A. Project Information
Final Report
Contract 13-0268-SA

Improving N use efficiency of cool season vegetable production systems with broccoli rotations

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B. OBJECTIVES

1. Determine the effective rooting depth of broccoli for removing residual N from the soil profile though direct evaluation of rooting pattern and replicated field trials
2. Adapt soil nitrate quick test for broccoli to guide N fertilizer applications by evaluating factors including soil sample depth, threshold of soil nitrate sufficiency, and crop stage.
3. Conduct commercial field trials evaluating the efficiency of broccoli to remove residual nitrate from the soil following a lettuce crop under normal production practices.
4. Examine the mineralization rate and quantity of nitrate mineralized from broccoli residue to assess its potential utilization by subsequent crops
5. Conduct an outreach program to growers and consultants on the results of the study and how to utilize the nitrogen scavenging attributes of broccoli to improve nitrogen utilization in the cool season vegetable production system

C. ABSTRACT

Evaluations of the ability of broccoli to take up residual soil nitrate were conducted in commercial broccoli fields and research station studies. Evaluations included surveys of the amount of nitrate taken up by broccoli from the top three feet of soil during the cropping cycle, broccoli rooting depth and the total quantity of N taken up by broccoli. These studies showed that broccoli rotations can scavenge residual soil nitrate from prior crops and effectively reduce the risk of nitrate leaching. However, the efficiency of recovery of residual soil nitrate-nitrogen (NO_3-N) declines as residual NO_3-N in the top 3 feet of soil at the beginning of the crop cycle is greater than 200 lbs/acre. Management strategies to achieve lower levels of residual soil nitrate in the lettuce crop prior to the broccoli include the use of the nitrate quick test to account for residual soil nitrate, accounting for nitrate levels in the irrigation water and adjusting fertilizer rates accordingly. In a survey of 10 commercial broccoli production fields, we observed that

growers use moderate fertilizer applications (app. 180 lbs N/A) while the crop routinely takes up >300 lbs N/A from the soil which indicates that the crop routinely scavenges N from the soil. Broccoli roots extend to 40 inches deep by the end of the crop cycle; however, we observed that the density of broccoli roots in the 2nd foot of soil increases significantly by 50 days after seeding. Soil samples taken of the 2nd foot at this time can help determine if sufficient residual soil nitrate is present to determine if late-season fertilizer applications are needed to finish out the crop, and may provide an opportunity to further improve fertilizer use efficiency. About 1/3 of the N taken up by the broccoli crop during the growing season is removed from the field in the harvested product; as a result, broccoli routinely returns 200-250 lbs N to the soil in crop residue. Nitrogen in crop residue is quickly and steadily mineralized following incorporation into the soil. The nitrate mineralized from broccoli crop residue can be effectively utilized by subsequent crops if careful irrigation management and soil testing to account for the residual soil N occur. However, nitrate released from broccoli residue incorporated prior to winter fallow is at risk for leaching with winter rains, but could be effectively captured by the use of winter-grown cover crops. This project provided data to develop and improve the accuracy of algorithms for N in the second foot of soil as a management practice for broccoli production.

D. INTRODUCTION

The cool season vegetable production areas of the Central Coast of California frequently grow more than one crop during the cropping season. Land rents and production costs are high which put pressure on the growers to intensify their rotations. As a result, two to three crops are routinely produced each year in each field. Crops such as lettuce, spinach, celery and cole crops are the dominant crops and all require robust applications of N to produce the yield and quality demanded by the highly competitive market. For instance, on average, lettuce uptake is about 120-150 lbs N/A. Fertilizer applications to lettuce vary widely, but often exceed uptake the of the crop; in addition, the amount of lettuce biomass N that remains in the field following harvest can be 55-65%. As a result, substantial amounts of residual soil N may remain in the soil following the production of a lettuce crop.

Water quality regulations implemented by the Central Coast Water Quality Control Board are challenging growers to evaluate and implement practices to improve the efficiency of applied nitrogen to vegetable crops. All of the cool season vegetables are listed as “at risk” crops and growers producing more than 500 acres of these crops are placed into Tier 3 compliance category that has the strictest regulations concerning the movement of nitrates to surface and ground waters. These regulations will require growers to implement a certified Irrigation and Nutrient Management Plans (INMP) that justify and document N application rates applied to crops.

The regulations have created an urgent need for development and implementation of practices for growers to make progress in improving nitrogen management and making measureable improvements in water quality. Key practices that can help growers improve nitrogen management include the use of the nitrate quick test to measure and utilize residual soil nitrate, thereby reducing the need for additional fertilizer applications when they are not needed. Improvements in irrigation efficiency are also critical to reducing the movement of nitrate to deeper in the soil profile. There have been many educational efforts to assist growers in these areas and a good deal of progress has been made.

Broccoli is grown on 79,950 acres in on the Central Coast and is a key rotational crop for lettuce because it helps to break the cycle of key soilborne diseases. Broccoli has been shown to scavenge more nitrate from the soil than is typically applied as fertilizer. This project is evaluating the role that broccoli rotations can play in reducing nitrate leaching in the cool season vegetable system.

E. WORK DESCRIPTION

Depth of fertilizer application trial: In 2014 and 2015 trials were established at the USDA Spence Research Station, Salinas in which drip tape, used to apply fertilizer, was placed in the soil at four depths: 0, 12, 18 and 24 inches. A piece of equipment was fabricated to inject the drip tape to 12, 24 and 36 inches deep as was proposed and the site was ripped to 36 inches deep by a cooperating grower in three directions to loosen the soil. However, the drip tape injector would not penetrate any deeper than 24 inches. We tried to partially overcome this issue by applying an excess of water during the injection of the calcium nitrate fertilizer to push the fertilizer a bit deeper than the drip tape was located. In addition to the drip tape used to inject fertilizer in the deep placement treatments, drip tape was also placed on the soil surface of each bed and was used to apply irrigations. The broccoli variety 'Patron' was seeded on July 22, 2014 and July 31, 2015 and first water was applied on July 23, 2014 and July 31, 2015. In 2014, there was high residual soil nitrate in 2014 and excess irrigation water was applied during the first 30 days of the crop cycle to leach the nitrate. There was low residual soil nitrate in 2015 and no leaching was necessary. Nitrogen fertilizer in the standard treatment was applied as UN 32 in surface drip tape. The form of N fertilizer used on the 12, 18 and 24 inch treatments was CN10 (calcium nitrate). Fifty lbs of N/A were applied approximately 50, 65 and 75 days after the planting for a total of 150 lbs N/A to each treatment. Soil samples to three feet were collected six to seven times during the crop cycle. Tissue samples were collected one time during the crop cycle and yield measurement was made by harvesting the crop 3 times (2014) and 2 times (2015). Crop yield was evaluated by cutting and weighing all mature heads on each harvest date. Crop biomass and biomass N was evaluated at harvest by harvesting all crop biomass and weighing it fresh and then drying and weighing it for total dry matter and biomass N content.

Broccoli N uptake survey: A total of ten commercial broccoli fields planted following a prior lettuce crop were evaluated in 2014 and 2015. Evaluations of the ability of the broccoli crop to take up residual soil N were made. Residual soil nitrate levels at one-foot increments down to three feet were evaluated to establish baseline soil nitrate levels for each field. Evaluations consisted of measurements of the grower's practices as well as unfertilized small plots set up in each field. The unfertilized beds were 3 80-inch beds wide or 4 40-inch beds wide by 50 feet and replicated 3 – 4 times in each field. Four replicate soil samples for nitrate-N were collected every 25 to 30 days from the standard grower practice and unfertilized plots. Total irrigation water applied to the fields was monitored with a flow meter to determine the amount of leaching.

Rooting Depth: Rooting depth of the broccoli was determined by digging a pit 4-5 times during the crop cycle and measuring the depth of the deepest root. Crop biomass and biomass N were evaluated on the same day as soil samples. Soil nitrate levels in the first two feet were posted on CropManage and made available to the grower; the results were discussed with the grower to inform them of the amount of residual soil nitrate-N available for crop growth.

Broccoli Residue Mineralization Evaluations: *Laboratory evaluations:* Fresh residue was obtained from two Salinas Valley broccoli fields. Residue was finely chopped, blended with air dried, well mixed soil loam and coarse sandy loam. Proportional amounts of leaf and stalk tissue were combined to approximate whole plant residue. The amount of residue added was based on estimated water content and estimated N concentration, with the goal of adding 100 PPM N (all forms, including mineral N) on a soil dry weight basis; actual N added turned out to be between 108-125 PPM. The soil/residue blends, and unamended control soils, were wetted to approximately 50% water filled pore space and incubated at constant temperature for 8 weeks, at high humidity to maintain soil moisture content. After 2, 4 and 8 weeks of incubation subsamples were collected and extracted in 2N KCl for determination of NH_4-N and NO_3-N. The increase in mineral N, compared to the unamended control soil at that temperature, estimated the amount of mineral N from the residue. The experiment was begun Oct. 14, with sampling Oct. 28, Nov. 11 and Dec. 9. The study was structured to evaluate the effects of soil type by comparing each of the residues in both soils at 20C. The effect of incubation temperature was evaluated by comparing both broccoli residues in both soils at 15, 20 and 25C.

