Organic N Fertilizers and Irrigation Influence Organic Broccoli Production in Two Regions of California

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ABSTRACT. Nitrogen and water management are essential factors for achieving adequate crop growth and development in organic production systems. A three-year field study examined effects of different forms of organic N fertilizers applied at side-dress and with different irrigation application rates on leaf, stem, and floret yields, volumetric soil water content (P_v), and crop water use efficiency (WUE) in organically-grown

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broccoli (*Brassica oleracea* L.) in two regions of California; Santa Cruz (UCSC farm) and Five Points (Harris farm). At preplant, 'compost only' treatment (CO) was applied at 140 kg·ha^{-1} of N with an additional 112 kg·ha^{-1} of N applied as side-dress in one of the following forms: (1) fish powder (FP); (2) Phytamin [bloodmeal and feathermeal mix (BF)]; (3) BF mixed with $NaNO_3$ (SN), or (4) seabird guano (SG). Leaf, stem, and floret yields collected from the UCSC farm had a greater response to additional N from side-dressing treatments irrespective of the form than plants at the Harris farm in all years. The interaction of side-dress and irrigation treatment significantly influenced leaf, floret, and stem yields at both locations. A greater P_v was measured from the 0-15, 15-45, and 45-90 cm depths when treated at 150, 100, and 80% crop evapotranspiration (ETc), respectively, on both farms. Soil samples collected from the 45-90 cm depth had the highest P_v levels at both locations. The Harris farm had higher levels of P_v than the UCSC farm at all depths. The greater WUE was achieved with 80 and 100% ETc at the UCSC farm and with 100% ETc at the Harris farm. Based on the results, it appears that a side-dress application of 112 kg·ha^{-1} of N in addition to 140 kg·ha^{-1} of N applied as compost at preplant, and irrigation at either 80 or 100% ETc on the UCSC farm, and at 100% ETc on the Harris farm achieves the highest level of WUE. Organic broccoli growers need to consider fertility status of the site, soil type, seasonal precipitation, and form of side-dress for achieving highest yields in a sustained manner. doi:10.1300/J484v12n04_04

KEYWORDS. Broccoli, crop evapotranspiration, irrigation, nitrogen, organic agriculture

INTRODUCTION

Increasing consumer demand for organic products has caused a rapid expansion of organic production in the U.S. during the past decade (Dimitri and Greene, 2002). The National Organic Farmers' Survey reported fertility management as farmers' third research priority demand to achieve profitable yields (Walz, 1999). Soil fertility management is a major tool for improving crop yields, especially for crops requiring high nitrogen (N) application. Broccoli is a vegetable that requires high N input and frequent irrigation to enhance yields. Broccoli has a shallow root system, which limits its ability to take up water and nutrients from the deeper soil profile. Broccoli growers are likely to over-apply both

N and water to achieve a desired yield, which results in higher risk of nutrient and water loss from the system. Broccoli requires moderate to high amounts of nitrogen fertilizer of approximately 112 to 224 kg·ha^{-1} of N during the growing season under conventionally farming practices in California (LeStrange et al., 1996). In this regard, approximately 46% of total N applied to conventional grown broccoli in Arizona was lost due to excessive N and water application (Thompson et al., 2000a). Over application of N fertilizer to broccoli can also diminish post-harvest quality of this crop by inducing symptoms of hollow stem (Hipp, 1974). This condition is most likely to occur in broccoli with high N inputs that results in rapid growth and development during the growing season (Hipp, 1974).

Fertilizer products and sources of N are available in both organic and inorganic (synthetic) forms. The amount of plant-available nutrients from synthetic fertilizer can be determined based upon the soluble inorganic forms. Nutrients gradually released from organic fertilizer and the ability of plant take them up are, however, difficult to accurately predict over time. For example, inorganic forms of N released from compost or manure can range from 20-90% during the first year of application (Chaney et al., 1992). Due to the slow and less predictable release of N from organic sources, e.g., compost, chicken and marine waste products, supplying more N at pre-plant and side-dressing is often recommended in organic vegetable production in California (Gaskell et al., 2000). Similar to the general practice of applying excessive N pre-plant to conventionally grown lettuce (Hartz et al., 2000) and expecting the leaching of soluble N below the root zone under heavy irrigation (Jackson et al., 1994), organic agriculture production could also produce high N losses from improper management of N source and irrigation rates.

Water used for agricultural irrigation accounts for 40% of all fresh water consumed in the U.S., and the highest water use for irrigation is in California (Hutson et al., 2004). Over-watering is a major concern in agricultural soils because of serious concerns regarding nitrate leaching to groundwater (Coppock and Meyer, 1980). Improper irrigation management not only wastes available water resources, but also causes nutrient losses by leaching, runoff, and denitrification of N in both organic and conventional farming. To quantify the exact amount of water required by a plant, it is necessary to consider two major parameters (Hanson et al., 1999). First, the amount of water required by the crop at different growth stages, determined with the aid of accurate crop coefficients (Kc), which is determined by the ratio of canopy coverage width to bed spacing and length, needs to be considered. Also, the rates of precipitation and evapotranspiration (ETo) need to be considered to improve the accuracy of the amount of water applied during the growing season. In California, location of production becomes an important factor to justify proper rates of N and water recommendations, because of the various climates, topography, and daily ETo rates.

