organic carbon, bulk density, soil microbial activity, and water holding capacity.

Results

Summary Results–Across All Sites

Nutrient availability

In addition to adding carbon to soils, compost contains a range of macro and micro- nutrients. When used to meet the nitrogen needs of a crop, compost will also potentially satisfy at least a portion of plant requirements for phosphorus, zinc, iron, copper, manganese and potassium. For nutrient availability, compost would be expected to increase nutrient content in compost amended soils comparison to samples taken from the unfertilized work row. For samples where the control was collected from other orchards or managed soils, nutrients in the compost-amended soils would be expected to be similar to the control sites which would have received synthetic fertilizers. In cases where control samples were collected from other orchards or managed fields, available Fe, Mg, Mn, P, and Zn concentrations were statistically similar in compost amended and control sites (Table 3). There was a tendency for increased availability of Mn, P and Zn in the compost amended soils in comparison to the control but this was not statistically significant ($p<0.05$). There was also a tendency for higher available Fe in the control soils, but again, this was not significant at $p<0.05$. Available K and Cu were increased in the compost-amended soils in comparison to the control. For cases where the control sample was collected from the work row, compost amendment increased available nutrient concentration for Fe, Mg, Mn, P and Zn in comparison to the control soils. The mean value of extractable K and Cu were also higher in the compost amended soils, however, samples showed high variability and so these increases were not significant. For copper, there was a very high available copper sample from one of the compost amended sites that resulted in the high standard error. There was no difference in nutrient availability following mulch application in comparison to control samples collected from the work row or another orchard site.

Table 3. Mehlich III available nutrient concentrations (mg kg^{-1}) for compost and control soils. Means ± standard error are shown. Within column pairs, values in bold are significantly different ($p<0.05$). For work row/same soil series, n=40, for other orchard/soil series n=10.

	Iron		Potassium		Magnesium		Copper		Manganese		Phosphorus		Zinc	
							mg kg							
							Control from other orchard/soil series							
Compost	243	±38.9	**583**	**±199**	1560	±428	**46.5**	**±7.29**	276	±135	104	±64	33.9	±23.3
Control	332	±101	**276**	**±104**	1500	±508	**25.3**	**±4.5**	206	±91	52	±14	9.2	±1.4
							Control from work row/same soil series							
Compost	**423**	**±124**	636	±477	**984**	**±393**	18	±24	**163**	**±36**	**409**	**±222**	**46**	**±41**
Control	**334**	**±146**	596	±520	**736**	**±305**	7.1	±9.8	**120**	**±53**	**186**	**±100**	**13**	**±9.7**

Soil nitrogen

Across all compost amended sites where the control was taken from the work row, compost application increased total nitrogen in the 0-15 cm horizon of the soil. Total N increased from 0.1±0.02% in the work row soils to 0.21±0.03% in the compost amended soils (Figure 1). There was no difference in total N in the compost amended soils (0.095%) in comparison to the control soils (0.094%)when the control sample was taken from another farm with a different soil series. There were also no significant differences in total soil N for the compost- amended soils in comparison to either control at the 15-30 cm depth.

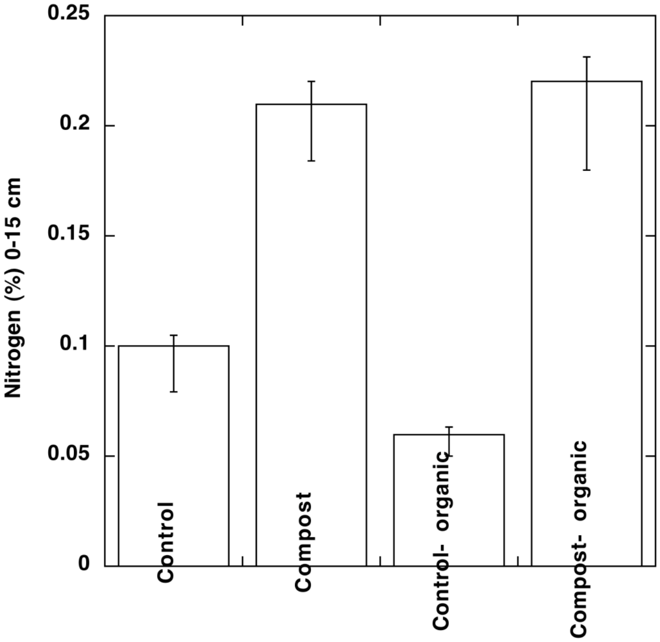


Figure 1. Soil nitrogen (%) in all compost amended soils and control soils sampled in the survey where soil series between control and compost amended was the same (n=40). Means and standard error are shown. Bars are also shown for organic managed fields where compost was the only source of nitrogen for the soil (n=21).

Some of the sites that we sampled were managed conventionally while others were certified organic. The above comparison does not take into account the N input from conventional fertilizers that may have contributed to the observed increase in soil N in the compost- amended soils. For conventionally managed farms, differences in total N in compost amended versus conventionally managed fields or work rows could be the result of a combination of nitrogen sources including the compost and synthetic fertilizers. To compensate for this, this analysis was also run to compare total soil N in the compost-amended soils of organic farms in comparison to control soils from these farms. Synthetic fertilizers are not permitted on organic farms so that any differences in total N in the compost amended soils in comparison to control soils on these farms would be the result of added nitrogen from the compost. Here also, the increase in soil nitrogen was significant and slightly more pronounced in the compost amended compared to the control soils in comparison to the data set as a whole.

Soil Carbon

Across all cases where the control samples were collected from the same soil series as the compost amended soils, the ratio variable showed significantly increased soil organic carbon ($p < 0.0001$)(Figure 2). Mean organic carbon in the compost amended soils measured 3 x that in the control soils. This difference was in the surface 0-15 cm soil horizon. There was no significant difference in organic soil carbon in the 15-30 cm soil depth. . Across all sites, the average % C in the 0-15 cm depth for both compost amended and control soils was 1.5± 1.2. In the 15-30 cm depth the average % C was 0.49 ± 0.33%. There is a potential that a portion of this increase was the result of increased irrigation in the compost- amended soils (Wu et al., 2008). Increased irrigation results in greater plant growth in comparison to non- irrigated soils in arid regions.

Soil microbial activity

Compost application also increased microbial activity ($p < 0.009$) in comparison to the control soils. Microbial activity was 2.23 times greater in the compost- amended soils in comparison to the control soil (Figure 2). The organic matter in compost provides food for microorganisms. All of the work rows that we sampled had a grass cover crop or organic mulch that would also have provided a substrate for microbial growth. It is likely that control soils with no plant cover or mulch would have had even lower microbial activity in comparison to the compost amended soils.

Water holding and bulk density

Increased water holding capacity ($p < 0.01$) as well as decreased bulk density ($p < 0.004$) were also observed in the compost- amended soils (Figure 2). Water holding capacity was 1.57 x that of the control soils and bulk density was 0.82 times the control soils. Results and standard errors for each variable are shown below (Figure 2). It should be noted that site was also significant for each of these variables as was the site x treatment interaction. This means that the response to compost addition varied by site. Because of the wide range of sites, soil series and application rates included in this sampling, this interaction would be expected.

