A. Project Information
Final Report
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Immobilization of nitrate in winter-fallow vegetable production beds to reduce nitrate leaching

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B. ABSTRACT

In the fall, following broccoli production, residual soil nitrate-nitrogen (N) levels increase when N-rich crop residues are incorporated into the soil. Soil temperatures during the winter fallow period are adequate to allow mineralization of crop residues as well as soil organic matter, which results in a pool of residual soil nitrate-N in winter-fallow beds that is vulnerable to leaching by winter rains. To mitigate leaching losses of this nitrate by winter rains, cover crops could be grown to take up the nitrate and maintain it in their biomass until they are incorporated into the soil the following spring. However, although growers may want to include cover crops in their rotations for the benefits that they provide, conflicts with spring planting schedules and high land rents often preclude their use. As result, cover crops are used on less than 5% of the vegetable production acreage in the Salinas Valley. The application of high carbon (C) amendments to immobilize soil nitrate-N and reduce leaching is an alternative practice to reduce leaching during the winter fallow period. In immobilization, soil microbes utilize labile C and soil nitrate to stimulate rapid growth. As a result of this microbial activity, the pool of soil nitrate is reduced which in turn reduces the risk of nitrate loss by leaching. Central Coast growers commonly apply compost
(commonly with C:N ratios that range from 13 to 20) in the fall to improve soil tilth and health. Given that use of compost is a normal practice, the use of high-carbon amendments could be readily substituted for compost. High carbon amendments are defined by the Central Coast Regional Water Quality Control Board (CCRWQCB) as containing a C:N ratio of >40. They can be sourced from materials such as uncomposted almond shells, olive pomace and ground limbs and trunks of trees. To be effective, high carbon amendments must be ground small enough to allow for the soil microbes to have rapid access decomposable forms of C. In addition, the material must be cheap enough to be economically viable. This project builds on prior research

that showed that almond shells ground to 2 mm and liquid glycerol were effective in reducing levels of residual soil nitrate in the soil and associated nitrate leaching. However, these materials were too expensive to be utilized by commercial growers. This project evaluated the efficacy of locally sourced woody material ground to pass through a 3/8 inch screen for immobilizing soil nitrate. The available material sourced from the Marina Landfill was too recalcitrant and did not effectively immobilize soil nitrate quick enough. Given that almond shells are abundant and have been shown to be effective, we decided to reevaluate almond shells that were unground or ground to ¼ to ½ inch particle size. Optimal particle sizes for immobilization are in the ¼ to ½ inch range and they are capable of immobilizing soil nitrate quickly. The cost of this material still remains high for widespread use by growers.

C. INTRODUCTION

In prior studies we determined that almond shells ground to 2 mm, were highly effective at immobilizing soil nitrate that builds up in the soil following the incorporation of broccoli in fall prior to the winter fallow. However, grinding almond shells to this small size adds substantial cost that makes it too expensive for widespread adoption by growers. This project initially evaluated a local source of C called Forest Mulch which is made from trees ground to pass through a 3/8 inch screen (the smallest screen used by the company). In a commercial-scale test and in laboratory incubations Forest Mulch was not sufficiently labile to immobilize sufficient soil nitrate to reduce nitrate leaching. Given the highly labile nature of the carbon in almond shells and their relative abundance in the state, we began evaluating other approaches to their use: unground and ground to ¼ to ½ inch particle size. More finely ground almond shells immobilize a greater percentage of nitrate more rapidly. However, small particles also can rapidly begin to mineralize the nitrate that was captured by immobilization. Incubation studies were conducted to find the "sweet spot" in the size of almond shell particles. Based on our initial evaluations the CCRWQCB granted a nitrogen removal discount of 30 lbs N/A credit for the use of high carbon amendments. However, the criteria to obtain the 30 lbs N/A credit are based on grinding the almond shells to 2 mm particle sizes which is effective but not economically within reach for widespread grower adoption. This project evaluated alternative materials and particle sizes and evaluated the economics of the use of high-carbon amendments for reducing nitrate leaching in winter fallow vegetable crop production beds.

D. OBJECTIVES

1. Identify and select locally sourced high C:N ratio green waste materials and conduct laboratory incubations of them at different particle sizes to determine the levels of N immobilization that they provide of cole crop residues.
2. Conduct large scale field trials with cooperating growers in commercial vegetable production fields evaluating the impact of materials identified in objective 1 on nitrate leaching during the winter fallow
3. Evaluate the magnitude and longevity of the impact of the high C:N materials on subsequent crop production, and determine if there is a negative effect of these materials on the yield and N fertilizer requirement of the subsequent vegetable crops
4. Develop algorithms for CropManage that can provide estimates of immobilization based on C:N ratio of the amendment and the quantity added to the soil
5. Conduct economic analysis of the cost of the use of high C:N amendments
6. Conduct grower outreach through blogs, trade journal articles and grower meetings.