Several studies documented water and N interactions under conventional practices on crop yield in cabbage (Gardner and Roth, 1989a), broccoli (Beverly et al., 1986; Gardner and Roth, 1989b; Thompson et al., 2002b), and lettuce production (Gallardo et al., 1996). Beverly et al. (1986) observed increased broccoli yields when N and water were applied at moderate levels and decreased yields when excessive water was applied at a given N level. They suggested the need to properly manage N and irrigation to achieve yield potential of a high value crop. In general, researchers recommended an intermediate application of N and soil water tension range to maximize crop N and water uptake for vegetable crops and normally it is site specific. Two major areas of organic broccoli production are the Central Coast and Central Valley of California where more than 90% of all broccoli production is grown (CDOF, 2003).

Synchronizing crop N demand with additional N fertilizer application as side-dressing or top-dressing is common for crops requiring high N input. These additional applications of N help minimize N losses from single large N application at pre-planting. More than 90% of broccoli N uptake takes place toward the end of the growing season, or about the button forming stage (Doerge et al., 1991). Conventional growers have the advantage of applying highly soluble synthetic N fertilizer to meet crop N demand and attain the desired yield. Unlike conventional growers, predicting N availability from organic N sources is more complicated. There is little information available on the effectiveness on improving yield with organic materials applied as side dressing and especially at different irrigation rates. Information on nitrogen and water management in organic broccoli production is not readily available. The objectives of this study were to examine the impact of water management (micro irrigation), form of organic N fertilizer inputs, and their interactions on broccoli yield, volumetric soil water content, and crop water use efficiency.

MATERIALS AND METHODS

Field Locations. The study was carried out at two organic broccoli farms from 2002 to 2004 in two regions of California. First, a small farm operation (0.13 ha) at the Center for Agroecology and Sustainable Food Systems (CASFS), University of California Santa Cruz (UCSC farm), represented organic broccoli production in the Central California Coastal region. The soil was classified as a Elkhorn sandy loam. Second, a large farm operation (4 ha) in Five Points, CA (Harris farm) represented organic broccoli production in the Central California Valley region, where soil was classified as a Panoche clay loam.

Broccoli (cv. Legacy) was planted at both field locations by direct seed for the growing seasons in 2002 to 2004. Plantings occurred during late-spring to early-summer in Santa Cruz, and from late summer to early fall in Five Points. Double rows of organic broccoli were planted in each bed by seed and thinned to a spacing of 15-20 cm between plants. Water was supplied with sprinkle irrigation for up to 30 days after seedlings emergence. Surface drip irrigation system (T-tape drip line, T-Systems International, Inc., San Diego, CA), was placed in the middle of each bed to provide water for the rest of the growing season for both sites.

The experimental design was a split-plot and the treatments are shown in Table 1. At the UCSC farm, the main plot was irrigation and the split-plot was the organic N fertilizer treatment. At the Harris farm, the main plot was the organic N fertilizer treatment and the split-plot was the irrigation treatment. This was done since statistical differences between main plots occurred due to limitations in the randomization of the irrigation treatment on a large-scale farm (Harris farm). The size of each main plot was three-raised beds 25 m long at the UCSC Farm and five-raised beds 150 m long at the Harris Farm. A total of four organic N fertilizers and three irrigation levels were tested at UCSC Farm (total of 12 treatments), while three organic N fertilizers and two irrigation levels were tested at Harris Farm (total of 6 treatments) due to limitations of the irrigation facility to randomize the large plot area with four replications for each treatment.

Treatments. Both field locations received manure-based compost (New Era Farm Service, Tulare, CA) applied at pre-plant rate of 140 $kg{\cdot}ha^{-1}$ of N. Organic N fertilizer treatments were applied twice as side-dresses for a total rate of 112 $kg{\cdot}ha^{-1}$ of N per growing season. Organic N fertilizers were fish powder (FP), Phytamin [blood meal and feather meal mix (BF)], and seabird guano (SG), (Peaceful Valley Farm Supply Inc., Grass Valley, CA). Sodium nitrate was also added to the BF treatment (SN) at <20% of total N application, this amount of inorganic N was allowed under USDA Organic Rules (USDA, AMS, 2002). Details of fertility treatments are presented in Table 1.

Water application rates were determined from the daily evapotranspiration rate (ETo) data of well-irrigated reference grass from the De Laveaga California Irrigation Management Information System (CIMIS)

TABLE 1. Various N and irrigation treatments studied at two field locations in California during 2002 to 2004 growing seasons.