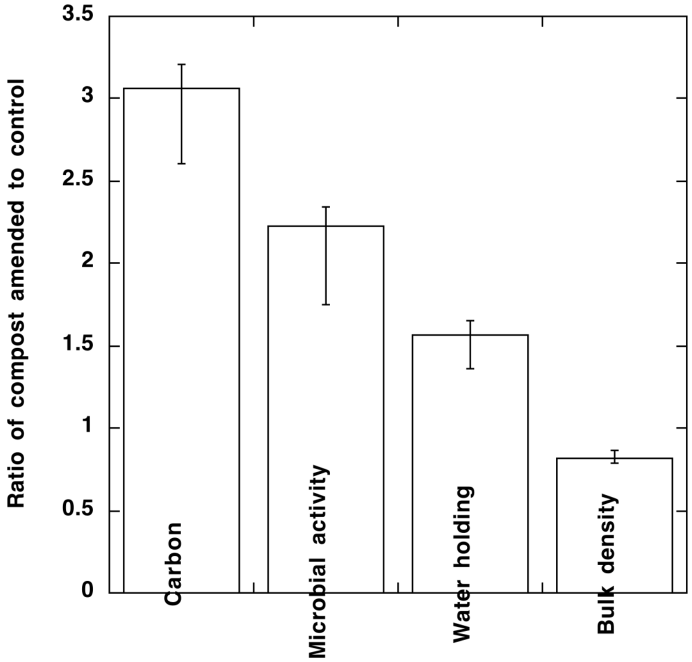


Figure 2. The ratio of soil organic carbon, microbial activity, water holding capacity and bulk density in compost amended soils in comparison to control soils (control soils taken from work row or other crop area with the same soil series). A value > 1 shows a positive response to compost addition, while a value < 1 shows a negative response or decrease in response to compost addition

Results--Effect of rate for compost

The effect of compost application rate on each of these variables was also examined. Here the results are less clear, however there is a tendency towards more pronounced differences with higher application rates of compost. In addition to application rate, factors such as soil texture will influence soil water holding capacity and bulk density. Because of the way that sites were selected for this sampling, we did not have sites with the same soil type and management practices and different application rates or cumulative loading rates for compost. It is impossible to isolate the effect of site and specific management practices from rate in this particular sampling. It is likely that if there had been more control of other factors including soil type that a more linear response to increased compost application rate would have been observed. It is likely that in a controlled study with multiple application rates over time at a single site, the effect of rate would be more pronounced and it would be possible to distinguish differences between rates in a more predictable manner.

Carbon related variables

Soil carbon showed a tendency to increase in comparison to the control soils with a slight but not statistically significant increase in the soil that had received a cumulative loading of 25 dry t/a

(Figure 3). This trend was more pronounced for the two locations where a total of 45 t/a of compost had been applied. It should be noted that at one of these sites, compost applications at a low annual rate of addition had been ongoing for over 15 years. A single site with a short (2 year) history of compost use and total application of 46 t/a showed very little increase in soil carbon. This site showed no change as a result of compost application for the majority of indices tested. The sites that had the highest rates of compost application showed the most significant increases in soil carbon.

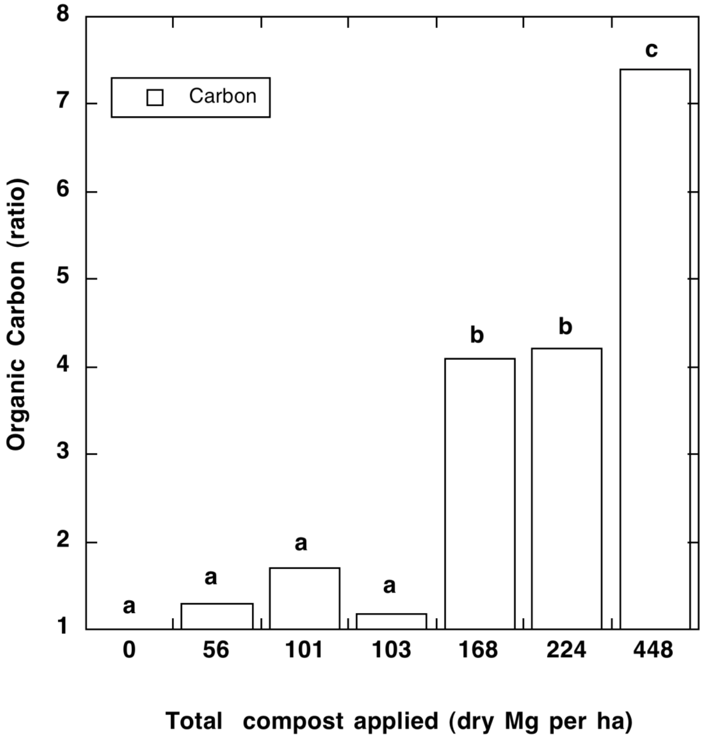


Figure 3. Total organic carbon in the 0-15 cm soil horizon as a function of total compost applied. Rates with the same letter are statistically similar ($p<0.05$).

It should be noted that increases in soil carbon were visible on all sites where compost had been surface applied. Soil analysis showed more pronounced increases in total soil carbon for sites that had received higher loading rates, with no significant increases in total carbon for sites that had received lower cumulative loading rates of compost. These results may be due in part to how we collected soil samples. For this study, rurface soil samples were defined as the top 15 cm of the soil. A dark surface horizon was visible on all sites that had received compost amendments in comparison to the control sites. The depth of this horizon decreased with lower total compost application. Any increases in total carbon in the top 5 cm of the soil may have been missed by mixing the surface 15 cm of the soil for analysis. . Measuring soil in 15 cm increments is standard practice. In hindsight, it may have been more appropriate to divide this into two depths.

Organic matter accumulation on the soil surface of an orchard sites that had received low annual compost applications (6.7 Mg ha) for 15 years is shown below. The color change at the soil surface indicates organic matter accumulation.

Organic matter accumulation (as evidenced by the surface soil color change) for a soil that received annual compost applications of 6.7 mg ha for 15 years.

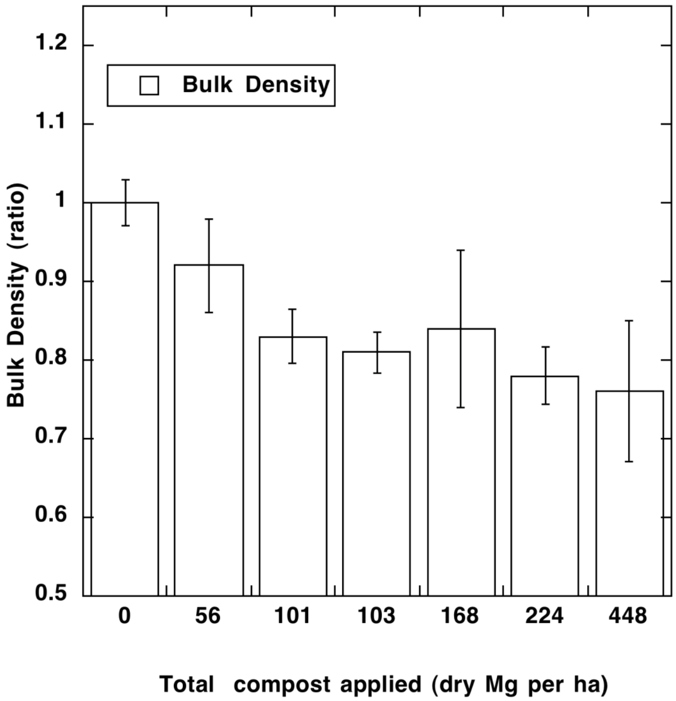


Figure 4. Soil bulk density in compost amended soils (ratio of observed values in amended soils in comparison to the control soils). Values <1 indicate reduced bulk density in comparison to the control soils.