E. METHODS

Identify and select locally sourced high C:N ratio green waste materials and conduct laboratory incubations of them at different particle sizes to determine the levels of N immobilization that they provide of cole crop residues:

2020-2021: We identified a triple screened uncomposted wood waste material sourced from a composting/soil amendment company based at the Marina Landfill (Keith Day Trucking) which was made from trees and shrubs called Forest Mulch which is ground to 3/8 inch particle size which is the smallest screen that they use. This material seemed like a good candidate to evaluate because it was local, inexpensive and abundant. It was included in the 2020-2021 and 2021-2022 commercial field trials as well as in the 2020 incubation study. However, it became apparent that this material was too recalcitrant to effectively immobilize soil nitrate. As a result, we decided to reevaluate almond shells as the key material for immobilizing soil nitrate. This decision was based on the 2020 incubation study which showed that almond shells are highly labile and are an excellent material to use for immobilizing soil nitrate. In the 2021-2022 commercial field study and in the 2021-2022 and 2022-2023 incubation studies we evaluated various particle sizes of almond shells. The rational for this decision was to see if almond shells that were unground or partially ground could be effective in immobilizing soil nitrate. If so, this would reduce the cost of using almond shells. Our earlier evaluations with grinding almond shells to 2 mm particle size was highly effective in immobilizing soil nitrate but added a great deal of cost. If unground almond shells or almond shells ground to ¼ or ½ inch particle size could be used, the almond shells might be more affordable, and this practice could achieve greater adoption by growers. Immobilization studies of various materials and particle sizes of almond shells were conducted in the Muramoto Lab at UCSC.

Conduct large scale field trials with cooperating growers in commercial vegetable production fields evaluating the impact of materials identified in objective 1 on nitrate leaching during the winter fallow: 2020-2021: Four rates of Forest Mulch were evaluated in a replicated commercial field trial. Plots were 100 feet long and 30 feet wide (the width of the throw by a commercial amendment applicator) and replicated four times. Soil samples from five locations in each plot were collected at one-foot increments to three feet deep once a month starting at the initiation of the trial and continuing through the winter fallow and the crop cycle of the subsequent lettuce crop grown the following spring (October 2020 to May 2021). The biomass and N uptake of the subsequent lettuce crop was evaluated at the rosette stage and at harvest.

2021-2022: Based on initial indications that Forest Mulch was too recalcitrant to quickly and effectively immobilize residual soil nitrate, the commercial trial only included two rates of this material as well as two rates of unground almond shells (unground to reduce the cost of the material). The materials were applied as described above. The biomass and N uptake of the subsequent lettuce crop was conducted as described above.

2022-2023: A large-scale commercial trial was conducted with almond shells ground to ¼ inch particle size applied at 0, 5 and 10 T/A. The field was split and the materials were incorporated with one or two passes of a chisel to evaluate the impact of more aggressive incorporation of the almond shells on their efficacy of immobilizing soil nitrate. However, this plot was terminated in March due to flooding of the Salinas River that inundated the plot.

Evaluate the magnitude and longevity of the impact of the high C:N materials on subsequent crop production, and determine if there is a negative effect of these materials on the yield and N fertilizer requirement of the subsequent vegetable crops:
2020-2021: A small plot study was conducted to evaluate rates of starter fertilizer needed to overcome residual immobilization soil nitrate from applications of high-carbon amendments. Plots were one 80-inch wide bed by 30 feet. Forest mulch was applied at 0, 5, 10, and 15 T/A prior to seeding the lettuce and four rates of 6-16-0 starter fertilizer were applied post planting over the seedline as a starter fertilizer.
2021-2022: A starter fertilizer trial was conducted with unground almond shells applied at 20 T/A was conducted as described above.

Develop algorithms for CropManage that can provide estimates of immobilization based on C:N ratio of the amendment and the quantity added to the soil: Data to achieve this objective has been collected and efforts to add immobilization to CropManage are underway.

Conduct economic analysis of the cost of the use of high C:N amendments: Cost comparisons of Forest Mulch and almond shells materials, grinding and transportation costs was conducted by interviewing a soil amendment/trucking company in 2022.