Field locations	N treatment[Z]	Total fertilizer N applications ($kg \cdot ha^{-1}$)[Y]			Irrigation treatments[X] (% ETc)
		Pre-plant	Side-dress#1	Side-dress#2	
UCSC Farm (Santa Cruz, CA)	Compost only (CO)	140	0	0	80-100-150
	Compost and Fish Powder (FP)	140	56	56	80-100-150
	Compost and Phytamin (BF)	140	56	56	80-100-150
	Compost and Phytamin and $NaNO_3$ (SN)	140	78	34	80-100-150
Harris Farm (Five Points, CA)	Compost only (CO)	140	0	0	100-150
	Compost and Phytamin (BF)	140	56	56	100-150
	Compost and Seabird guano (SG)	140	112	0	100-150

[Z]Compost was added as a preplant application to all N treatments at both field locations. The additional side-dress N was added as designated above.

[Y]The total amount of fertilizer N application for each treatment applied during the growing season according to the designated treatment.

[X] For economical purposes, Harris farm did not apply water at 80% ETc.

weather station for the UCSC farm, and from the Westlands CIMIS weather station for the Harris farm. Data were retrieved weekly to calculate the amount of water for irrigation treatments prior to irrigation scheduling for the following week. Irrigation was applied to organic broccoli based on crop evapotranspiration (ETc), which was calculated from the ETo multiplied by crop coefficient (Kc) values of broccoli reported by Hanson et al. (1999). Each organic fertilizer treatment received three levels of irrigation at 80, 100, and 150% ETc, at the UCSC Farm; and two levels of irrigation at 100 and 150% ETc were supplied at the Harris Farm. For economic reasons, cooperators at Harris Farm did not wish to have 80% ETc treatment due to the possibility of decrease yields. All irrigation treatments including seasonal precipitation rates are reported in Table 2.

Data Collection, Fresh Weight Yield. Broccoli plants were harvested from each treatment at the same period as the commercial harvest. Broccoli plants were collected from three 1 m^2 samples randomly selected from each replicate of each treatment. Plants were cut 2 cm above the ground, bagged, and separated into leaf, stem and floret samples. Leaf yield included leaves and petioles separated from stem, and floret yield was the flower head of broccoli cut about 2 cm below the bottom of the floret branch where it meets the top part of stem.

Crop Water Use Efficiency (WUE). To quantify WUE from various N and irrigation treatments tested, the ratio of commercial broccoli yield, defined as the yield of floret fresh weight combined with a quarter of whole stem fresh weight, to the total amount of water applied by drip irrigation, sprinkler, and precipitation during each growing season (Table 2) at each location was calculated by the following formula:

$$\text{WUE} = \frac{\text{Commercial broccoli yield (kg)}}{\text{Total water application (cm)}} \tag{1}$$

Volumetric Soil Water Content. Composite soil samples were collected from three soil cores in each replicate from the UCSC farm and Harris farm at depths of 15 cm during the growing season at the following times: pre-compost, post-compost, post-side dress#1, pre-side dress#2, post-side dress#2 and post-harvest. In addition, soil samples were collected from the 15-45 cm and 45-90 cm depths during the growing season at the following times: post-compost, pre-side dress#2, and post-harvest period. Soil moisture content was measured from each sample to correct for the dilution factor when determining the final concentration of soil NO_3-N and soil NH_4-N measured in $mg \cdot kg^{-1}$. The percent gravimetric soil moisture content (GSM) was calculated by Equation (2), while the volumetric soil water content (P_v) was calculated by Equation (3):

$$\text{GSM } (g \cdot kg^{-1}) = \frac{\text{soil weight (g) at field condition} - \text{soil weight (g) after oven-dried}}{\text{soil weight (g) after oven-dried}} \times 100 \tag{2}$$

$$\text{Volumetric soil water content } (P_v) = \text{GSM x soil bulk density at an appropriate depth} \tag{3}$$

TABLE 2. Total amount of water application rates supplied via drip-irrigation system based on ETc to UCSC and Harris farms during 2002 to 2004 growing seasons.

Field locations	Year	Growing season	Precipitation (mm)	Crop evapotranspiration (% ETc)[Z] (cm)		
				80	100	150
UCSC Farm	2002	May-July	28.2	37.5[Y]	47.3	71.8
(Santa Cruz, CA)	2003	July-Sept	0.0	46.0	56.7	84.6
	2004	Jun-Aug	2.5	45.4	56.5	84.3
Harris Farm	2002	Sept-Jan	71.1	NA	13.4	20.2
(Five Points, CA)	2003	Oct-Feb	109.1	NA	21.1	31.7
	2004	Oct-Mar	251.0	NA	11.8	17.8

[Z]ETc = Kc × ETo; ETo was retrieved weekly from CIMIS station in Santa Cruz and Five Points, CA for UCSC and Harris farm, respectively.