Soil bulk density followed a predictable pattern with decreased bulk density at increasing rates of compost application (Figure 4). Soil bulk density is a measure of weight per unit area, normally expressed as g cm^3. Low bulk density indicates increased pore space and is indicative of improved soil tilth. Tilth refers to the friability of the soil that is a function of both soil texture and aggregation. Improved tilth increases root penetrability, water infiltration and soil aeration. Organic amendments improve soil bulk density by aggregating soil mineral particles. In addition, the organic fraction is much lighter in weight than the mineral fraction in soils. Increases in the organic fraction decrease the total weight and bulk density of the soil.

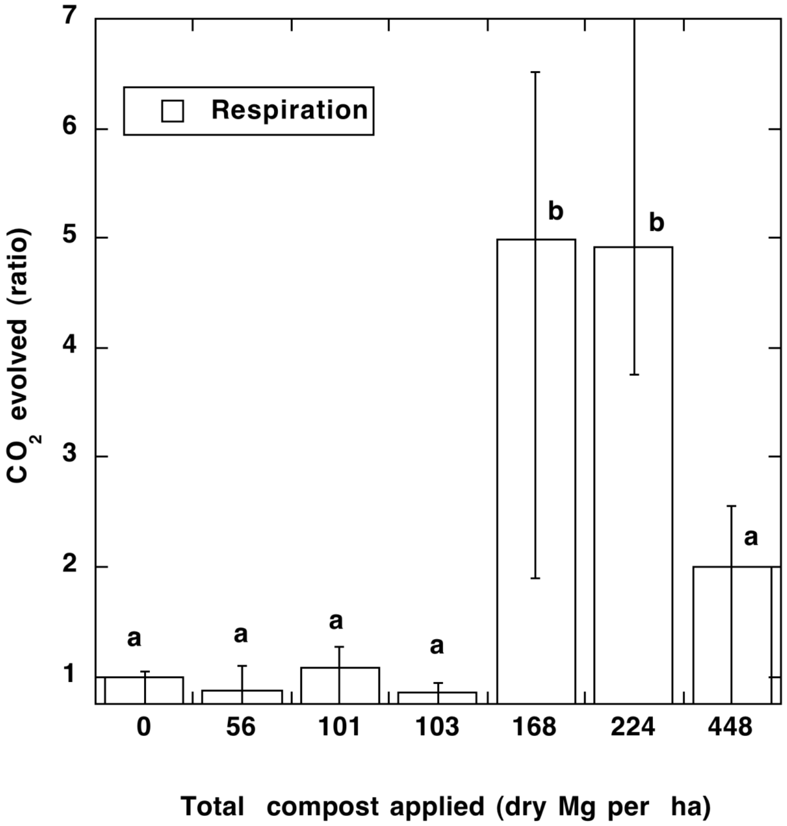


Figure 5. Soil respiration (CO_2 evolved) used as an indicator of soil microbial activity. The ratio of CO_2 in the compost- amended soils to that evolved in the control soil can be used as a measure of increase or decrease in microbial activity in relation to compost amendment.

Soil respiration significantly increased ($p<0.05$) in the soils that received total cumulative compost applications of 75 and 100 t/a or more (Figure 5). There was a slight but insignificant decrease in microbial respiration in both the soil that received 25 t/a and the soil that received 46 t/a of compost. It would be expected that compost application would increase soil microbial activity as the organic matter in compost provides a food source for soil microorganisms. However, one measure that our sampling wasn't able to factor in was the time between soil sampling and the last compost application. It is possible that microbial activity increases immediately after compost amendment as well as during certain parts of the growing season. For some of the sites that we sampled, harvest was complete, while for others crops were still ripening. Microbial activity in soils will respond to availability of substrates, quantity of available substrate is likely to vary by the growth stage of the plant and the time following compost amendment. These factors may influence this measure. However, for the highest rates of compost application, microbial activity increased in comparison to the control soils.

Soil water

Potential changes in soil water after compost amendment was measured using two indices; water holding capacity and infiltration rate. The most pronounced increases in soil water holding capacity were in the sites that received 75 and 200 t/a cumulative application, these were also the soils with the coarsest texture (Figure 6). The soil texture for both of these soils was loamy sand whereas the texture for the site that had received 100 t/a was silty loam. The sites with lower application rates ranged in texture from sandy loam to silty loam. Coarser textured soils have lower water holding capacity than finer textured soils and so are more likely to see improvements as a result of compost addition (Brady and Weil, 2002).

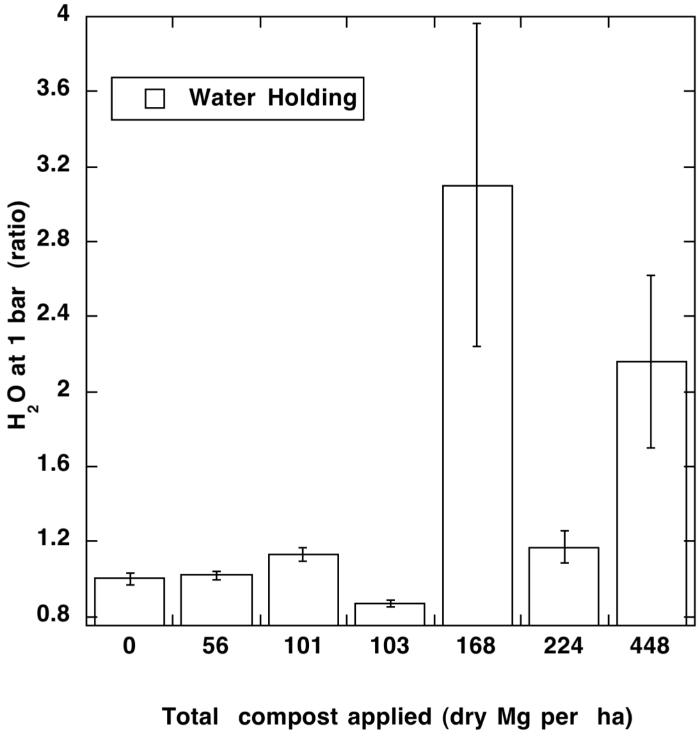


Figure 6. Water holding capacity in compost amended soils in comparison to the control soils. Quantity of soil water at 1 barr pressure was used to determine the water holding capacity. The ratio of water in comparison to the control soil is shown.