Conduct grower outreach through blogs, trade journal articles and grower meetings: Presentations and articles written are summarized below.

F. DATA/RESULTS

Identify and select locally-sourced high C:N ratio green waste materials and conduct laboratory incubations of them at different particle sizes to determine the levels of N immobilization that they provide of cole crop residues:
2020-2021: Four rates of Forest Mulch material with a C:N Ratio of 37.3 (Table 1) were evaluated in a commercial field evaluation in a growers field. The material was applied at 0, 5, 10, 15 and 20 T/A. There was little reduction of soil nitrate levels in the first, second or third foot of soil (Figures 1, 2, and 3, respectively) in any of the treatments. In addition, in the incubation study, the wood fines material had low immobilization (Figure 4). These results caused us to reconsider the use of a high-carbon material made from wood. The smallest particle size available for this triple screened material was 3/8 inch. It is possible that a material that is ground to a finer particle size may be more active, but it was not available. 2021-2022: We evaluated unground almond shells at 5 and 10 T/A (C:N 84.4) with Forest Mulch at 5 and 10 T/A (C:N 96.5) in a commercial-scale trial. Almond shells at 10 T/A and Forest Mulch at 10 T/A had the lowest nitrate in the top foot on two dates before a significant rain event (Figure 5). Forest Mulch had a higher C:N ratio than in the prior year. There is a trend indicating that almond shells might have had lower nitrate in the second foot and third foot in this trial (Figures 6 and 7), but in general the data is not conclusive. In the incubation study almond shells ground to 2 mm particle size had quick immobilization (Fig. 8), but also began to remineralize the nitrate quickly after peak immobilization. One quarter to ½ inch particle sized almond shells immobilized nitrate quickly and remineralized it slower rate than the 2 mm particle sized almond shells (Figure 9). This brings up a nuance in this practice. Ideally, almond shells would immobilize and sequester nitrate for the winter fallow (6-8 weeks) and then begin to mineralize after the risk of leaching rains had diminished. Rapid immobilization is desirable to

assure that the process is underway when the risk of leaching rains begins. Delayed mineralization of nitrate may necessitate the need for addition starter fertilizer to reduce the risk of affecting the growth of the crop early in the crop cycle. <u>2022-2023:</u> The study evaluated a 0, 5, and 10 T/A rate of applied almond shells ground to ¼ inch particle size in a large-scale commercial field. The material was applied in one strip the length of the field (30 feet wide by 900 feet long) which allowed us to evaluate one pass with a soil chisel vs two passes to incorporate the material into the soil (the thoroughness of incorporation of the high-carbon amendments may have been an issue in the prior trials). Prior to the field getting flooded by the Salinas River in March 2023, there was reduced residual nitrate in the 10 T/A almond shell treatment that was incorporated with two passes of a soil chisel (Figure 10). There is a trend indicating less soil nitrate in the second foot of soil in the second foot (Figure 11) but no differences among the treatments was observed at the third foot of soil (Figure 12). No further observations were made after the flooding event in March 2023. Incubations of 5 T/A of almond shells that were unground, or had particle sizes of 2 mm, ¼ and ½ inch size showed that peak immobilization occurred 2 weeks after the initiation of the evaluation (Figure 13). Greater immobilization occurred with smaller particle sizes. Incubations of 10 T/A of almond shells that were unground, or had particle sizes of 2 mm and ½ inch size showed that peak immobilization also occurred 2 weeks after the initiation of the evaluation (Figure 14). Greater immobilization occurred with smaller particle sizes and residual immobilization persisted longer with larger particle size almond shells.

Conduct commercial scale field trials with cooperating growers in commercial vegetable production fields evaluating the impact of materials identified in objective 1 on nitrate leaching during the winter fallow: Soil sampling to three feet in the large-scale commercial trials was discussed above. There was no impact of the amendments on the biomass or N uptake of the subsequent lettuce crop in the 2020-2021 or 2021-2022 trials indicating that residual immobilization was not sufficient to adversely affect the growth of the subsequent lettuce crop in these trials (Table 2, 3, 7 and 8).

Evaluate the magnitude and longevity of the impact of the high C:N materials on subsequent crop production, and determine if there is a negative effect of these materials on the yield and N fertilizer requirement of the subsequent vegetable crops: In the 2020-2021 starter fertilizer trial there was no immobilization and there was no need for starter fertilizer to counteract residual immobilization by the high carbon amendment (Table 4). However, in the 2021-2022 starter fertilizer trial there was greater yield with the use of more starter fertilizer (64 lbs N/A; Table 9). This result stresses the need to increase the rate of starter fertilizer to offset residual immobilization in a situation where a high rate of almond shells was applied (20 T/A).