[Y]Not including the amount of water applied by sprinkler system during bed preparation, and 30-day seedling stage prior to drip installation at each growing season.

Statistical Analysis. Analyses of variance for a split-plot design were performed using the Number Cruncher Statistical Systems (NCSS) 2004 software (Hintze, 1998). The Tukey-Kramer multiple-comparison test method at $P < 0.05$ was applied to plant yield and WUE data.

RESULTS

Fresh Weight Yields. Overall total yields significantly increased with additional N from side-dress treatments and irrigation treatment at 100 or 150% ETc (Tables 3 and 4). Organic N fertilizers applied as side-dress in addition to CO at the total rate of 112 kg·ha^{-1} of N significantly increased broccoli leaf, stem, and floret yield on the UCSC farm (Table 5), and to a lower extent on Harris farm (Table 6). The range of irrigation rates applied to the UCSC and Harris farms influenced broccoli leaf, stem, and floret yield differently at each site. There appeared to be a stronger response affecting overall crop yield to both N source and irrigation rates at the UCSC farm as opposed to the Harris farm.

TABLE 3. Summary of ANOVA table obtained from various parameters tested at UCSC Farm during 2002 to 2004 growing seasons.

		Plant yield					Volumetric soil water (P_v) depth (cm)		
Year	Source	Leaf	Stem	Floret	Total	WUE	0-15	15-45	45-90
2002	N	***[z]	**	***	***	***	ns	***	**
	Water	**	ns	*	*	**	**	**	***
	N × Water	*	ns	ns	ns	ns	ns	*	**
	Block	ns	ns	ns	ns	ns	ns	ns	*
2003	N	***	***	***	***	***	ns	ns	ns
	Water	*	ns	***	**	*	***	***	***
	N × Water	*	*	***	***	***	ns	ns	***
	Block	ns	ns	ns	ns	ns	*	*	*
2004	N	***	***	***	***	***	ns	***	ns
	Water	*	ns	ns	ns	***	***	***	***
	N × Water	**	ns	ns	*	*	ns	***	**
	Block	ns	*	ns	*	ns	*	*	*

[z]ns, *, **, and *** non-significant or significant at $P \leq 0.05$, 0.01, and 0.001, respectively.

Leaf and stem yields were higher from all treatments collected from the UCSC farm in 2003 and 2004 than in 2002. Nitrogen source, water application rate, and their interaction (N × water) significantly influenced leaf yield on the UCSC farm in all years (Table 3). On the Harris farm, the highest leaf yields were in the order 2003 > 2004 > 2002 (Table 6), and N source significantly affected leaf yield only in 2004, but water application rate significantly affected leaf yield in both 2002 and 2003 (Table 4). On the UCSC farm, stem yield was significantly different due to N source from 2002 to 2004, and significant N × water interaction and block effect was observed in 2003 and 2004, respectively, (Table 3), while water application rate and N × water interaction significantly influenced stem yield in 2003 and 2004, respectively, on the Harris farm (Table 4).

Floret yield significantly responded to N sources from 2002 to 2004 on the UCSC farm (Table 3), and from 2003 and 2004 on Harris farm (Table 4). Generally, floret yield from the UCSC farm was ten times greater for all treatments in 2004 than yields in 2002, while floret yield

TABLE 4. Summary of ANOVA table obtained from various parameters tested at Harris Farm during 2002 to 2004 growing seasons.

		Plant yield					Volumetric soil water depth (cm)		
Year	Source	Leaf	Stem	Floret	Total	WUE	0-15	15-45	45-90
2002	N	ns[z]	ns	ns	ns	*	ns	*	**
	Water	*	ns	ns	ns	**	***	ns	ns
	N × Water	ns	ns	ns	ns	**	*	ns	*
	Block	ns	ns	ns	ns	ns	ns	ns	ns
2003	N	ns	ns	*	ns	*	ns	ns	*
	Water	***	*	ns	**	***	***	**	**
	N × Water	ns	ns	ns	*	ns	ns	ns	ns
	Block	ns	ns	ns	ns	ns	ns	ns	ns
2004	N	*	ns	*	*	*	ns	ns	ns
	Water	ns	ns	**	ns	ns	**	**	**
	N × Water	ns	*	**	ns	*	ns	ns	*
	Block	ns	ns	ns	ns	ns	ns	ns	ns

[z]ns, *, **, and *** non-significant or significant at $P \leq 0.05$, 0.01, and 0.001, respectively.

from the Harris farm indicated only slight differences between the 2002 and 2004 growing seasons. In 2003, the highest floret yield was obtained from side-dressing FP at 100 and 150% ETc, BF at 80 and 150% ETc, and SN at 150% ETc, respectively at the UCSC farm. The CO at 100% ETc treatment produced floret yields as high as any side-dress treatments in 2004 on the UCSC farm. On the Harris farm, only floret yields in 2003 and 2004 responded significantly to side-dress and irrigation treatments. The significantly lowest floret yield was collected from the CO at 100% ETc treatment in 2004, while other forms of side-dress and irrigation treatments had no effect on floret yields. The highest floret yield was achieved from the BF at 100% ETc treatment in 2003, and from the SG at 150% ETc treatment in 2004. Water application rates significantly influenced floret yield at the UCSC farm from 2002 to 2004 (Table 3), but were only significant at the Harris farm in 2004 (Table 4). The N source × water interaction significantly affected floret yield only in 2003 on the UCSC farm (Table 3), and at the Harris farm only in 2004 (Table 4).