A stepwise regression was carried out to determine the primary factors that affected water - holding capacity for this study. This type of regression adds and removes variables from the analysis based on their ability to explain significant quantities of the variation in the data. For this analysis the probability was set for 0.05. The regression was carried out twice, once using the actual values for water content at a particular volume of soil and the second time using the ratio variable for water. The variables entered into the model for the initial run included soil texture, bulk density, total compost applied, and organic carbon content. For the second run of the model the variables included soil texture, the ratio variables for carbon and bulk density, and total compost applied. The ratio variable for water holding capacity was used as the dependent variable.

For the first run, the significant factors in determining water -holding capacity were soil texture (0.36), bulk density (0.556) and organic carbon (0.59). The values in the parenthesis represent the cumulative adjusted R^2 value of the model. For the second run of the model using the ratio variables in an attempt to normalize the data across sites, the significant factors were total compost applied (0.26) and bulk density (0.34) with a model R^2 of 0.34. These results indicate that while overall, texture is the primary factor affecting water holding capacity, increasing organic carbon is a significant factor for improving soil water holding capacity. Using the ratio variables to eliminate the influence of variation as a result of soil texture, compost loading rate was the most significant factor effecting water holding capacity.

Water infiltration rate was also measured. Across all soils, compost addition increased water infiltration rate compared to the control soil (Figure 7). Increased infiltration is another indication of increased efficiency in water use as a higher fraction of irrigation or rainfall is likely to enter soils with higher infiltration rates. More rapid infiltration is associated with reduced runoff, better aeration, and improved irrigation efficiency. As with water holding capacity, soil texture will have a significant effect on infiltration rate. However, unlike water holding capacity, the largest improvements would be expected in fine textured soils that tend to be poorly drained. Because of this, soil texture is a significant factor in infiltration rate. In this study, the largest improvements in water holding capacity were seen in the coarse textured or sandy soils. The largest improvements in water infiltration rate were observed in the finer textured soils. For example, at the site in Monterey County, infiltration rate in the control averaged 17.5 minutes. In the compost- amended soils, this time was reduced to < 1 minute. This site was tilled, discounting the potential for work row compaction to be a factor. Texture in this soil was a silty loam. However, in the coarser textured soils there were no significant differences in infiltration rates as a result of compost amendment for the sandy soils. At the Bruce Rucker site the soil texture was loamy sand. The infiltration rate in the control soil was 3.3 ± 0.3 minutes. This increased to 4.1 ± 0.9 minutes in the compost amended soils. Vehicle traffic in the work rows may have also lead to compaction that would have also reduced infiltration rate. However, the number of vehicles in orchard sites is relatively limited in comparison to tilled sites

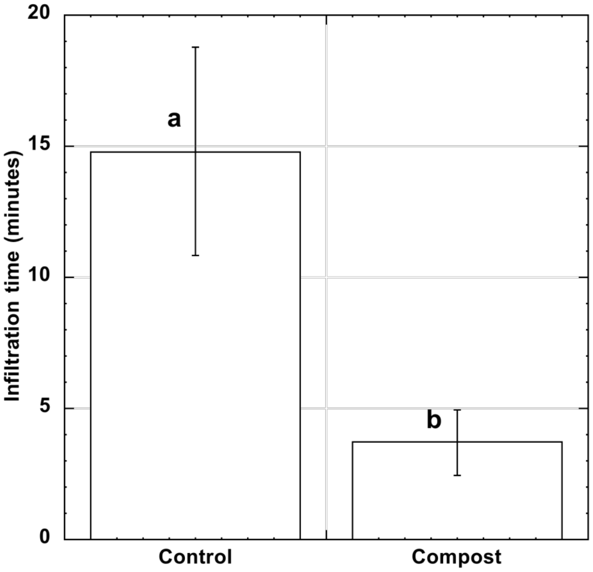


Figure 7. Water infiltration (minutes) for all compost amended and control soils with the same soil series. Means and standard errors are presented. Different letters above each mean indicate that the values are significantly different ($p < 0.05$).

Specific Sites

Two of the sites that we sampled can be used to illustrate the benefits of compost for different types of high value agriculture. Bruce Rucker's farm in Riverside County is representative of the benefits associated with use of high rates of compost over an extended period in organic orchard crops. Two crops on the same soil series were sampled at this site increasing the number of both treated and control samples in comparison to other sites. The combination of high rates of compost use and a large number of data points make this a good site to use. The crops that we sampled were citrus and grapes. However, the compost application here is representative of a wide range of perennial crops that are important in California. Compost application to orchard crops is managed as annual surface application under the trees or vines. The same type of application at similar application rates was seen on this sampling trip for almonds, citrus, grapes, apricots, and mangos. The two highest revenues crops in neighboring Kern County are almonds and grapes, with close to $1 billion in revenue annually. Grapes require approximately 5 acre ft of water per year to grow, so any increases in soil water availability would have a significant impact. It is also likely that the benefits that were observed with surface application to orchards would be similar to those observed in landscaping where compost is surface applied to ornamentals annually or at high one time rates of application (Cogger et al., 2008).

Compost application rates and methods are similar for a wide range of orchard crops including (a) grapes, (b) mangos, and (c) almonds.

The T&A site in Monterey County provides an example of the benefits of compost use in high value annual crops and results from this site will be applicable to a wide range of high value annuals where annual tillage is standard. As the only tilled site included in our sampling, it provides the only point of reference for this type of end use. The soils that we sampled had been cropped to lettuce and cauliflower. Row crops would follow similar management practices. An agricultural extension agent from Kern County noted that carrots, a row crop, were potentially the largest compost users in that county. A more detailed description of the results will be presented for these sites. We also sampled two sites where mulch (coarsely ground and minimally processed yard debris) was surface applied. Mulch application offers an alternative end use for organics diverted from landfills. Results from these sites can be used to evaluate the benefits of direct mulch application.

Orchard crops

The farm that we sampled was located in Riverside County. We sampled soils from under lemon trees and grape vines at this site. It has been managed as an organic orchard for an extended period with compost applications 2 times per year, banded of 24 dry Mg per ha. Total application at this site was approximately 448 dry Mg per ha. This is the cumulative application following 10 years of compost addition. The benefits observed from compost use at this site were the greatest of any of the sites sampled. It was also the highest cumulative loading of compost. At the other farm that was sampled in Riverside County, we were not able to get a precise cumulative loading rate for compost. However, the best guess of the farmer was somewhere over 168 dry Mg ha. The benefits observed on this site were very similar to that seen in the 448 Mg ha site with a greater increases in water holding capacity and microbial activity and lower increases in soil carbon content (see above tables to compare 168 and 448 Mg ha responses). This suggests that a high level of response is possible once a certain loading rate is reached (Albiach et al., 2001; Aggelides and Londra, 2001; Annabi et al., 2007; Bresson et al., 2001; Kong et al., 2005; ROU, 2006; Tian et al., 2009).