Develop algorithms for CropManage that can provide estimates of immobilization based on C:N ratio of the amendment and the quantity added to the soil: Realistically, this objective was a bit too ambitious to complete during the timeframe of this project. However, work towards being able to model immobilization is underway and will dovetail with results from the mineralization model being developed by Daniel Geisseler. It is likely to take the form of a calculator to predict soil nitrate levels during and following immobilization by the addition of a high-carbon amendment. Modeling will take into account the amendment, the C:N ratio, rate of application, as well as soil type, temperature and moisture content.

Conduct economic analysis of the cost of the use of high C:N amendments: Cost comparisons of forest mulch compost and almond shells (ground and unground) are shown in Table 5. The costs (including spreading) of the materials tested in these evaluations are as follows: Forest mulch costs $28/ton, ground almond shells cost $80.50/ton and unground almond shells cost $60.50/ton. If a grower budgets $150/acre for compost, they could justify using 5.4 tons/A of forest mulch, 1.9 tons/A of ground almond shells and 2.5 tons/A of unground almond shells.

Conduct grower outreach through blogs, trade journal articles and grower meetings: Five presentations and three publications based on this project were completed (see below).

Table 1. 2020-2021. Forests Mulch amendment analysis

	Percent					
C:N	N	C	P	K	Ca	Mg
37.3	0.571	21.3	0.131	0.61	3.90	0.564

PPM - DTPA extracted					mg/L	meq/L
Na	Zn	Mn	Fe	Cu	B	Cl
1170	55	162	7740	24	0.61	32.4