Field evaluations: Five field evaluations were conducted in which 40 foot by 40 foot square areas were cleared of broccoli residue; the cleared areas were replicated 2-3 times in each field. The grower tilled in the broccoli residue in the rest of the field using normal practices: discing, ripping, chiseling and relisting beds. No preplant N fertilizer was applied to the fields. Soil nitrate in the top two feet of soil was measured every four weeks in the areas with and without broccoli residue over the winters of 2014-15 and 2015-16.

Outreach/Demonstration Plot: Field trials were established in a commercial broccoli field in 2015 and 2016. The fields were grown following a prior lettuce crop. In 2016, all nitrogen inputs to the prior romaine lettuce crop were measured. Evaluations consisted of sampling the soil to 3 feet deep over the course of the crop cycle, documenting all fertilizer N applications and monitoring the amount of water applied to the soil and the concentration of nitrate in the water. Broccoli was planted July 28, 2015 and July 12, 2016. In each year, an area 24 beds wide by the length of the field (900 feet) was established in the fields; the experimental area was supplied with a separate irrigation manifold to allow different irrigation and fertigation timings and rates based on recommendations from CropManage. The remainder of the field was managed by grower's standard practices. In addition, in the grower standard area, unfertilized control plots 4 beds by 50 feet long were established. Soil in the broccoli field was sampled to two feet deep weekly over the course of the crop cycle. Crop biomass and biomass N was measured once a month and at harvest. Yield was measured in replicated small plots and by a commercial harvest crew. The trials were conducted with close cooperation with the grower. The trial served as a demonstration for outreach to growers on irrigation and nutrient management as well as CropManage.

F. DATA/RESULTS

Depth of fertilizer application trial: The depth of the drip tape affected the yield of broccoli in trials conducted at the USDA Spence Research Station. Drip tape on the soil surface had the highest yield and drip tape placed at 24 inches had the lowest yield while tape at 12 and 18 inches was intermediate (Tables 1 and 2). The trial site had low levels of residual soil nitrate in these experiments to facilitate observing the effect of N placement on broccoli growth and yield. 150 lbs N was applied to all treatments, however it appears that low levels of soil nitrate through the first month of the crop stressed the broccoli plants for N and resulted in generally low yields in this trial, especially for the deep placement treatments, indicating that broccoli does not take up nitrate deeper in the soil profile until later in the crop cycle. Nitrogen applied at 24 inches in the soil was not available to broccoli until approximately 50 days after planting (Figure 1). The higher yield of the standard treatment occurred presumably because there were higher levels of fertilizer N that the shallow roots could access earlier in the crop cycle. Deep soil samples indicate that there were spikes of nitrate at the second and third foot of soil at mid growth of the broccoli following N applications; soil nitrate levels returned to low levels in all treatments later in the crop cycle (Tables 3 and 4), presumably the result of crop uptake and/or leaching. By mid-growth, 50-55 days after planting, there are sufficient broccoli roots in the second foot of soil to allow the crop to begin taking advantage of residual soil nitrate that is found there. Generally, by mid-growth, nitrate-N in the first foot of soil is drawn down to low levels by mid-growth (depending on fertilization practices) and the plant begins to utilize and depend on N in the second foot of soil. These studies support the need for sufficient early-season N applications to assure that the plant has sufficient nutrition to then be able to take advantage of residual soil nitrate-N deeper in the profile later in the crop cycle.

Broccoli N uptake survey: Evaluations of ten broccoli fields grown in rotation with a prior lettuce crop were conducted in 2014 and 2015. Evaluations of the amount of residual soil nitrate in the top three feet of soil were made at the beginning of the broccoli crop cycle, and residual soil nitrate levels ranged from 134 to 431 lbs N (Tables 5, 6, 7 and 8). Fertilizer applications ranged from 169 to 240 lbs N/A and total N uptake by the broccoli crops ranged from 220 to 370. On average broccoli took up 73% of all initial soil mineral nitrogen + fertilizer N. At nine of the ten sites, broccoli took up more N than was applied as fertilizer and thereby scavenged N from the soil. At the site where application of fertilizer N was higher than crop uptake, the yield was low probably due to N management on a sandy soil. Based on the amount of N taken up by the broccoli and the amount of residual mineral N at the end of the growing season, broccoli N uptake resulted in 0.0 lbs N/A leached to as much as 219.5 lbs N/A potentially leached. High leaching potential occurred at sites with high levels of residual soil nitrate at the beginning of the broccoli crop cycle. The results of this survey indicate that broccoli has the potential to scavenge significant quantities of residual soil N from the soil at sites with moderate levels of residual soil nitrate at the beginning of the broccoli crop cycle. However, at sites with high levels of residual soil nitrate, broccoli can only take up a portion of the available mineral N. It is interesting to note that at sites with high available N produced biomass with high concentrations of N in the biomass, indicating that broccoli may have some ability to take up luxurious amounts of N into the tissue beyond what is needed for maximum growth.

Rooting Depth: Figure 1 shows the growth rate of broccoli roots over the course of the crop cycle, and shows the time for broccoli roots to get to deeper depths in the soil. Figure 2 shows the proportion of roots at various depths in the soil. Based on these data, we know that by about 50 days after seeding, there are sufficient roots in the 2nd foot of soil to allow the crop to effectively access NO_3-N there. Sampling the 2nd foot of soil can provide information on the amount of residual soil N available to guide a late-season fertilizer decision.

Broccoli Residue Mineralization Evaluations: *Laboratory evaluations:* Broccoli took up from 220.5 to 370.0 lbs N/A. About 25-30% of N is in the harvested heads. Thus, broccoli returns to the soil from 165 to 277 lbs N/A in crop residue. In the laboratory evaluations the N concentration of broccoli residue was a larger factor in the rate of N mineralization than were either the temperature of incubation or the soil in which the residue was incubated (Table 9). Averaged across soils, temperatures and residue N concentrations, the fraction of residue N mineralized was 32 and 53% after 2 or 4 weeks of incubation, respectively; N mineralization plateaued after 4 weeks. Residue containing 5% N showed 63% of its N content mineralized after 4 weeks, compared to only 43% for the residue containing 3.8% N.

Field evaluations: Field evaluations were conducted during the winter fallow period. This is the most at-risk time of year for broccoli residue to be incorporated into the soil because winter rains can leach nitrate mineralized from the residue. Figure 3 shows soil nitrate levels in the soil over the winter fallow period in plots with and without broccoli residue. Broccoli residue increases the levels of soil mineral nitrogen; however, the figure shows that even without broccoli residue, there is substantial mineralization of soil organic matter. This soil nitrate is subject to leaching during significant winter rain events if it is not utilized by a subsequent vegetable or cover crop (Figure 4).

Outreach/Demonstration Plot: We conducted evaluations in close collaboration with a cooperating grower using the on-line decision support program, CropManage, compared with the standard grower fertilizer and irrigation practices. Evaluations consisted of large strips in commercial fields (the width of a harvest machine to facilitate obtaining commercial harvest data) in which the CropManage and grower standard practices were managed separately. Separate irrigation practices were accomplished during the drip irrigation phase of the crop (initiated app. 30 days after seeding) by use of a separate manifold feeding the drip lines to the CropManage strip. Soil samples to three feet deep were collected every 10 days and analyzed for mineral nitrogen over the course of the growing cycle to account for nitrogen in the second foot of soil for making N fertilizer application decisions. In 2015 we conducted two trials, and we applied less N than the grower standard in both trials (Table 10). However, at Site 1 the grower fertilizer program was already quite moderate, 169 lbs N/A. At Site 5 we applied 88 lbs less N to the CropManage strip based on soil nitrate levels at the first fertilization event (57.4 ppm nitrate-N first foot of soil) and residual soil nitrate at the second fertilization event (25.0 ppm nitrate-N in the second foot of soil) (Table 10). At Site 1 there was higher biomass production and lower N uptake at harvest in the CropManage treatment; commercial yield was lower in the CropManage treatment (Table 11). The CropManage strip was heavily infested by cabbage maggot which may have affected the yield. At Site 5 the CropManage treatment had lower biomass and N uptake at harvest and lower commercial yield. The CropManage treatment harvested earlier than the commercial strip due to a more rapid growth rate which may have caused a greater incidence of heads with hollow heart which were culled and may account for the reduced yield. The large commercial strips were not replicated, so statistical comparison of yields with the grower standard was not possible.

In 2016 we conducted a more detailed evaluation romaine lettuce followed by broccoli rotation. The romaine crop took up 157 lbs N of which 77 lbs N was left behind in the field as crop residue. At harvest, a total of 210 lbs N of residual mineral N were in the top 3 feet of soil for a total of 288 lbs N in the soil and the crop residue (Tables 12 and 13). Following tillage to prepare the field for planting the broccoli crop, mineralization of crop residue and soil organic matter resulted in an increase in mineral nitrogen, and there was 358 to 368 lbs mineral N at the beginning of the broccoli crop (Tables 13). Intensive soil sampling down to three feet was conducted over the broccoli crop cycle; based on these soil test, 161 and 147 lbs fertilizer N were applied to the CropManage and Grower Standard treatments, respectively (Tables 14 and 15).