Row crops

The truck farm that we sampled was located in Monterey County. We sampled two compost amended fields and one control field, all within the same soil series and in close proximity to each other. All fields had recently been harvested and so were in similar conditions. The owner of the compost treated sites leased his ground and required compost use as a condition of the lease. We did not get any additional information on management practices of the tenant farmer. One of the fields was managed as an organic site and had received total compost application of approximately 100 dry Mg ha. The other site was managed conventionally and had a lower annual compost application rate with total cumulative applications of 56 Mg ha. For both of these fields compost was applied to the entire field and tilled into the surface soil. The soils produced 2-3 crops per year and were tilled several times each year. This was the only site that we sampled with this type of usage where compost application rates were known and the control soil was the same soil series. Extensive use of irrigation water in Monterey has resulted in saltwater intrusion into the ground water table. As a way to minimize dependence on groundwater, reclaimed water from wastewater treatment plants is now used extensively in Monterey to irrigate truck crops. Any increases in soil water holding capacity would further reduce dependence on groundwater.

The three sampling sites in Monterey, (a) freshly tilled organic compost (b) newly harvested compost and (c) harvested control

Mulch application

We sampled two sites where mulch had been applied. These were both in Ventura County. We also visited a site where mulch was being applied. According to the mulch purveyor, the primary reason for mulch application at all sites was to limit water runoff. Direct application of mulch is potentially more economical than compost application as there is minimal processing involved. Mulch has the potential to offer an alternative to compost. However, direct application of mulch provides a highly reactive, potentially nitrogen and nutrient limiting material to soils. There is also a potential for contaminants in the mulch that would have been screened out as part of the compost finishing process. Weed seeds are also a potential concern with direct mulch application. There is also the potential for a high carbon mulch to limit nitrogen availability. The decomposition and high temperatures required for composting kill all noxious weed seeds and provide a stable product that has a uniform nutrient content.

Mulch in (a) an application vehicle, (b) freshly applied to a citrus grove and (c) an intact soil core from a field where mulch had been applied the previous year.

Table 4. Response to compost or mulch application for three specific sites. Means ± standard error are shown.

Organic Orchard (448 Mg ha cumulative)

	Total N	**Available P**	**Organic Carbon**	**Bulk Density**	**Microbial activity**	**H_2O per 100g**	**Infiltration rate**
	%	**mg kg**	**%**	**g cm3**	**ml CO_2/d/kg/dry soil**	**mls**	**minutes**
Control	0.04 ± 0.007	115 ± 15	0.37 ± 0.1	1.5 ± 0.2	31.5 ± 5	9.6 ± 0.6	3.3 ± 0.3
Compost	0.28 ± 0.04	624 ± 59	2.7 ± 0.4	1.1 ± 0.1	64 ± 14	21.3 ± 3.7	4.1 ± 0.9
% change	700%	543%	730%	-27%	206%	225%	+24%

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High value row crops (56 and 100 Mg ha cumulative)

	Total N	**Available P**	**Organic Carbon**	**Bulk Density**	**Microbial activity**	**H_2O per 100g**	**Infiltration rate**
Control	0.08	333 ± 6	0.7 ± 0.02	1.7 ± 0.1	19 ± 4.4	25 ± 0.08	18 ± 17
Compost							
low	0.1 ± 0.003		0.9 ± 0.03	1.5 ± 0.1	17 ± 4	25.6 ± 0.6	
high	0.1 ± 0.002	394 ± 85	1.1 ± 0.05	1.3 ± 0.08	27.8 ± 5	29 ± 0.6	0.67 ± 0.1
% change	125%	118%	157%	-24%	146%	116%	-96%

Mulch (260 Mg ha single application)

	Total N	**Available P**	**Organic Carbon**	**Bulk Density**	**Microbial activity**	**H_2O per 100g**	**Infiltration rate**
Control	0.2 ± 0.07	257 ± 67	2.3 ± 0.9	1.3 ± 0.1	33 ± 5	32 ± 2.5	24 ± 2.9
Mulch	0.2 ± 0.04	225 ± 57	2.1 ± 0.6	1.1 ± 0.4	54 ± 8	38 ± 1	0.9 ± 0.6
% change	no change	-13%	-9%	-15%	164%	119%	-96%

The values for each of the measured variables (both quantitative values and % change) for the three specific sites are shown in Table 4. These values will be used to compare the expected benefits for compost use reported in the ROU study with the values collected in our sampling trip.

Comparison with Recycled Organics Unit LCA

The Recycled Organics Unit (2007) modeled benefits associated with the use of compost in grapes based on a surface application of 75 dry metric tons once every three years. The primary purpose of this application was to provide a surface mulch for the vines. Benefits were also modeled for application as a soil conditioner at an annual application rate of 12 Mg ha (5 tons per acre) to cotton, a high value row crop. Two types of compost were used in this study, a low N compost with negligible fertilizer value was used for mulch and a higher N compost was used as a soil amendment. General benefits as well as benefits for GHGs were observed. These included: reduced water consumption, avoided use of synthetic fertilizers, herbicides and pesticides, carbon sequestration, soil structure improvement (% decrease in bulk density), increased plant productivity and reduced erosion. This study noted increasing benefits with increased application, although it was noted that this increase was not linear and that at a certain point, a maximum level of benefits would be reached. Transport distance to the application site had a minimal effect on total net benefits. For mulch application, benefits ranged from 400 Mg CO_{2eq} for application of 83 Mg ha to 600 Mg CO_{2eq} for application of 125 Mg ha. Benefits for soil conditioner were significantly lower with benefits of 100 Mg CO_{2eq} for application of 25 Mg ha and benefits of 200 Mg CO_{2eq} for applications of 50 Mg ha. We have compared the values from our sampling to those used in the ROU study (Table 5). Specific information for each category is given below. In general, the magnitude of the benefit per Mg of compost applied from our sampling was similar in magnitude to the reported benefits in the ROU study (Table 5). Our values, while comparable, were consistently higher than the reported values in the ROU study.

Water use

The ROU study quantified benefits associated with compost use for increased water use efficiency. Data from previous studies was plotted as % increase in soil moisture per Mg compost applied. This increase was then multiplied by the water use for the crop to determine the decrease in water use as a result of compost application. The % increase in water use efficiency and associated decrease in water demand was taken to be 0.125% per metric ton of compost applied (Table 5). Based on the results from our sampling, % increase in water use efficiency ranged from 0.44% per metric ton mulch applied, 0.5% for use of compost applied as a surface mulch in orchards, and 1.1% for incorporation into row crops. It should be noted that increases in water use are likely not linear across application rates and will also vary by soil series. As the stepwise regression analysis showed earlier, soil texture, bulk density and organic carbon were the factors that explained the most variation in water holding capacity on all soils when quantitative data were used in the analysis (adjusted R^2 of 0.58). When the ratio variables were used to normalize the data, total compost application and bulk density were the most important factors affecting changes in soil water holding capacity (adjusted R^2 0.34). On a more basic level, what the data collected from this study suggests is that the % improvement used for mulch application in the ROU study can be used as a very conservative value for all types of compost use in California. For grapes that require 5 acre feet of water, this would mean a per acre decrease in water use of approximately 0.3" per acre for each 4 US tons of compost applied.