TABLE 5. Broccoli yield produced from different forms of side-dresses N and water application rates at UCSC Farm during 2002 to 2004 growing seasons.

N treatment[Z]	Irrigation (% ETc)	2002 Leaf (Mg·ha^{-1})	2002 Stem	2002 Floret	2002 Total	2003 Leaf (Mg·ha^{-1})	2003 Stem	2003 Floret	2003 Total	2004 Leaf (Mg·ha^{-1})	2004 Stem	2004 Floret	2004 Total
CO	80	17.5a[Y,X]	7.8a	1.6ab	26.9a	29.7ab	15.4a	5.4a	50.5a	29.0a	18.4a	13.8a	61.2a
	100	22.6abcd	12.0ab	1.7abc	36.3bcd	33.2abc	17.0abc	6.4ab	56.6ab	27.9a	18.7a	16.8abc	63.4ab
	150	19.0ab	10.2ab	1.3a	30.5ab	31.6ab	16.9ab	6.1ab	54.6ab	29.0a	19.5ab	15.7ab	64.2ab
FP	80	22.8bcd	11.1ab	2.4abcd	36.3bcd	39.8def	19.7abcd	7.9abc	67.4bc	31.7ab	20.2ab	18.9abc	70.8abc
	100	27.6d	12.3b	3.6d	43.5cd	45.7f	23.2d	11.9cde	80.8cde	38.3cde	21.0ab	23.6bc	82.9cd
	150	24.7cd	12.9b	3.8d	41.4cd	42.7ef	23.5d	15.0ef	81.2de	37.6cd	19.4ab	19.9abc	76.9bcd
BF	80	22.5abcd	12.0ab	2.4abcd	36.9bcd	38.9cde	22.4bcd	12.5cde	73.8cde	37.2bcd	23.6ab	23.9c	84.7cd
	100	23.1bcd	12.2ab	2.8abcd	38.1bcd	37.7bcde	20.3abcd	9.6bcd	67.6bcd	35.1bc	21.0ab	19.9abc	76.0bc
	150	25.7cd	12.7b	3.1cd	41.5cd	40.2def	22.6cd	14.5ef	77.3cde	43.7e	24.2b	23.5bc	91.4d
SN	80	21.0abc	11.2ab	2.7abcd	34.9abc	36.1abcd	16.4a	6.6ab	59.1ab	38.6cde	23.3ab	21.1abc	83.0cd
	100	27.4d	12.5b	3.0cd	42.9cd	42.5def	22.1bcd	10.8cde	75.4cde	38.8cde	22.3ab	23.2bc	84.3cd
	150	26.9d	14.3b	3.4d	44.6d	44.5f	23.9d	17.9f	86.3e	42.5de	20.6ab	21.9bc	85.0cd

[Z] CO is "compost only"; FP is fish powder; BF is Phytamin; SN is BF and $NaNO_3$.

[Y] Mean values.

[X] Values in a column followed by the same letter are not significantly different, $P \leq 0.05$, using Tukey-Kramer multiple-comparison test.

TABLE 6. Broccoli yield produced from different forms of side-dresses N and water application rates at Harris farm durng 2002 to 2004 growing seasons.

N treatment[z]	Irrigation (% ETc)	2002 Leaf	2002 Stem	2002 Floret	2002 Total	2003 Leaf	2003 Stem	2003 Floret	2003 Total	2004 Leaf	2004 Stem	2004 Floret	2004 Total
		($Mg \cdot ha^{-1}$)				($Mg \cdot ha^{-1}$)				($Mg \cdot ha^{-1}$)			
CO	100	45.6a[Y,X]	29.5ns	18.2ns	93.3ns	81.7abc	32.5ab	20.5a	134.7a	61.1a	23.5b	15.4a	100.0ab
	150	54.5ab	33.3ns	18.1ns	105.9ns	78.0a	30.1a	24.4ab	132.5a	58.8a	20.8ab	19.2b	98.8a
BF	100	54.3ab	31.4ns	18.2ns	103.9ns	85.2c	35.1b	26.6b	146.9b	61.6a	21.7ab	21.9bc	105.2ab
	150	55.6b	32.5ns	19.9ns	108.0ns	80.0ab	30.2a	25.0ab	135.2a	61.1a	21.2ab	20.7b	103.0ab
SG	100	53.5ab	32.2ns	23.4ns	109.1ns	82.2bc	32.3ab	23.8ab	138.3ab	65.8ab	19.5a	21.5bc	106.8ab
	150	54.3ab	31.5ns	20.8ns	106.6ns	78.6ab	33.0ab	23.6ab	135.2a	71.3b	24.4b	24.0c	119.7b

[Z] CO is "compost only"; BF is Phytamin; SG is seabird guano.