The results of this study were used to improve the N fertilizer algorithm for broccoli in CropManage. Crop N uptake data were used to more accurately reflect the seasonal N demand of the crop.   Early season soil nitrate-N thresholds were increased from 15 to 20 ppm as shown in Figure 5. Soil N concentration of the second foot depth is weighted in the algorithm approximately 40 to 50 days after planting.

In replicated small plot evaluations conducted just before the commercial harvest began, CropManage took up 347 and the grower standard 316 lbs N/A in crop biomass. The CropManage treatment had a higher yield than the grower standard because it was one week ahead in maturity than the grower standard (Table 16). However, the CropManage treatment had a lower yield than the grower standard practice in the commercial harvest evaluations (Table 17). The broccoli crop in the CropManage treatments in 2015 and 2016 grew differently than the grower standard and matured earlier. In 2015 we installed watermark tension sensors at Site 5 which showed that the CropManage treatment was irrigated more evenly than the grower standard (Figures 6 and 7). The grower standard treatment suffered significant soil moisture stress between irrigations; in prior studies, we have observed that when vegetables such as broccoli and lettuce are stressed for water between irrigations, the growth rate declines significantly during those periods. The differences in irrigation strategies between the two treatments probably accounts for why the CropManage treatments at Site 5 in 2015 and in the 2016 evaluation were a week ahead in maturity than the grower standard. Unfortunately for the purposes of this experiment, the difference in the growth rate affected the commercial harvest of the CropManage strips which was primarily timed to harvest the bulk of the field and may have reduced the commercial yield in the CropManage strips.

In summary, these studies showed that broccoli rotations can scavenge residual soil nitrate from prior crops and effectively reduce the risk of nitrate leaching. However, the levels of residual soil nitrate at the start of the broccoli crop cycle need to be moderate for broccoli to effectively scavenge nitrate from the soil. These results indicate that the nitrogen applications to the prior crop need to be carefully managed to finish the crop with low to moderate levels of soil nitrate for the broccoli rotation to effectively take up the residual soil nitrate. Management of the N in the prior lettuce crop can be more effectively managed by use of the nitrate quick test to account for residual soil nitrate, accounting for nitrate levels in the irrigation water and adjusting fertilizer rates accordingly. In general, growers use moderate levels of fertilizer on broccoli crops, but these studies indicate that broccoli roots proliferate the 2nd foot of soil by about 50 days after seeding and that soil samples of the 2nd foot of soil taken at this time can help determine if late-season fertilizer applications are needed to finish out the crop. About 1/3 of the N taken up by the broccoli crop during the growing season is removed from the field in the harvested product; as a result, broccoli routinely returns 200-250 lbs N to the soil in the crop residue. We observed that a large portion of this N is mineralized following incorporation within four weeks. The nitrate mineralized from broccoli crop residue can be utilized by subsequent crops if careful irrigation management and soil testing to account for the residual soil N occur. Nitrate released from broccoli residue incorporated prior to winter fallow is at risk for leaching with winter rains. However, it could be effectively captured using winter-grown cover crops.

Table 1. 2014. N application by depth evaluation: Yield, tissue N and biomass N on the first harvest date and nitrogen use efficiency of the treatments

Treatment	Combined Yield (three harvests)				18-Sep		23-Oct		Nitrogen use efficiency[1]
	marketable heads (No. A)	marketable weight (lbs/A)	cull heads (No. A)	cull wt weight (lbs/A)	petiole NO_3-N ppm	leaf blade %N	Whole plant %N	Whole plant lbs N/A	
Untreated	3,103.7	1,037.7	11,107.8	2,764.3	2,958	3.25	1.54	71.0	---
Standard	22,542.3	8,145.3	8,494.2	2,890.2	10,655	5.45	2.45	137.5	44.3
12” drip tape	16,825.1	6,927.8	7,840.8	2,600.6	7,340	4.41	2.58	154.8	55.9
18” drip tape	18,948.6	7,505.1	7,514.1	2,624.0	5,740	4.13	2.36	136.9	43.9
24” drip tape	10,944.5	4,271.4	8,330.9	2,715.7	5,395	4.05	2.13	122.8	34.5
Pr>F treat	<0.0001	0.0001	0.4383	0.9793	0.0012	0.0031	0.0013	0.0001	0.1150
$LSD_{0.05}$	5,749.9	2,306.6	NS	NS	2,872	0.89	0.41	25.1	NS

1 – calculated by subtracting the N content of the untreated control from the N content of the treatment and dividing by the amount of N applied to the treatment (150 lbs N/A)

Table 2. 2015. N application by depth evaluation: Combined yield of two harvests (October 21 and 27), crop biomass (October 27), and tissue samples on September 8 and 18.

Treatment	Combined Yield (two harvests)				Crop Biomass October 27				Sept 8	Sept 18
	marketable heads No./A	marketable heads lbs/A	cull heads No./A	cull wt weight lbs/A	Fresh wt (tons/A)	Dry wt (lbs/A)	%N in tissue	Crop N uptake lbs N/A	leaf blade %N	leaf blade %N
Untreated	81.7	17.6	15,436.6	2,659.1	15.6	4,805.2	1.29^{C}	61.6^{B}	3.03	2.15
Standard	15,109.9	4,942.7	21,888.9	4,876.9	26.9	6,067.4	2.49^{A}	150.1^{A}	4.81	3.94
12” drip tape	11,979.0	4,092.9	18,703.6	4,138.5	23.7	5,444.3	2.41^{A}	131.4^{A}	3.77	3.01
18” drip tape	10,862.8	3,869.3	18,540.2	4,307.8	26.3	5,934.9	2.36^{A}	139.7^{A}	3.24	2.96
24” drip tape	3,512.0	1,117.5	18,785.3	4,287.1	21.5	5,746.9	1.75^{B}	99.9^{B}	2.95	2.65
Pr>F treat	<0.0001	<0.0001	0.1981	0.0038	<.0001	0.0616	<.0001	0.0003	0.0030	<0.0001
$LSD_{0.05}$	2,671.3	1081.9	NS	965.9	3.4	NS	NA[1]	NA[2]	0.86	0.28

1 – blocked ANOVA performed on $\log_{10}(x+1)$ transformed data; 2 – rank-analog of Friedman’s test performed.

Table 3. 2014. Soil nitrate-N (mg/kg soil) by depth over the crop cycle

Treatment	NO3-N (mg/kg soil)							
	depth (ft)	July 18[1]	Aug. 22	Sept. 11[2]	Sept. 18	Sept. 26[3]	Oct. 13[3]	Nov. 3[4]
Untreated	0-1	12.4	5.1	1.9	3.3	1.1	1.1	0.9
	1-2	7.2	10.7	2.3	7.1	1.3[C]	1.3	1.8
	2-3	7.5	8.3	2.0	5.7	4.5	1.2[C]	1.5
Standard	0-1	12.4	5.7	1.9	8.2	2.2	1.1	1.5
	1-2	7.2	11.2	2.3	8.9	1.8[C]	1.2	1.1
	2-3	7.5	7.8	2.0	7.6	2.5	2.3[BC]	1.3
12" drip tape	0-1	12.4	9.2	-	6.8	1.8	3.3	1.7
	1-2	7.2	12.3	-	17.3	6.0[AB]	2.8	1.1
	2-3	7.5	8.1	-	7.1	8.5	6.5[AB]	4.4
18" drip tape	0-1	12.4	7.5	-	6.1	3.1	1.9	1.6
	1-2	7.2	9.5	-	17.1	9.3[A]	2.1	1.5
	2-3	7.5	6.3	-	9.9	15.8	9.9[A]	4.8
24" drip tape	0-1	12.4	4.3	-	8.3	1.5	1.6	2.0
	1-2	7.2	9.0	-	13.2	3.7[BC]	1.1	1.4
	2-3	7.5	7.0	-	6.8	9.3	2.4[BC]	2.9
0-1 ft	Pr>F treat	NA	0.6207	NA	0.7000	0.2559	0.0859	0.6058
	Pr>F block	NA	0.6443	NA	0.7370	0.0063	0.9188	0.0802
	LSD 0.05	NA	NS	NA	NS	-	NS	NS
1-2 ft	Pr>F treat	NA	0.9175	NA	0.6059	0.0108	0.4179	0.5767
	Pr>F block	NA	0.594	NA	0.9951	0.1945	0.6488	NA
	LSD 0.05	NA	NS	NA	NS	4.1077	NS	-
2-3 ft	Pr>F treat	NA	0.8233	NA	0.4753	0.1438	0.0125	0.1874
	Pr>F block	NA	0.0582	NA	0.581	0.7855	0.7446	0.3435
	LSD 0.05	NA	NS	NA	NS	NS	-	NS