Fertilizer value

In contrast to the ROU model, all of the organic growers that we questioned use compost as their sole source of nitrogen fertilizer. Orchard growers in Kern County use an annual application rate of 9 Mg ha primarily to meet the fertilizer needs of the crop. This was similar to the responses that we saw with annual or bi-annual applications ranging from 9-45 Mg/ha/yr. Here the fertilizer value of the compost was taken into account. We heard concerns from compost producers that growers were demanding higher N content in the composts. This was difficult to provide with lower N feedstocks such as yard debris. Manures, biosolids and food scraps are potential sources of high N feedstocks for the compost producers. In the ROU study, a fraction of total N and P in the compost is taken to be plant available during the first growing season with additional N and P becoming soluble during subsequent growing seasons. The CO_2 required to produce N, P and K is given as 3.96, 1.76 and 1.36 kg per kg, respectively (Table 5). The ROU report considered that for each metric ton (1000 kg) of compost applied, a total of 2.5- 5 kg N, 0.6-5 kg P and 0.6-2 kg K would be plant available over time. There was no discussion of micro-nutrient content of the composts. One of the compost - manufacturers that we worked with provides a product sheet to customers that lists plant available nutrients as 18 lbs N, 19 lbs P_2O_5 and 20 lbs K per ton applied. The nutrient value of this compost in comparison to the value of the other composts used in this study is shown in Table 1. This is equivalent to 9, 9.5 and 10 kg per dry Mg or 35.6 kg CO_2 per 9 kg N, 7.2 kg CO_2 per 9.5 kg P_2O_5 and 13.6 kg CO_2 per kg K. The GHG avoidance based on the total NPK value of one Mg of this particular compost would be equivalent to 56 kg CO_2. This was a relatively low nutrient value compost. It was used by one organic orchard as the sole source of fertilizer and was supplemented with chicken manure compost at another orchard.

Results from our sampling effort confirm the value of composts as a source of plant nutrients. For the specific sites, we saw increases in plant available P of 543% times in the orchard in comparison to the work row, 18% in the row crop in comparison to a conventionally fertilized field and to a decrease of 13% in the mulch. Increases in total **N ranged from 7 X the control** in the orchard, 25% for row crops and no change for mulch. In the orchard site, the control was the work-row that was planted in a grass but had likely received no additional fertilizer applications. In the row crop, the control was another farmed field that had likely received fertilizer application. Compost addition increased the residual fertility in the soil post harvest in comparison to synthetic fertilizers. In addition, increases in micro nutrients were seen in the compost amended soils in comparison to control soils with available micronutrients similar in the compost amended soils to treated fields. Although values for micronutrients were not included in the ROU study or the published literature, they will also require energy to manufacture.

We would recommend using a per dry ton credit of 78 lbs CO_2 for N, 16 lbs for P (taking the fraction of P in P_2O_5 into account) and 30 lbs for K or a total fertilizer credit of 124 lbs CO_2 per dry ton compost applied. If specific product information is available, that can be substituted for this default. There was no increase in soil fertility for the mulch- amended soils tested in this study.

Herbicide/pesticide use

The ROU study considers the potential for compost use to replace the needs for certain herbicides and pesticides. The GHG avoided from this is given as 30 kg CO_2 per kg pesticide/herbicide. In addition, other environmental concerns associated with use of herbicides may make this a valuable aspect of compost use. We did not specifically ask farmers if one of the benefits of compost used as mulch was reduced weeds. However, organic farms are prohibited from using herbicides and pesticides. That leaves mechanical weed control or use of mulches for weed control. Based on the discussion of compost used as a mulch in the ROU study to reduce weed competition and the high prevalence of compost in organic orchards in our sampling, it is likely that these farmers may be realizing some of the benefits of compost in regards to weed and pest control. Organic farmers have to rely on alternative measures as synthetic herbicides and pesticides are not allowed in organic agriculture. It was beyond the scope of the present sampling to quantify changes in herbicide and pesticide use. The ROU study estimated use of herbicide use as 2-6 L per ha for vineyards with 30 kg CO_2 required to manufacture and apply each kg of herbicide. Using the low end of this estimate, 2 L, the potential CO_2 credits associated with compost use would be 60 kg CO_2 per acre. As organic farms are prohibited from using herbicides, it seems clear that compost would be an acceptable alternative.

Total organic carbon

The ROU uses a value of 70 kg C per metric ton of compost as a default value for carbon sequestration in soils as a result of compost application (Table 5). Expressed as CO_2, that is equivalent to 257 kg CO_2 per metric ton compost. For the California sampling, if a surface 0-15 cm or 0-6" soil weight of 2000 metric tons per ha or 1000 tons per acre is used as an approximation, then each 1% increase in soil carbon has an associated CO_2 increase of 20 metric tons C per hectare or 73 metric tons of CO_2 per ha (Brady and Weil, 2002). At the orchard site used for this specific comparison, soil carbon increased from 0.37 to 2.7% after application of 200 t/a compost. This is an increase in soil carbon equivalent to 23.3 tons per acre based on the weight of an acre furrow slice (top 6" of soil equal to 1000 tons). On the basis of each ton of compost applied, this increases equals 0.427 tons of soil C. In metric units, this increase is equivalent to 381 kg per metric ton of dry compost. For the row crop site used for this specific comparison, the increase in soil carbon equals 291 kg CO_2 per metric ton of compost applied. The value for the orchard site was significantly higher than the value used by the ROU while the value for the row crop site was similar. Frequent tilling will increase aeration in the soil and result in faster mineralization of organic carbon. The orchard application is representative of a no till management practice. No till farming has been widely recognized as a means to increase soil carbon. There is an existing protocol on the Chicago Climate Exchange that gives carbon credits for farms that convert from conventional tillage to no till practices (http://www.chicagoclimatex.com/content.jsf?id=781). The results from the California sampling highlight the potential for compost amendments to increase the carbon reserves in soils. Higher carbon sequestration rates are also suggested for no till sites. The values for carbon sequestration used by the ROU appear to be conservative for no till sites and appropriate for sites where frequent tilling is standard. For no till sites, a more appropriate value would be 300-325 kg CO_2 per dry metric ton compost applied.