[Y] Mean values.

[X] Values in a column followed by the same letter are not significanty different, $P \leq 0.05$, Tukey-Kramer multiple-comparison test; ns is not significantly different.

Crop Water Use Efficiency. Broccoli at the Harris farm received less irrigation compared with UCSC farm due to the high amount of precipitation received during all growing seasons (Table 2). Consequently, the greater levels of WUE were calculated from all N and irrigation treatments at Harris farm in all years (Table 7). At the UCSC farm, the highest WUE levels were obtained from the 80 or 100% ETc treatments in all years. Irrigation at 150% ETc generally produced the lowest WUE in all years for all treatments, except for the SN treatment in 2003. Fewer WUE differences were detected between 'compost only' and all side-dress treatments in 2002, however, these differences significantly increased in 2003 and 2004. At the Harris farm, the significantly higher WUE was observed in the SG at 100% ETc treatment in 2002, in the BF and SG at 100% ETc treatment in 2003 and 2004, and in the SG at 150% ETc treatment in 2004.

Volumetric Soil Water Content. In general, P_v was significantly influenced by ETc, soil type, and soil depth (Figures 1and 2). The form of side-dress did not cause distinct differences in P_v compared to the "compost only" treatment at both locations. Irrigation water rates at 100 and 150% ETc likely contributed to higher P_v for all side-dress treatments, while P_v collected from the clay loam soil at the Harris farm (Figure 2) always remained higher than P_v from the sandy loam soil at the UCSC farm (Figure 1). All P_v values collected at the 45-90 cm depth were the highest followed by those collected at the 15-45 and 0-15 cm depths, at both locations for all years. The greater difference of P_v was observed among irrigation treatments at the UCSC farm than at the Harris farm for all years. Regardless of N source, P_v measured from the 150% ETc treatment remained highest at all depths on the UCSC farm in all years, however, we observed only significantly different P_v among the 0-15, 15-45, and 45-90 cm depths from the Harris farm for all years.

DISCUSSION

The influence of different forms of side-dress and irrigation rates on organic broccoli production in were examined in two regions of California. It was determined that N applied as side-dress and water management are site-specific components that are essential to achieve marketable yield. The efficacy of side-dress and water management are, however, dependent upon the fertility background of each site, location, form of side-dress N, soil type, and ETc. All the individual factors influence

TABLE 7. Water use efficiency of organic broccoli calculated from different forms of side-dress N and water application rates at UCSC and Harris farms during 2002 to 2004 growing seasons.

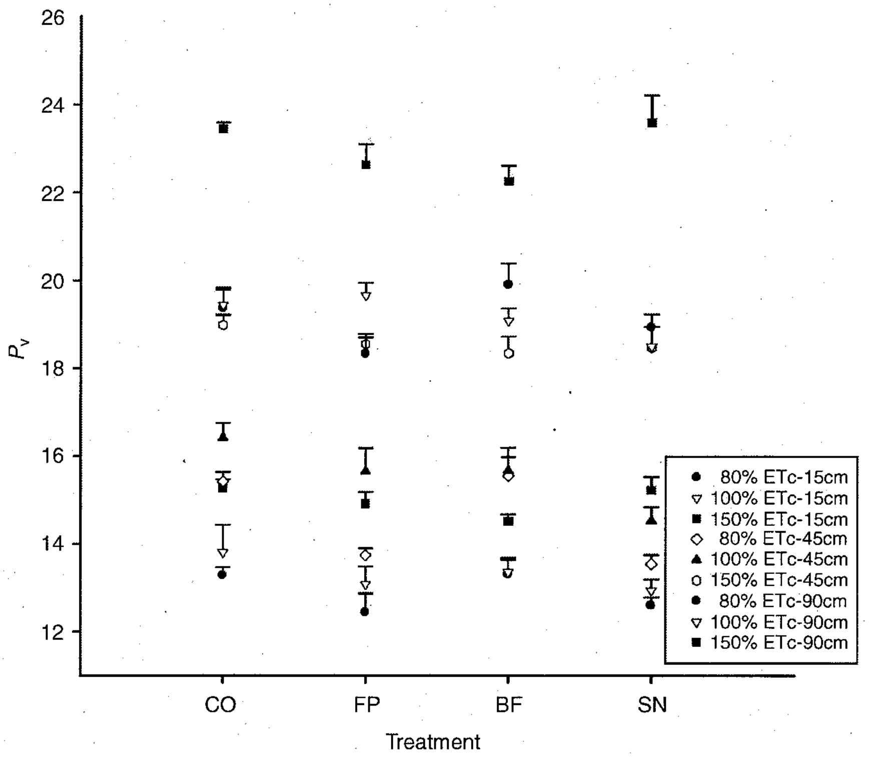
		UCSC farm			Harris farm		
	Irrigation	2002	2003	2004	2002	2003	2004
N treatment[Z]	(% ETc)		(kg·cm^{-1})			(kg·cm^{-1})	
CO	80	78ab[Y,X]	181abc	362abc	NA	NA	NA
	100	85abc	173ab	347abc	720a	607a	409a
	150	49a	116a	229a	626a	553a	420a
FP	80	113bc	250cde	472cde	NA	NA	NA
	100	121c	287ef	467cde	NA	NA	NA
	150	88bc	233bcde	276ab	NA	NA	NA
BF	80	119c	354f	588e	NA	NA	NA
	100	106bc	238bcde	407bcd	733a	753b	527c
	150	79ab	225bcde	330ab	664a	564a	450ab
SN	80	121c	209bcd	531de	NA	NA	NA
	100	112bc	264de	466cde	NA	NA	NA
	150	88bc	267de	302ab	NA	NA	NA
SG	80	NA	NA	NA	NA	NA	NA
	100	NA	NA	NA	1,112b	679ab	508bc
	150	NA	NA	NA	677a	553a	520bc