1-Composite baseline soil sample; 2-composites of untreated and standard treatments only; 3-blocked ANOVA performed on $\log_{10}(x+1)$ transformed data for Sept. 26 1-ft depth and Oct. 13 3-ft depth; 4-rank analog of Friedman's test used for 1-2 ft depth, Reported means are for original data with superscripts to indicate mean separation

Table 4. 2015. Soil nitrate-N (mg/kg soil) by depth over the crop cycle

Treatment	NO3-N (mg/kg soil)						
	depth (ft)	Aug 17	Sept 3	Sept 10	Sept 22	Oct 6	Nov 6
Untreated	0-1	15.4	4.2	9.6	1.8	0.3	0.0
	1-2	9.0	7.9	5.9	3.5	1.1	0.0
	2-3	5.2	4.8	1.8	3.7	1.2	0.0
Standard	0-1	11.9	7.3	8.1	3.8	1.3	0.4
	1-2	8.9	10.0	5.8	2.9	2.5	0.1
	2-3	6.3	6.4	4.9	6.9	3.4	0.0
12” drip tape	0-1	19.0	9.6	6.8	2.4	1.4	0.0
	1-2	11.6	11.1	7.8	8.8	4.8	0.4
	2-3	8.7	6.9	4.1	14.2	3.7	1.5
18” drip tape	0-1	15.5	7.8	3.7	5.3	0.4	0.6
	1-2	8.0	9.7	15.0	16.4	1.4	0.0
	2-3	6.0	7.2	6.4	17.2	11.2	0.0
24” drip tape	0-1	16.1	9.1	4.9	3.1	2.2	0.0
	1-2	6.0	9.9	6.9	3.4	0.3	0.0
	2-3	7.1	10.1	5.3	11.9	3.1	0.1
0-1 ft	Pr>F treat	0.7295	0.4223	0.308	0.7524	0.6033	0.2490
	Pr>F block	0.3264	0.4793	0.4412	0.7933	0.1476	NA
	LSD 0.05	NS	NS[1]	NS	NS	NS[1]	NS[2]
1-2 ft	Pr>F treat	0.1084	0.5447	0.1555	0.0552	0.1499	0.3627
	Pr>F block	0.057	0.6339	0.1857	0.2958	0.0546	NA
	LSD 0.05	NS	NS	NS	NS	NS	NS[2]
2-3 ft	Pr>F treat	0.2212	0.1748	0.5178	0.5245	0.2759	0.8143
	Pr>F block	0.1342	0.7026	0.6374	0.5571	0.1045	NA
	LSD 0.05	NS	NS[1]	NS	NS	NS[1]	NS[2]

1-blocked ANOVA performed on log10(x+1); 2 – rank-analog of Friedman’s test performed

Table 5. 2014. Analysis of total N available from residual soil N and fertilizer and broccoli N uptake and its impact on N utilization and nitrate leaching

Site	Soil texture	Dry biomass tons/A	Initial soil nitrate-N[1] lbs/A	Total N fertilizer Applied lbs/A	Total available mineral N lbs/A	Biomass N percent	Total N uptake by crop lbs/A	Percent of total N taken up by broccoli	Final soil mineral N[1] lbs/A	Total soil residual and crop uptake N lbs/A	Total water applied	Total Crop ET	Total N potentially leached[2] lbs/A
Site 1	loam	4.37	136.8	178.0	314.8	3.6	313.4	99.5	8.4	321.8	15.7	10.2	23.0
Site 2	loam	4.38	347.3	178.0	525.3	4.2	370.0	70.4	104.9	474.9	15.6	12.4	80.4
Site 3	loam	4.51	125.4	190.0	315.4	3.0	268.1	85.0	17.9	286.0	17.0	11.5	59.4
Site 4	loam	4.76	171.4	190.0	361.4	3.9	369.6	102.2	44.8	414.4	12.0	10.6	-23.0
Site 5	loamy sand	3.53	225.3	240.0	465.3	3.1	220.5	47.4	80.6	301.1	17.4	8.6	194.2

1 – total nitrate-N in the top three feet of soil calculated assuming bulk density = 1.4 (3.8 million lbs/acre ft); 2 – calculated by subtracting total residual soil N and crop uptake plus total mineral N from total initial available mineral N (also includes an estimate of N mineralized from soil organic matter of 30 lbs N/A as part of the total available mineral N)

Table 6. 2015. Analysis of total N available from residual soil N and fertilizer and broccoli N uptake and its impact on N utilization and nitrate leaching

Site	Soil texture	Dry biomass tons/A	Initial soil mineral N[1] lbs/A	Total N fertilizer Applied lbs/A	Total available mineral N lbs/A	Biomass N percent	Total N uptake by crop lbs/A	Percent of total N taken up by broccoli	Final soil mineral N[1] lbs/A	Total soil residual and crop uptake N lbs/A	Total water applied	Total Crop ET	Total N potentially leached[2] lbs/A
Site 1	Sandy loam	4.00	274.0	169.1	443.1	3.98	318.2	71.8	4.6	322.8	23.1	17.3	150.3
Site 2	Sandy loam	4.47	281.7	180.0	461.7	4.25	315.1	68.2	59.7	374.8	16.3	16.1	116.9
Site 3	Sandy loam	3.77	408.5	180.0	588.5	4.61	333.2	56.6	108.3	441.5	---	---	177.0
Site 4	Sandy loam	3.95	163.4	180.0	343.4	4.08	364.3	106.1	20.1	384.4	17.0	12.5	-11.0
Site 5	Silt loam	3.71	431.3	205.9	637.2	3.28	256.2	40.2	191.5	447.7	15.5	12.2	219.5

1 – total nitrate-N in the top three feet of soil calculated assuming bulk density = 1.4 (3.8 million lbs/acre ft 2 – calculated by subtracting total residual soil N (end of season) plus crop uptake from total mineral N (beginning of season); total mineral N (beginning of season) also includes an estimate of N mineralized from soil organic matter of 30 lbs N/A over the course of the season.

Table 7. 2014. Soil nitrate-N (ppm) at three depths in the fertilized and unfertilized treatments over the course of the growing season at five commercial broccoli fields

Site No.	Treatment	Soil Depth	Baseline pre fert.	Baseline pre fert.	Mid growth	Heading	Harvest	Overall Mean
1	No Fertilizer	1st foot	9.5	13.8	18.0	0.2	0.7	8.5
		2nd foot	16.2	15.0	16.9	1.0	0.7	10.0
		3rd foot	10.3	12.7	13.1	5.4	0.8	8.5
	Fertilizer	1st foot	9.5	13.8	15.5	0.7	0.7	8.1
		2nd foot	16.2	15.0	18.4	2.5	0.7	10.6
		3rd foot	10.3	12.7	14.2	8.1	0.9	9.2
2	No Fertilizer	1st foot	19.7	32.2	40.1	5.9	1.3	19.8
		2nd foot	35.2	36.5	41.4	17.6	12.0	28.5
		3rd foot	36.5	43.7	47.9	23.4	19.3	34.2
	Fertilizer	1st foot	19.7	32.2	25.2	5.5	1.3	16.8
		2nd foot	35.2	36.5	38.9	18.9	8.0	27.5
		3rd foot	36.5	43.7	47.1	31.5	18.3	35.4
3	No Fertilizer	1st foot	8.5	13.1	7.0	1.3	1.0	6.2
		2nd foot	11.9	15.8	11.5	1.1	0.9	8.2
		3rd foot	12.6	17.1	15.5	3.0	2.6	10.2
	Fertilizer	1st foot	8.5	13.1	8.1	1.1	1.0	6.4
		2nd foot	11.9	15.8	14.0	2.3	1.0	9.0
		3rd foot	12.6	17.1	18.7	7.8	2.7	11.8
4	No Fertilizer	1st foot	12.6	26.5	17.6	1.1	1.7	11.9
		2nd foot	17.0	24.7	14.4	2.8	1.1	12.0
		3rd foot	15.5	22.6	18.0	8.6	2.5	13.5
	Fertilizer	1st foot	12.6	26.5	21.3	1.9	2.9	13.0
		2nd foot	17.0	24.7	18.1	11.1	2.2	14.6
		3rd foot	15.5	22.6	13.5	16.7	6.7	15.0
5	No Fertilizer	1st foot	22.7	12.8	3.7	3.7	4.0	9.4
		2nd foot	23.3	27.8	7.4	6.6	6.3	14.3
		3rd foot	13.3	22.8	11.3	12.9	7.3	13.5
	Fertilizer	1st foot	22.7	12.8	3.3	2.5	2.8	8.8
		2nd foot	23.3	27.8	14.5	5.3	3.1	14.8
		3rd foot	13.3	22.8	16.0	8.6	15.3	15.2

Table 8. 2015. Soil nitrate-N (ppm) at three depths in the fertilized and unfertilized treatments over the course of the growing season at five commercial broccoli fields