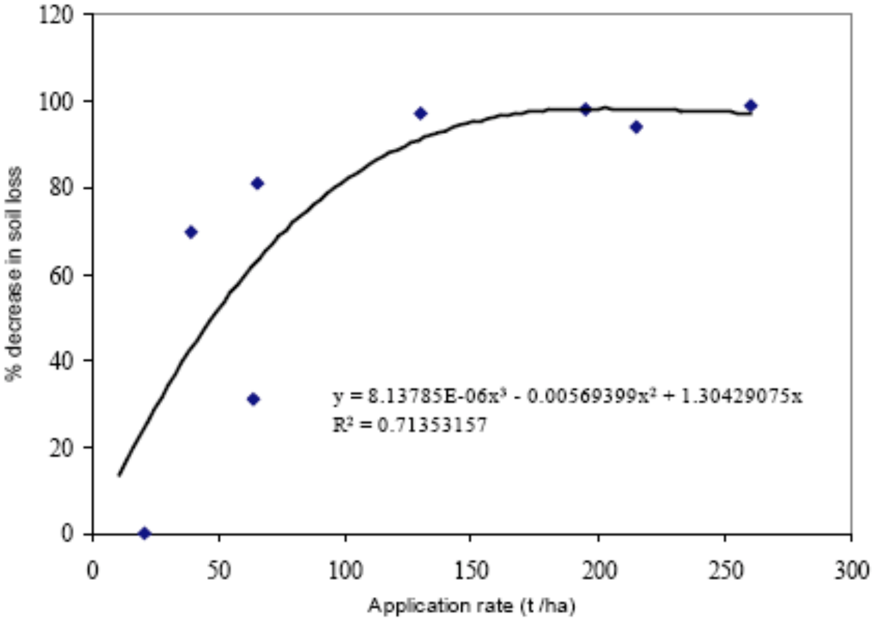
Remediation of saline/sodic soils

The ROU includes the potential for compost to ameliorate soil sodicity as part of the benefits associated with compost use (Table 5). Potential mechanisms for the observed benefit include, improved soil structure, solubilization of precipitated Ca, increased water holding capacity and improved drainage. For almost all of the farms that we sampled, gypsum was routinely mixed with compost prior to application as means to reduce soil salinity and sodicity. Some of the farmers we spoke to said that salinity was a concern and one of the reasons for their use of compost. Although we measured pH and electrical conductivity (EC), gypsum addition made it impossible to distinguish any potential effects of compost on soil salinity. Because of the widespread use of gypsum, our sampling suggests that would be difficult to isolate the benefits of compost in relation to soil salinity. The potential benefits associated with compost use would include replacement and conservation of gypsum as well as an increase in productivity of the affected soils. There is also a potential for the land available for growing salt sensitive crops to increase. For example, grapes and almonds see yield declines with soil EC>2 dS m^{-1}. In Kern County, 2006 revenues from these crops was in excess of $950 million. Salinity is a major concern in Kern County. University of California extension bulletins for Kern County suggest planting of salt tolerant crops, appropriate soil sampling, and chemical means to ameliorate these soils (Sanden et al.). This suggests that research trials in high salt soils with different combinations of gypsum and compost would be an effective means to determine if compost can substitute for gypsum at these sites. This would then provide an alternative to chemical remediation methods for high salt soils.

Erosion

Soil erosion is a major concern. Soil erosion occurs as a result of rain, flooding or wind events that transport soil particles. Eroded soils are often deposited in streams and can result in water quality degradation through increased eutrophication, increased turbidity, and decreased water depth which can lead to elevated water temperatures in streams. High intensity rain events carry a greater potential for soil erosion. In addition to soil erosion, low water infiltration rates increase the potential for water erosion via overland flow. This reduces water storage in soils. It also increases the potential for nutrient movement to streams via dissolution of nutrients from the soil surface into the water eroding from the soil surface. The ROU used existing literature to develop a graph of compost application (x axis) versus soil loss (y axis). From this graph, they calculate that use of compost as a soil conditioner, incorporated into the soil at 12 t ha^{-1} would reduce soil erosion by 14.8%.

Figure 7.10 Effect of compost as a soil conditioner on soil loss.



Based on the literature, they suggest that application of compost as a mulch in vineyards at a 10 cm depth would completely eliminate soil loss (Table 5). We did not measure soil erosive potential as part of this survey. Water infiltration rate can give some indication of erosive potential. If water enters the soil more rapidly, it is less likely to erode off of the soil surface. For this sampling we saw an increase of average infiltration rate across all sites that had received compost with infiltration requiring 33% less time as control sites. This suggests that the estimates for reduced erosion used by the ROU would be sufficiently conservative for California sites. It should be noted that these benefits would be most pronounced in areas prone to erosion, such as areas with slope as well as areas where high intensity rainfall can occur (Susan Bolton, University of Washington). These benefits are not limited to agricultural sites. Reduced soil loss has been observed in compost- amended sites following forest fires (Meyer et al., 2001). Reductions in water quantity as well as improvements in water quality have also been observed when composts have been used alongside roads and in new home construction (McDonald, 2005).

Soil structure

The ROU used soil bulk density as a measure of improved soil structure. Changes in soil aggregation have also been used (Annabi et al., 2007). In their analysis, the ROU discounts the potential for surface applied compost to alter soil bulk density, noting the time required for surface applied materials to alter the subsoil. Changes in bulk density were considered for compost tilled into soils with a predicted 2% decrease in bulk density for each 12 Mg of compost that is incorporated (Table 5). In our sampling we saw statistically significant decreases in bulk density in the tilled site, the long-term orchard site with surface applied compost as well as for mulch application. These ranged from a 15% decrease for the mulch, a 24% decrease for the tilled site and a 27% decrease for the orchard site. In general, decreases in bulk density were more pronounced with higher rates of compost application. However, changes were apparent at both surface applied and tilled sites. On the basis of a 12 t ha application rate, we saw a decrease in bulk density of 0.7% in both the orchard site and the mulch site and a decrease of 2.9% in the tilled site. This suggests that the value used by the ROU would be applicable for tilled sites in California and that a value of 0.5% decrease in bulk density would be appropriate for use in orchard or mulch sites.

Plant response

The ROU study included yield increases as part of their evaluation process. They note that responses vary significantly by season and soil type. Increases in yield for cotton were assumed to be 11.5% for an application of 12 t ha of compost (Table 5). Grape yields were taken to be 27% based on a 10 cm surface mulch application of compost. Most of the farmers across all sites that we spoke to said that they used compost because of the beneficial effects on fruit quality and plant health. However, yield increases were not quantified as part of this sampling exercise.

Soil tilth

Arable land area in New South Wales is 104,000 km^2. The ROU study noted that degradation of arable lands results in an annual loss in revenue of $700 million Australian. This is equivalent to $67.30 Australian per ha per year. Reduced soil organic matter concentrations were seen as the primary factor responsible for this degradation with many soils having total organic carbon concentrations of < 1%. Concentrations ≥ 2% were sited as desirable for maintaining soil structure and plant productivity. For this study, the average organic carbon concentration in control soils collected from the same soil series as the treated soils was 0.69%. In comparison, the organic carbon concentration in the paired compost amended soils was 1.27%.

In addition to using total soil carbon as an indicator of soil tilth, another index that reflect a healthy soil is soil microbial activity. There are a range of indicators of soil microbial activity. For this sampling, CO_2 production was measured on soils following an incubation period at a fixed temperature and moisture. The ml CO_2 produced per kg dry soil measured 28.6 in the control soil and 50.2 in the compost- amended soils. While this average shows a significant increase in microbial activity as a result of compost addition, the increases in microbial activity were only significant at the higher application rates (>168 Mg ha). This may be the result of the way that the soil samples were collected. Surface soil samples were taken from the top 15 cm of the soil. For the majority of sites, the compost was surface applied. For lower rates or for sites with a shorter history of compost application, the effect of compost on microbial activity may have been diluted when the compost was mixed with the soil from the bottom portion of the 0-15 cm horizon.