[Z] CO is "compost only"; FP is fish powder; BF is Phytamin; SN is BF and $NaNO_3$; SG is seabird guano.
[Y] Mean values.
[X] Values in a column followed by the same letter are not significantly different, $P \leq 0.05$ using Tukey-Kramer multiple-comparison test; ns is not significantly different; NA is not applicable.

crop yield, water use efficiency, and volumetric soil water content. Soil mineral N concentrations are not reported in this paper. These data are essential to improve our understanding on the effects of N sources and irrigation rates on soil quality in organic broccoli yield from this study.

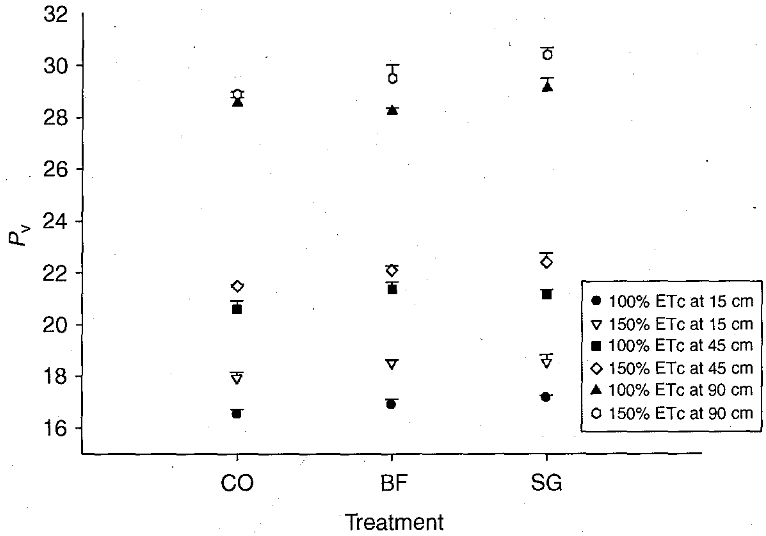
Yield increases from additional side dress at the Harris farm were less pronounced than yields observed at the Santa Cruz farm. The soil at the Harris farm, a clay loam, retains more plant available nutrients and has a greater water holding capacity than the sandy loam soil at the UCSC location. In addition, the Harris farm had been farmed organically for over five years prior to this study, while the location at UCSC had only one year of organic production with no record of soil

FIGURE 1. Mean volumetric soil water content (± SEM) at 0-15, 15-45, and 45-90 cm depths at different ETc rates collected from UCSC farm during 2002 to 2004 growing seasons. CO is 'compost only'; FP is fish powder; BF is Phytamin; SN is BF and $NaNO_3$.



amendment incorporation prior to 2002. In addition, the field had been previously planted with potato and ryegrass, respectively, which led to lower levels of plant nutrients available for the first year crop of broccoli. These conditions likely contributed to low broccoli yield collected from UCSC farm for the first year of this study. As observed at Harris farm, soil fertility in organic farming can improve over time with the continuous incorporations of organic matter such as compost, and green manure (Gaskell et al., 2000), and lead to higher yields, as observed after three-years of organic operation at the UCSC farm. In this regard, floret yields significantly increased with continuous applications of

FIGURE 2. Mean volumetric soil water content (± SEM) at 0-15, 15-45, and 45-90 cm depths at different ETc rates collected from Harris farm during 2002 to 2004 growing seasons. CO is 'compost only'; BF is Phytamin; SG is seabird guano.



compost with or without side-dress at the Harris farm. However, the capacity of soil to sustain a high crop yield can reach its limit when additional N inputs no longer increases crop yield, as observed elsewhere with continuous applications of N fertilizers over years (Mulvaney et al., 2001). Similarly, we observed no significant additional contributions to yield with side-dress treatments compared to 'compost only' treatment at the Harris farm in 2002. We suspect that longer organic farming production at this location contributed to a high level of plant available nutrients prior to starting of the experiment in 2002.