Site No.	Treatment	Soil Depth	Baseline pre plant ppm	Early growth 30 days ppm	Mid growth 50-55 days ppm	Heading 65-70 days ppm	Harvest 84-99 days ppm	Overall Mean ppm
1	0 lbs N/A	1st foot	57.2	16.5	6.2	2.6	0.8	16.7
		2nd foot	11.5	24.2	10.8	19.0	0.0	13.1
		3rd foot	3.4	13.2	12.1	29.4	1.9	12.0
	169.1 lbs N/A	1st foot	57.2	19.0	8.3	37.3	0.5	24.5
		2nd foot	11.5	24.6	7.4	39.3	0.0	16.6
		3rd foot	3.4	12.8	9.5	16.1	0.7	8.5
2	0 lbs N/A	1st foot	26.6	14.7	0.8	0.1	0.6	8.5
		2nd foot	23.9	23.3	5.1	0.7	0.8	10.8
		3rd foot	23.0	21.9	17.2	14.0	4.6	16.1
	180 lbs N/A	1st foot	26.6	12.6	4.7	5.3	1.0	10.0
		2nd foot	23.9	22.0	12.3	9.4	4.8	14.5
		3rd foot	23.0	31.9	18.3	15.8	9.9	19.8
3	0 lbs N/A	1st foot	54.0	46.6	2.1	1.3	1.7	21.1
		2nd foot	32.0	31.2	14.4	5.4	3.4	17.3
		3rd foot	21.5	33.4	34.2	17.8	12.3	23.8
	180 lbs N/A	1st foot	54.0	49.5	27.1	1.2	10.6	28.5
		2nd foot	32.0	28.0	17.2	8.5	9.0	18.9
		3rd foot	21.5	31.0	20.2	15.0	8.9	19.3
4	180 lbs N/A	1st foot	18.1	5.4	0.6	---	0.2	6.1
		2nd foot	13.2	9.8	2.6	---	0.3	6.5
		3rd foot	11.7	12.7	9.2	---	4.8	9.6
5	0 lbs N/A	1st foot	52.9	9.3	3.4	7.8	10.9	16.9
		2nd foot	23.8	23.0	18.8	4.3	2.3	14.4
		3rd foot	36.8	---	33.6	17.2	11.8	24.8
	205.9 lbs N/A	1st foot	52.9	11.2	7.8	23.4	29.3	24.9
		2nd foot	23.8	19.9	28.2	10.9	3.4	17.2
		3rd foot	36.8	---	22.7	18.6	17.7	23.9

Table 9. 2014. Effect of temperature, concentration of N in residue and quantity of N added to soil on the rate of mineralization of N from broccoli crop residue

Soil Type	Incubation temperature °C	Percent N in residue	Mean percent of initial N in mineral form on three dates		
			2 week incubation	4 week incubation	8 week incubation
Coarse sandy loam	15	5.04	25	60	54
	15	3.75	19	42	44
	20	5.04	37	60	65
	20	3.75	38	41	51
	25	5.04	36	64	70
	25	3.75	28	42	53
Loam	15	5.04	41	62	60
	15	3.75	16	45	42
	20	5.04	46	60	58
	20	3.75	25	38	38
	25	5.04	46	72	55
	25	3.75	20	49	38

Table 10. 2015. Soil nitrate-N (ppm) at three depths in the CropManage and grower standard treatments.

Trial	Treatment	Soil depth	Baseline pre plant ppm	Early growth 30 days ppm	Mid growth 50-55 days ppm	Heading 65-70 days ppm	Harvest 84-99 days ppm	Overall Mean ppm	Water applied inches	Total N in irrigation water lbs N/A	Fertilizer N applied lbs/A
Site 1	CropManage	1st foot	55.0	18.2	5.6	22.7	0.5	20.4	20.4	147.3	153.8
		2nd foot	9.3	17.0	14.1	4.7	0.7	9.2			
		3rd foot	3.3	10.8	13.1	8.9	1.9	7.6			
	Standard	1st foot	57.2	19	8.3	37.3	0.5	24.5	23.1	165.0	169.1
		2nd foot	11.5	24.6	7.4	39.3	0.0	16.6			
		3rd foot	3.4	12.8	9.5	16.1	0.7	8.5			
Site 5	CropManage	1st foot	57.4	10.4	14.7	3.2	19.0	21.0	16.0	73.2	117.6
		2nd foot	21.4	30.1	25.0	4.5	1.5	16.5			
		3rd foot	33.8	---	31.3	27.2	15.4	26.9			
	Standard	1st foot	52.9	11.2	7.8	23.4	29.3	24.9	15.5	71.0	205.9
		2nd foot	23.8	19.9	28.2	10.9	3.4	17.2			
		3rd foot	36.8	---	22.7	18.6	17.7	23.9			
	Unfertilized	1st foot	52.9	9.3	3.4	7.8	10.9	16.9	15.5	71.0	0.0
		2nd foot	23.8	23.0	18.8	4.3	2.3	14.4			
		3rd foot	36.8	---	33.6	17.2	11.8	24.9			

Table 11. 2015. Dry biomass of CropManage vs standard and unfertilized treatments.

Trial	Treatment	Early growth 30 days		Mid growth 50-55		Heading 65-70		Harvest 84-99		Commercial Yield Lbs/A
		Dry biomass lbs/A	Nitrogen Uptake lbs/A	Dry biomass lbs/A	Nitrogen Uptake lbs/A	Dry biomass lbs/A	Nitrogen Uptake lbs/A	Dry biomass lbs/A	Nitrogen Uptake lbs/A	
Site 1	CropManage	236.6	14.8	2,811.47	125.90	6,645.8	249.1	8,795.9	294.8	12,896.6
	Standard	263.6	16.5	3,189.59	141.81	6,689.1	253.9	7,998.6	318.2	13,933.6
Site 5	CropManage	875.6	44.1	2,237.9	114.4	5,892.1	251.3	7,004.6	302.3	7,745.6
	Standard	773.3	39.8	2,436.3	128.4	6,737.1	316.8	7,420.1	315.0	8,067.6
	No Fertilizer	---	---	---	---	---	---	7,160.3	295.5	---

Table 12. 2016. Mineral nitrogen in soil over the crop cycle of romaine

Total soil mineral N (mg/kg soil)										
depth feet	Feb 10	Mar 4	Mar 9	Mar 16	Mar 31	Apr 4	Apr 27	May 5	May 27	Jun 8
1	36.0	44.1	17.4	24.3	19.7	27.2	18.0	15.6	10.2	11.0
2	44.4	43.8	36.7	40.7	36.2	40.7	32.7	21.1	17.0	16.1
3	27.3	29.6	39.1	41.3	44.8	50.6	50.1	36.9	36.9	28.4

Table 13. 2016. Grower Standard: Evaluation of N balance in prior lettuce crop and following broccoli crop

	Romaine crop				Broccoli crop						
Treatment	Crop harvest biomass N lbs/A	Crop residue biomass N after harvest lbs/A	Mineral N after harvest in top 3 feet lbs /A	Total N From lettuce crop lbs/A	Initial mineral N in top 3 feet at planting lbs/A	Total fertilizer N applied lbs/A	Total NO3-N in irrigation water* lbs/A	Total mineral N available for crop growth lbs/A	N uptake by broccoli lbs/A	Percent of total N taken up by broccoli	Mineral N after harvest in top 3 feet lbs /A
Grower Standard	157.0	77.3	210.9	288.2	368.6	147.1	80.0	595.7	316.1	53.1	71.1
Crop Manage	157.0	77.3	210.9	288.2	358.3	161.7	78.3	598.3	347.4	58.1	169.1

Table 14. 2016. Nitrogen fertilizer and irrigation applications to lettuce and broccoli crops

Treatment	Romaine			Broccoli		
	Nitrogen fertilizer Date	Nitrogen fertilizer lbs N/A	Irrigation Acre inch[1]	Nitrogen fertilizer Date	Nitrogen fertilizer lbs N/A	Irrigation Acre inch[2]
Crop manage	April 12	103.0	17.2	Aug 17	44.1	17.10
	April 26	598.9		Aug 22	44.1	
	May 10	58.9		Aug 30	44.1	
	Total	220.8		Sept 12	29.4	
				Total	161.7	
Standard	April 12	103.0	17.2	Aug 3	88.3	17.5
	April 26	598.9		Sept 1	29.4	
	May 10	58.9		Sept 12	29.4	
	Total	220.8		Total	147.1	

1 – 7 sprinkler applications from March 17 to April 4; 13 drip applications from April 18 to May 30;
2 – 10 sprinkler applications from July 12 to July 25; 15 drip applications
(crop manage) and 16 drip applications (standard) from August 10 to October 12

Table 15. 2016. Mineral soil mineral (mg/kg soil) in soil over the crop cycle of broccoli

Treatment	depth (ft)	Jul 6	Jul 27	Aug 2	Aug 10	Aug 16	Aug 26	Aug 29	Sep 7	Sep 12	Sep 19	Sep 30	Oct 5
Crop Manage	1	51.9	32.5	28.8	39.8	13.8	---	16.3	9.2	9.3	15.4	2.1	2.5
	2	16.1	36.6	---	---	---	---	31.5	18.3	22.7	18.2	2.6	9.9
	3	26.3	28.4	---	---	---	---	---	---	31.3	---	---	32.1
Standard	1	47.1	27.0	31.6	35.5	12.4	5.1	5.0	7.6	---	4.0	3.4	2.4
	2	19.7	30.7	---	---	---	27.9	22.0	7.0	---	25.6	1.0	2.0
	3	30.2	30.6	---	---	---	---	---	---	---	---	---	14.3
Unfertilized	1	---	---	---	---	---	5.4	5.6	5.1	---	4.5	---	2.0
	2	---	---	---	---	---	32.2	24.1	9.4	---	2.3	---	2.5
	3	---	---	---	---	---	---	---	---	---	---	---	8.4

Table 16. 2016. Small plot biomass and final yield evaluations.