Table 5. A comparison of sampling results from this study with ROU Life Cycle data. The ROU study (2006) quantified potential benefits of compost use for row crops and orchard crops for soils in New South Wales using an extensive literature review of benefits associated with use of compost to develop values. The results of our sampling are compared to the results of the ROU study and default recommendations are suggested.

Parameter	Unit	ROU	CA tilled	CA- surface	CA- mulch	Recommended Default Value
			per dry metric ton compost (unless otherwise specified)			
Fertilizer	NPK kg CO_2eq	11.8-31.3*	56	56	0	56- based on NP(as P_2O_5)K of 9, 9.5 and 10 kg per Mg of compost Use specific compost analysis when possible
Organic carbon	kg CO_2	256 kg CO_2	291 kg CO_2	382 kg CO_2	0	256 kg CO_2 for tilled sites, 300-325 Mg for no till or orchard sites
Water efficiency	% increase	0.125	1.1	0.5	0.44	0.125
Soil structure-bulk density	% decrease	2% decrease per 12 Mg compost for incorporated	2.9% decrease per 12 Mg	0.7% decrease per 12 Mg	0.7% decrease per 12 Mg	2% per 12 Mg incorporated, 0.5% per 12 Mg for surface application

Water infiltration rates	% decrease	1.2% reduction in tilled crops, complete reduction for mulch applications	96% decrease overall 1% decrease per Mg	24% increase overall 0.005% increase per Mg	96% decrease overall 0.4% decrease per Mg	We saw an overall average improvement in water infiltration rate of 33% across all sites that received compost or mulch. This can be used as an indicator of reduced erosion potential. Use 1% per Mg compost
Herbicide	kg CO2eq	30 kg CO_{2eq} per kg herbicide				60 kg CO_{2eq} per ha/compost application rate in orchard crops based on 2 herbicide sprays per season
Saline/sodic		Gypsum replacement				California specific studies recommended
Plant yield	% increase	1-2% yield increase per Mg compost				1-2% yield increase per Mg compost
Soil Tilth- using carbon and microbial activity (as CO_2 evolved through microbial respiration) as indicators		Degradation of soils has a cost of $64.00 Australian per ha	146% increase in CO_2 emissions/ increase in carbon from 0.7 to 1.1%	Overall 33% increase in CO_2 emissions/ overall increase in carbon from 0.7% to 1.27%	164% increase in CO_2 emissions/ no increase in soil carbon	ROU notes soil with organic C> 2% has improved tilth. Use of compost over time has the potential to improve soil tilth and result in quantifiable $ savings per ha

The ROU study was done using standard units. The standard unit of land is a hectare. One hectare measures 100 x 100 meters and is equivalent to 2.47 acres. The standard unit for mass is one metric ton (Mg) which is equivalent to 1000 kg. Compost applied at 1 US ton per acre is the same as compost applied at 2.24 Mg ha.

Conclusions

In our limited field sampling we saw a range of improvements in soil quality as a result of compost application. In general, the improvements that were observed were greater than those predicted by the Recycled Organic Unit (2006) in their life cycle analysis of windrow composting. A direct comparison of the results of this field survey and the ROU recommendations is shown in Table 5. . The total benefits associated with compost use include GHG savings, water savings and improvements in both soil quality and plant yield. For this study, it was only possible to measure a portion of the variables that were evaluated in the ROU literature review. However, for those variables that we were able to measure, results from this study are comparable to those reported in the ROU study. This suggests that response to compost application for the variables outside the scope of the current sampling effort may also be comparable to those reported in the ROU study. Many of these benefits have no direct GHG associated savings. In other cases, GHG savings are small in comparison to other environmental or financial benefits. Water savings (as estimated by increases in water holding capacity) were sited as one benefit of compost use in the ROU study. More pronounced benefits were observed in our sampling particularly on coarser textured soils. The energy required to irrigate a field in relation to predicted water savings could be calculated to estimate potential GHG savings. However, the more significant impact is likely to be in water savings and reduced use of water in compost amended agricultural soils. Similarly, yield increases are likely not a significant source of GHG credits. However, the associated economic benefits of yield increases are highly significant.

The ROU study estimated potential GHG savings for both surface applied compost and compost tilled into the soil (Table 6). For their study, the compost used as mulch is a low nutrient value material. Compost in California is not classified based on its nutrient content. For our sampling, the nutrient value of the compost was equally important in tilled and surface applications. In fact, for organic farming, composts are often the primary source of nutrients for the crop. Our sampling showed consistently significant increases in plant available nutrients in compost-amended soils in comparison to soils collected from work rows/same soil series. The plant available nutrients were generally similar in compost- amended soils and conventionally managed soils. These results confirm the nutrient value of composts used in California agriculture. The ROU study gave significant GHG credits for compost use for increasing soil carbon, reducing use of pesticides/herbicides and for replacing synthetic fertilizer. The quantity of credits varied by the type of compost as well as the end use. This study was able to quantify GHG credits based on soil carbon and fertilizer value of the compost. The GHG benefits for both the ROU study and our sampling are shown in Table 6. The highest credits were associated for use as mulch where herbicide avoidance was also taken into account. The ROU study credited 316 kg CO_2 per dry Mg compost used in orchards where the result from our study, based on data from the Rucker farm, totaled 508 kg. It should be noted that this farm had the highest cumulative loading rate of compost of all of the farms included in our sampling. However, the % change in soil carbon in relation to quantity of compost applied was similar for the Rucker site and the two other highest cumulative loading rates sites. This indicates that benefits/GHG credits for soil carbon calculated on the basis of credit per dry Mg compost applied would be similar for these sites as well. For tilled sites, the ROU study credited 277 kg CO_2 per dry Mg compost used. Here, based on the results from the T&A site, our credits totaled 357 kg CO_2 per dry Mg compost.

Table 6. Greenhouse gas savings associated with the use of compost for surface application (mulch) and tilled into soils (till). Results presented include savings calculated in the Recycled Organics LCA and from samples collected at an organic orchard and tilled row crop site in CA.

	Mulch		**Till**	
	ROU	CA	ROU	CA
	kg CO_2 per dry Mg Compost			
Fertilizer		66	21	66
Herbicide	60	60*		
Soil Carbon	256	382	256	291
Total GHG benefits	**316**	**508**	**277**	**357**

* This credit must be distributed based on the application rate of compost and refers to a per hectare credit and not a per Mg credit

Due to the variety of soils, topography, rainfall frequency and intensity, and types of compost use, response per dry ton of compost applied will vary across the state. However, our study showed consistently better responses with increased compost applications over time. The results from both our sampling and the ROU study suggest that consistent use of compost over time will improve soil health and plant yield. This suggests that compost use can result in increased profits in the agricultural sector from higher yield as well as improved soil structure. Overall benefits from use of compost can have a significant impact on GHG balances, water use efficiency, soil sustainability, and income from agriculture. Impacts for certain categories will need to be accompanied by appropriate educational materials so that farmers or homeowners will understand the potential changes in water and fertilizer needs for a crop and adjust their inputs accordingly. Water savings are also most likely to be observed in coarser textured, well- drained soils. In addition to agricultural use, which was the focus of our survey, similar benefits would be expected for compost use in landscaping, restoration, urban areas, and on greenscapes adjoining roads.

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