A number of crops that require a high rate of N fertilization pose a great challenge to organic growers; especially as related to the timing of these applications. A very large application of manure was needed to achieve desirable organic corn yield; however, this also increased N losses during the growing season (Pang and Letey, 2000). Split applications of N fertilizer are widely recommended to satisfy crop N demand and minimize N loss. Organic farmers should consider this approach to meet their marketable yield on crops requiring high N inputs. Conventional growers have an advantage by utilizing highly soluble synthetic N fertilizers, while organic growers have less readily available source of N.

More than 80% of farmland in California rely on some types of irrigation system (DWR, 2006). Delivering irrigation water with a drip-irrigation system is recommended to achieve high water use efficiency (Shrestha and Gopalakrishnan, 1993; Waddell et al., 1999), and to maximize crop yield. A water application rate based on ETc is advantageous because growers have to consider crop growth stage, as well as the daily reference evapotranspiration rate. This latter consideration helps to minimize water losses especially when the crops are small. The irrigation rate at 80% of pan ETo was recommended for conventional broccoli growers to reach maximum irrigation production efficiency (Imtiyaz et al., 2000). Our study showed that only the liquid form side-dress, for example, BF and SN, could be used with this recommendation, while the solid form of side-dresses, for example, FP and SG, require water application rates as high as 100% ETc to obtain the greatest floret yield.

Generally, Santa Cruz receives a large amount of precipitation during the winter, and farmers commonly plant cover crops in this region to meet environmental regulations specifically implemented in this area. In our study, a minimal amount of rainfall occurred during this study at the UCSC farm, which resulted in a greater response of leaf, stem and floret yield to irrigation treatments. In contrast, there was significantly more precipitation during the growing seasons at the Harris farm, and less irrigation was necessary to produce organic broccoli. Depending on the precipitation occurring during the growing season, the importance and impact of water application rates may vary. For example, the Harris farm is located in Central Valley of California where cool-season crops can only be planted at specific cool times during the year due to extremely high summer temperature. In contrast, growers in the Central Coast of California, the site of the UCSC farm, can often plant broccoli three times during the year. Consequently, rates of irrigation may be more important on the Central Coast.

We inconsistently observed organic broccoli yields response to N source, water application rate, and their interaction in both locations in all years. Beverly et al. (1986) recommended that frequent sprinkler irrigation in combination with a relatively low N rate (140 kg·ha^{-1}) with split applications could produce yields as high as 10 Mg·ha^{-1}. They discovered broccoli yield increased when both N and water application rates were considered; however, excessive N or water application decreased yield because denitrification occurred. To obtain marketable yields of 24.5 to 27 $Mg{\cdot}ha^{-1}$ of conventional broccoli under drip-irrigated system in Central Mexico, researchers suggested total applications of N as high as 400-425 $kg{\cdot}ha^{-1}$ of N (Castellanos et al., 2001). We were able to obtain floret yields as high as 23.9 Mg ha^{-1} at the UCSC farm in 2004 and 26.6 $Mg{\cdot}ha^{-1}$ at the Harris farm in 2003, respectively, with a total N application of 224 $kg{\cdot}ha^{-1}$ for growing organic broccoli at both locations. Although application rates as high as 400 $kg{\cdot}ha^{-1}$ of N were used by organic broccoli growers in other regions of California (M. Gaskell, personal communication), this study indicates that high yields can be achieved with total N application of 252 $kg{\cdot}ha^{-1}$ and 100% ETc irrigation rate during the growing season in two different regions of California.

Nitrogen rate and water management in organic broccoli production in California can be optimized to achieve potential high marketable yield and high water use efficiency. The fertility background of the field location, soil type, seasonal precipitation, and form of side-dress N, and other environmental factors are all essential in influencing organic broccoli yield, WUE, and P_v. Application of organic N fertilizer in a solid form, for example, FP and SG, will likely require greater amounts of irrigation than use of the liquid form, for example, BF and SN. Utilizing available information from a local weather station helps growers to effectively manage the amount of water to apply to a crop during the growing season. Application of a N side-dress to a preplant application of compost is essential to a newly converted organic farm like the UCSC location and should dramatically improve yields over three years of application, however, a N side-dress may not be as necessary to improve yield on a farm with a long history of applying organic amendments.

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