Treatment	Sept 12				Oct 5				
	Crop plants/A	Dry biomass T/A	N in tissue Percent	Lbs N uptake Lbs/A	Dry biomass T/A	N in tissue Percent	Lbs N uptake Lbs/A	Marketable crowns[1] No./A	Marketable crowns[1] T/A
Crop Manage	47,298	2.234	4.77	212.9	4.123	4.21	347.4	6,534.8	2.006
Standard	79,039	2.247	4.77	214.8	3.697	4.29	316.1	3,267.4	1.148
Unfertilized	---	---	---	---	3.971	3.92	311.3	1,633.7	0.466
Pr>F treat						0.1109	0.3562	0.0539	0.0651
$LSD_{0.05}$						NS	NS	NS	NS

1 – heads greater than 5 inches in diameter

Table 17. 2016. Commercial harvest evaluations (12 beds wide by length of field - 896 feet)

Treatment	Harvest date	Export[1] Boxes/A	Crowns[2] Boxes/A	Florets[3] Boxes/A	Bunches[4] Boxes/A	Total Boxes/S	Total broccoli lbs/A
Crop manage	Oct 6	112	0	23	0	134	2,938
	Oct 11	166	51	1	0	219	4,497
	Oct 17	75	104	19	0	199	3,781
	Total	354	156	43	0	552	11,216
Standard	Oct 10	123	0	40	0	163	3,439
	Oct 17	134	241	6	0	380	7,348
	Oct 21	0	0	0	141	141	2,715
	Total	256	241	46	141	684	13,501

1 – 38 count boxes; 2 – 20 lb boxes; 3 – xx

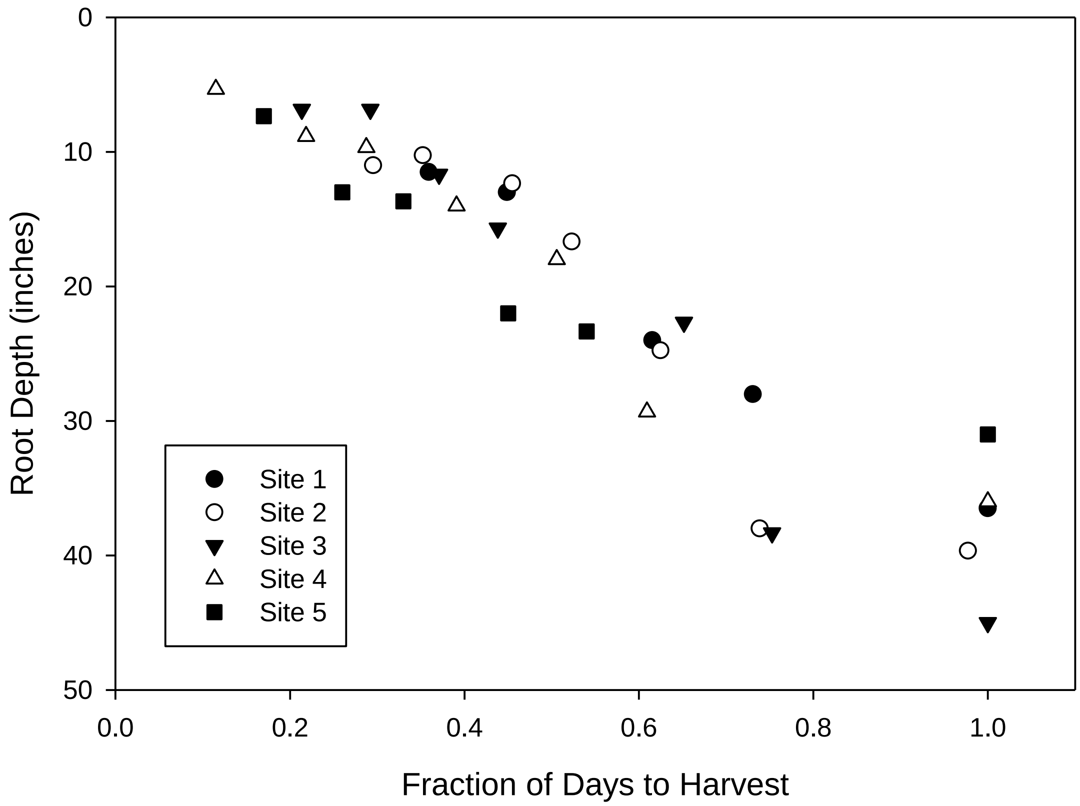

Figure 1. 2014. Fraction of the growing season and rooting depth of broccoli in the five survey sites

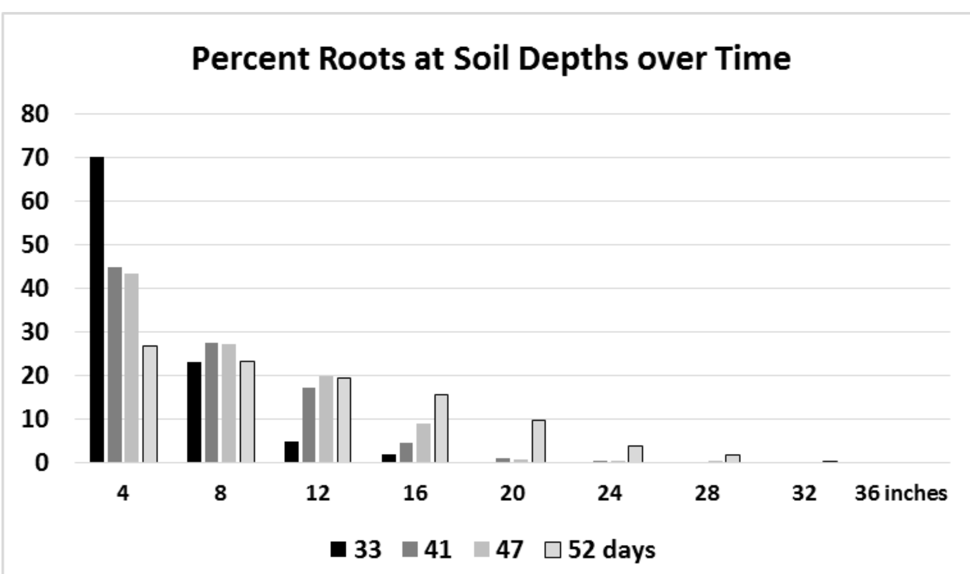

Figure 2. 2015. Percent of roots at various depths in the soil on four evaluation dates

after germination (mean of three fields)

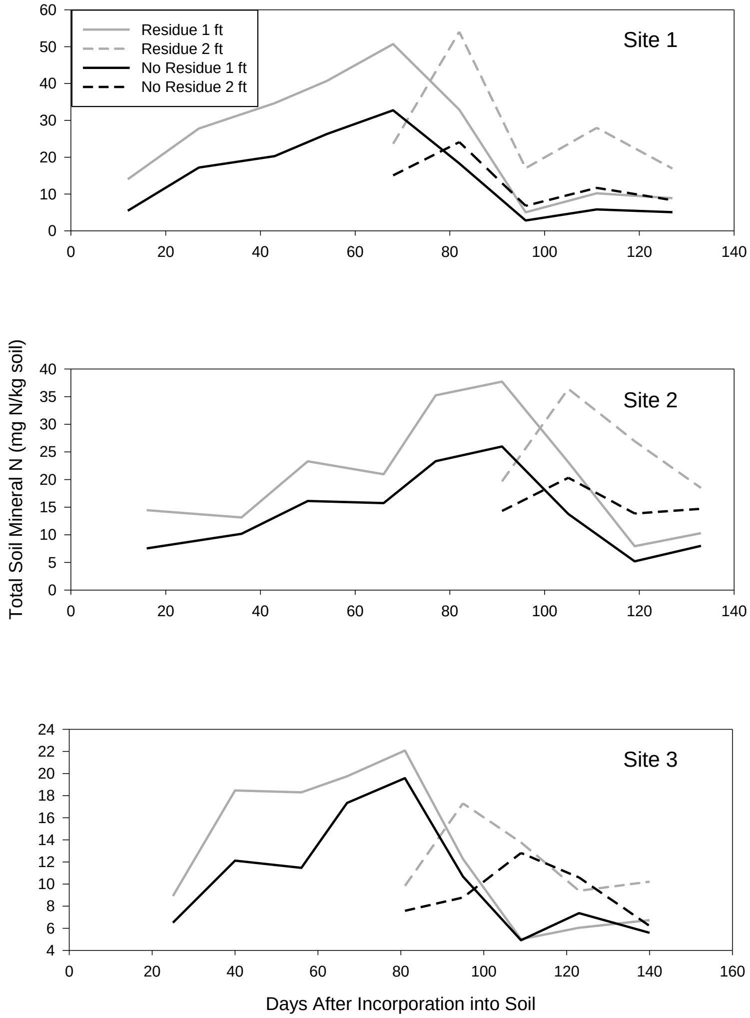

Figure 3. 2015. Soil nitrate levels in plots with and without broccoli residue following harvest in the one and two foot soil depths over 140 days after harvest

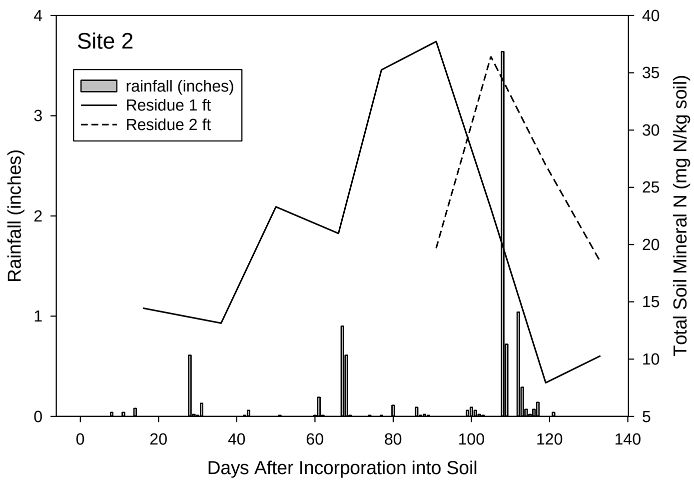

Figure 4. 2015. Details of soil nitrate levels in the soil following
The incorporation of broccoli residue at site 2 in the fall.
Shown in relation with a strong leaching rainfall event.

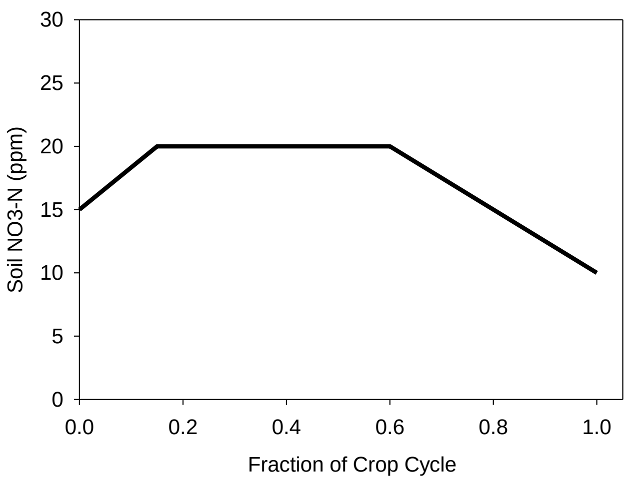

Figure 5. Soil nitrate-N thresholds used in the CropManage N fertilizer recommendation algorithm for broccoli.

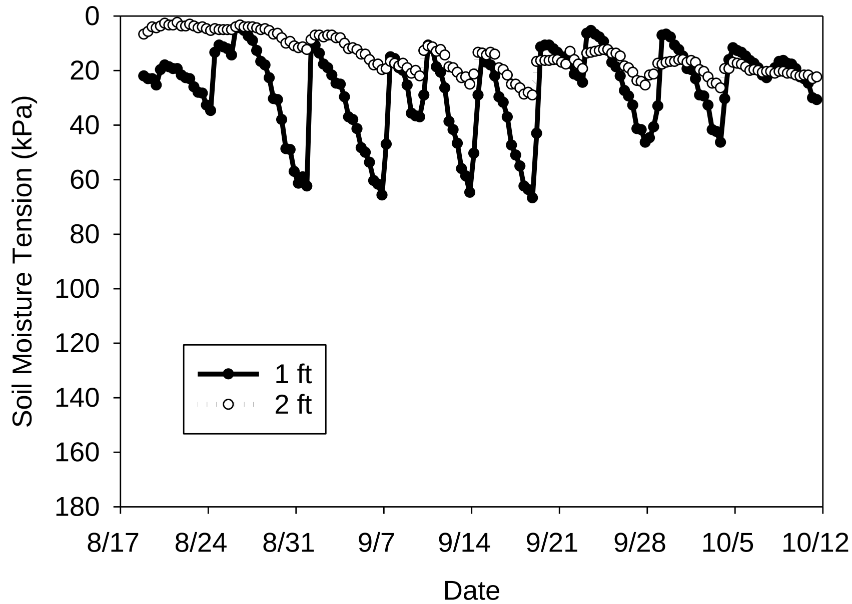

Figure 6. Soil moisture tension at 1 and 2 ft depths, CropManage treatment, 2015 broccoli strip trial.

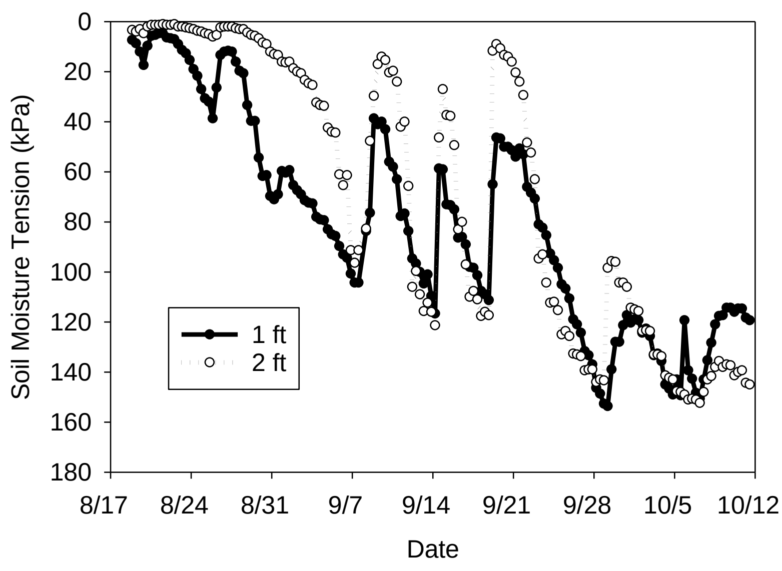

Figure 7. Soil moisture tension at 1 and 2 ft depths, Grower treatment, 2015 broccoli strip trial.

G. DISCUSSION AND CONCLUSIONS

We observed that sufficient broccoli roots proliferate in the second foot of soil and can take up sufficient N to supply crop needs. However, the roots do not reach down to the second foot of soil until approximately 50 days after seeding. The amount of residual soil NO_3-N in the second foot of soil can be measured at this time to better understand the amount of residual soil N available for crop growth. Broccoli roots continue to grow down to 40 inches deep by the end of the crop cycle. Broccoli needs adequate levels of N in the top foot of soil early in the crop cycle to allow the plant to vigorously develop to be able to take advantage of residual soil N at deeper levels in the soil profile later in the crop cycle. A survey of 10 commercial broccoli fields indicated that broccoli was capable of taking up a significant amount of the residual soil N left by a prior lettuce crop. On average broccoli took up 73.3% of all initial soil mineral nitrogen + fertilizer N. At nine of the ten sites, broccoli took up more N than was applied as fertilizer and thereby scavenged N from the soil. However, broccoli was most effective at reducing the risk of nitrate leaching at sites where levels of residual soil nitrate were left by the prior lettuce crop were moderate. For instance it appears that when there is no more than 200 lbs residual soil N/A in the top three feet of soil, broccoli can significantly reduce the risk of nitrate leaching. However, beyond this amount, the system becomes leakier and the risk of nitrate leaching increases. In general, grower broccoli fertilization practices were moderate in the fields surveyed in these studies and provide for the needs of the crop early in the season when sufficient N is needed to develop a vigorous crop capable of scavenging nitrate deeper in the soil profile. Following harvest, broccoli residues contain >200 lbs N/A. The residues typically contain >3% N and mineralize 40-50% of residue N in 4 weeks. After 4 weeks mineralization of N in broccoli residue plateaus. Broccoli crops incorporated into the soil in the summer that are followed by a crop of lettuce can provide much of the N needs of the lettuce. This residual soil N can be effectively monitored with the use of the nitrate quick test. Broccoli residue incorporated into the soil prior to the winter fallow period mineralize over the course of the winter even though soil temperatures may be in the 50's °F. The resulting buildup of residual soil nitrate is at risk for nitrate leaching in significant rain events. These results indicate that broccoli can serve as a best management practice (BMP) for capturing nitrate that otherwise might be lost to leaching, but that care needs to be taken to account for the N in the residues that are returned to the soil.

H. PROJECT IMPACTS

This project provided information on the potential benefits of reducing nitrate leaching by broccoli rotations in the leafy green production areas. It was the first comprehensive examination of the benefits that a rotational cash crop can have on reducing nitrate leaching in an intensive vegetable production system. Given the high value of the land and intensive production schedules, there is little opportunity to fit cover crops into the rotations and this study showed that under certain situations, broccoli can play the role of a cover crop, when initial levels of residual soil nitrate in the top three feet of soil are <200 lbs N/A and fertilizer programs are moderate (<180 lbs N/A). This project provided data to develop and improve the accuracy of algorithms for N in the second foot of soil as a management practice for broccoli production.

I. OUTREACH ACTIVITIES SUMMARY

Meetings:

- Nov 14, 2014; American Society of Agronomy, Long Beach, CA
    - Use of broccoli in rotation with lettuce to reduce nitrate leaching; 50 attendees; R. Smith
- Jan. 13, 2015; Willamette Horticultural Society, Corvallis, OR
    - Role of broccoli rotations in managing nitrogen in vegetable production; 60 attendees; R. Smith
- Feb 3, 2015; Green Valley Farm Supply, Gonzales
    - Nitrogen management of cole crops and vegetables; 65 attendees, R. Smith
- March 26, 2015; Salinas Valley Ag Technology Summit, Gonzales
    - Nutrient management of cool season vegetables, issues and solutions; 45 attendees, R. Smith
- April 21, 2015; Hartnell College Fertilizer Class, Salinas
    - Nitrogen management of vegetables in the Salinas Valley; 35 attendees, R. Smith
- July 30, 2015; Ventura County Horticulture Meeting, Oxnard
    - Nitrogen management of cool season vegetables; 75 attendees; R. Smith
- Feb. 17, 2016; 2016 Irrigation and Nutrient Management Meeting. 97 attendees.
    - Field studies on nitrogen and water management of broccoli; 97 attendees, R. Smith
- Feb. 11, 2016; San Benito County Water District Growers Workshop
    - Nitrogen use by vegetables and nitrogen technology for addressing water quality. 36 Attendees, R. Smith.
- March 28 and 31, 2016. Central coast Groundwater Coalition
    - Nitrogen management of vegetables, 54 attendees, R. Smith.
- April 20, 2016. International Plant Nutrition Institute
    - Nitrogen management challenges of intensive vegetable production systems, 45 attendees, R. Smith
- March 1-2, 2017. Western Nutrient Management Meeting
    - The potential of broccoli in rotations with lettuce to reduce nitrate leaching. 120 attendees, R. Smith.

Publications:

- Smith, R.F., M. Cahn, T. Hartz, T. Love and B. Fararra. 2015. Role of rotations in addressing water quality issues; Monterey County Crop Notes, Jan/Feb.
- Smith, R. M. Cahn, T. Hartz and T. Love. 2016. The ability of broccoli to serve as a best management practice. Monterey County Blog: http://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=20440
- Smith, R.F., M.D. Cahn, T.K. Hartz, P. Love and B. Fararra. 2016. Nitrogen dynamics of cole crop production: Implications for fertility management and environmental protection. HortScience 51:1586-1591.

J. FACT SHEET/DATA BASE TEMPLATE

Contract 13-0268-SA

1. Improving N use efficiency of cool season vegetable production systems with broccoli rotations
2. 13-0268-SA
3. Richard Smith and Michael Cahn, University of California Cooperative Extension, Monterey County and Tim Hartz University of California, Davis
4. January 2014 to June 2016
5. Salinas, CA
6. Monterey, Santa Cruz and San Benito Counties
7. Highlights:
   - These studies showed that broccoli rotations can scavenge residual soil nitrate from prior crops and effectively reduce the risk of nitrate leaching. However, the levels of residual soil nitrate at the start of the broccoli crop cycle need to be moderate for the broccoli crop to effectively scavenge nitrate from the soil (e.g. <200 lbs nitrate-N in the top 3 feet of soil).
   - In a survey of 10 commercial broccoli production fields growers applied moderate amounts of fertilizer (app. 180 lbs N/A) while the crop routinely took up >300 lbs N/A in crop biomass. These observations indicate that broccoli routinely scavenges residual soil NO_3-N from the soil to supply its N needs.
   - Sufficient broccoli roots proliferate in the 2nd foot of soil by about 50 days after seeding. Soil samples taken of the 2nd foot at this time can help determine if there is sufficient residual NO_3-N at this depth of soil to supply the crop until harvest. Accounting for residual soil N in the second foot may provide an opportunity to forgo further fertilizer N applications and help improve nitrogen use efficiency.
   - About 1/3 of the N taken up by the broccoli crop during the growing season is harvested; as a result, broccoli routinely returns 200-250 lbs N to the soil in the crop residue. We observed that 40-50% of residue N mineralizes in four weeks and then the release plateaus.
   - The nitrate mineralized from broccoli crop residue can be utilized by subsequent crops if careful irrigation management and soil testing to account for the residual soil N occur.
   - Nitrate released from broccoli residue incorporated prior to winter fallow is at risk for leaching with winter rains, but could be effectively captured by the use of winter-grown cover crops.
8. Introduction

The cool season vegetable production areas of the Central Coast of California frequently grow more than one crop during the cropping season. As a result of the intensive crop rotations, substantial amounts of residual soil N may remain in the soil following the production of a lettuce crop. Water quality regulations implemented by the Central Coast Regional Water Quality Control Board are challenging growers to evaluate and implement practices to improve the efficiency of applied nitrogen to vegetable crops. These regulations are requiring growers to implement a certified Irrigation and Nutrient Management Plans (INMP) that justify and document N application rates applied to crops. The regulations have created an urgent need for development and implementation of strategies and practices for growers to make progress in improving nitrogen management and making measureable improvements in water quality. Broccoli is grown on 79,950 acres in on the Central Coast and is a key rotational crop for lettuce because it helps to break the cycle of key soilborne diseases. Broccoli has been shown to scavenge nitrate more nitrate from the soil than is typically applied as fertilizer. This project evaluated the role that broccoli rotations can play in reducing nitrate leaching in the cool season vegetable system.

9. Methods/Management

Trials were established at the USDA Spence Research Station, Salinas to evaluate the effect of placement of fertilizer at various depths in the soil on broccoli growth: 0, 12, 18 and 24 inches. 150 lbs N/A was applied to each treatment. Ten commercial broccoli fields planted following a prior lettuce crop were evaluated in 2014-15. Evaluations of the ability of the broccoli crop to take up residual soil N were made. Rooting depth of broccoli was determined by digging soil pits during the crop cycle and measuring the length and density of roots. Broccoli Residue Mineralization Evaluations were conducted in laboratory and field evaluations. Outreach/Demonstration evaluations were conducted in commercial broccoli fields in 2015-16 in which N balance evaluations were made of a broccoli crop grown following a prior lettuce crop.

10. Findings

These studies showed that broccoli rotations can scavenge residual soil nitrate from prior crops and effectively reduce the risk of nitrate leaching. However, the levels of residual soil nitrate at the start of the broccoli crop cycle need to be moderate for the broccoli crop to effectively scavenge nitrate from the soil (e.g. <200 lbs nitrate-N in the top 3 feet of soil). These results indicate that the nitrogen applications to the prior crop need to be carefully managed in order to finish the crop with low to moderate levels of soil nitrate in order for the broccoli rotation to effectively take up the residual soil nitrate. Management of the N in the prior lettuce crop to achieve lower levels of residual soil nitrate can be accomplished by use of the nitrate quick test to account for residual soil nitrate, accounting for nitrate levels in the irrigation water and adjusting fertilizer rates accordingly. In a survey of 10 commercial broccoli production fields we observed that growers use moderate fertilizer applications (app. 180 lbs N/A) while the crop routinely takes up >300 lbs N/A from the soil indicating that the crop scavenges N from the soil to make up this difference. Broccoli roots extend to 40 inches deep by the end of the crop cycle; however, broccoli roots proliferate in the 2nd foot of soil by about 50 days after seeding. Soil samples taken of the 2nd foot at this time can help determine if late-season fertilizer applications are needed to finish out the crop and may provide an opportunity to further improve fertilizer use efficiency. About 1/3 of the N taken up by the broccoli crop during the growing season is removed from the field in the harvested product; as a result, broccoli routinely returns 200-250 lbs N to the soil in the crop residue. We observed that this N is quickly and steadily mineralized following incorporation into the soil. The nitrate mineralized from broccoli crop residue can be utilized by subsequent crops if careful irrigation management and soil testing to account for the residual soil N occur. However, nitrate released from broccoli residue incorporated prior to winter fallow is at risk for leaching with winter rains, but could be effectively captured by the use of winter-grown cover crops. This project provided data to develop and improve the accuracy of algorithms for N in the second foot of soil as a management practice for broccoli production.

K. COPY OF THE PRODUCT/RESULT

Refined algorithms developed by this project for crop growth, nitrogen uptake from both the 1^{st} and 2^{nd} foot of soil and water use are now in the CropManage web based decision support program and are now available for growers to use to effectively fertilize and irrigate broccoli.

UC ANR 8000 series publications will now be developed to provide technical information to assist growers to effectively use broccoli rotations to reduce nitrate leaching in the intensive cool season production area.