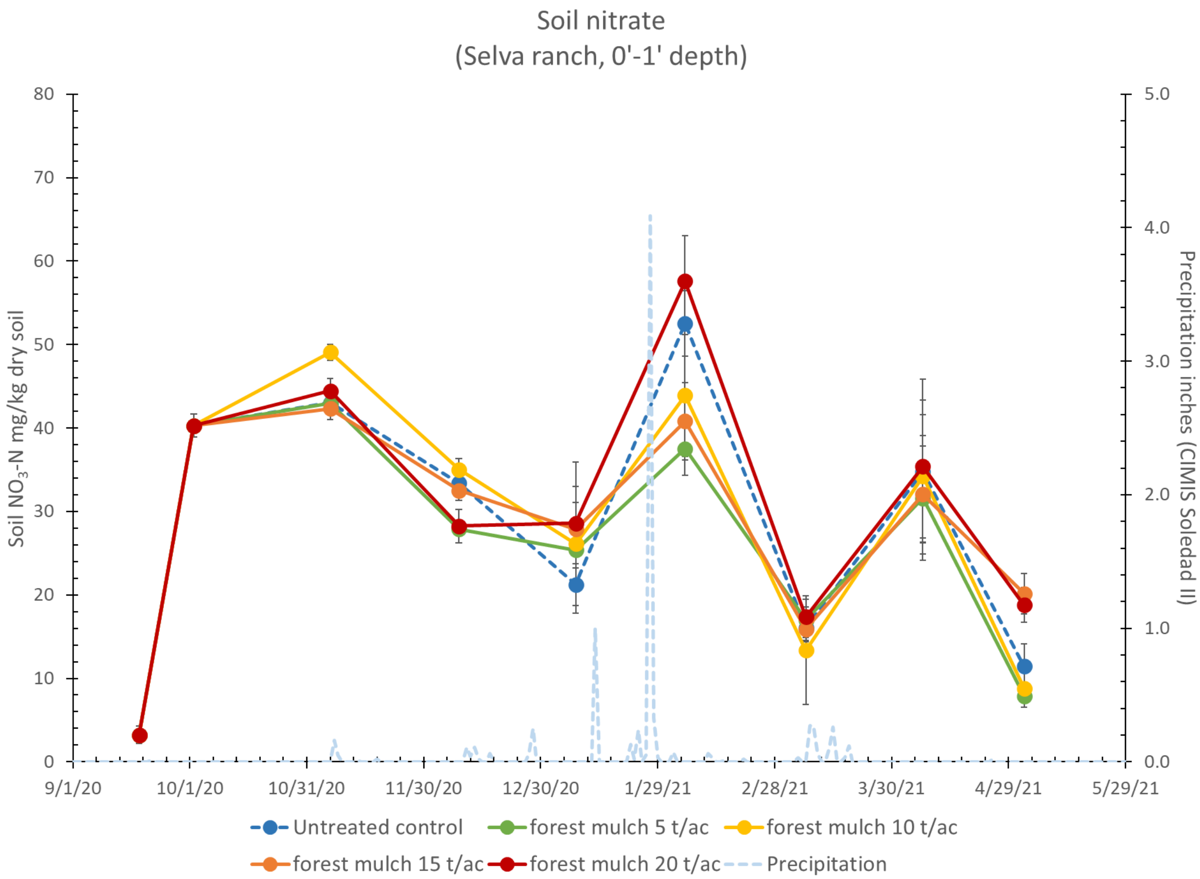

Figure 1. 2020-2021. Impact of various rates of high-carbon compost treatments on soil nitrate levels in the first foot of soil.

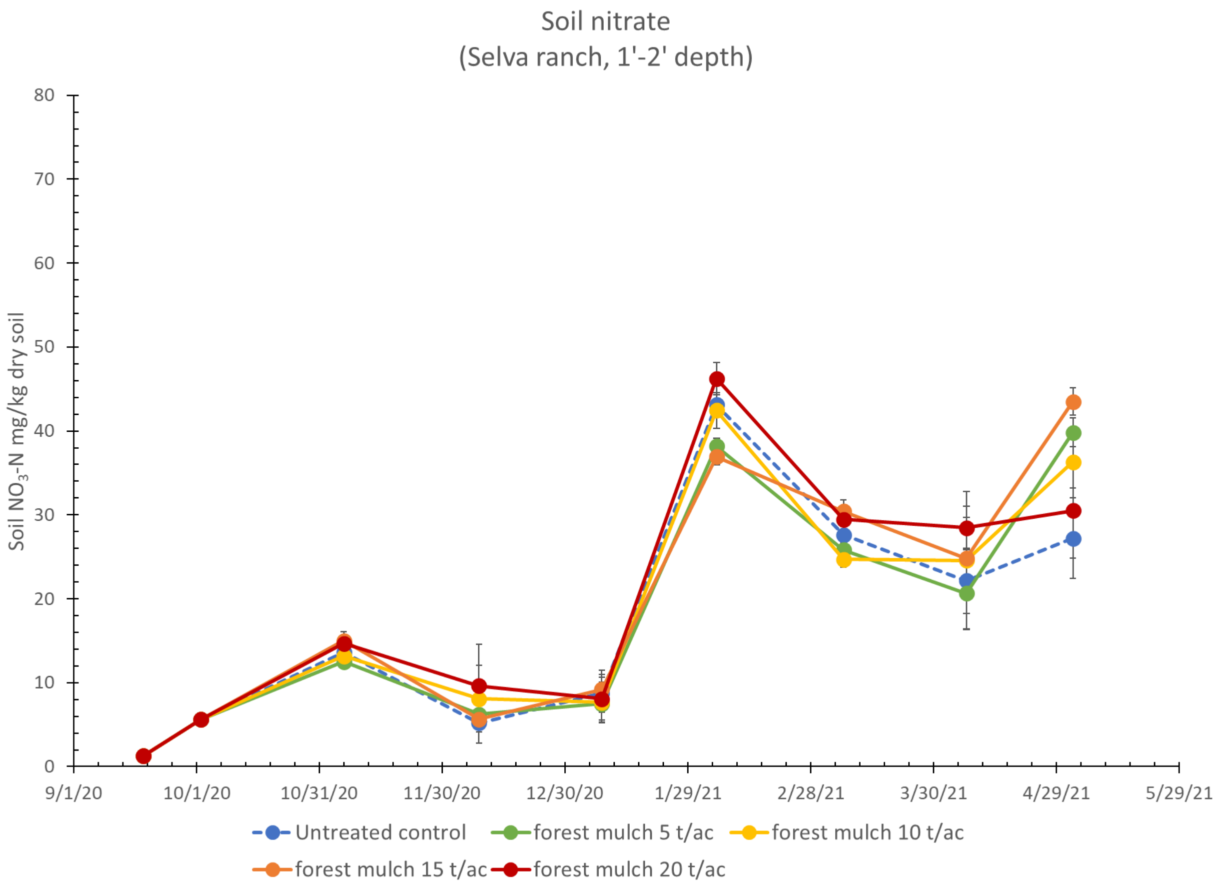

Figure 2. 2020-2021. Impact of various rates of high-carbon compost treatments on soil nitrate levels in the second foot of soil.

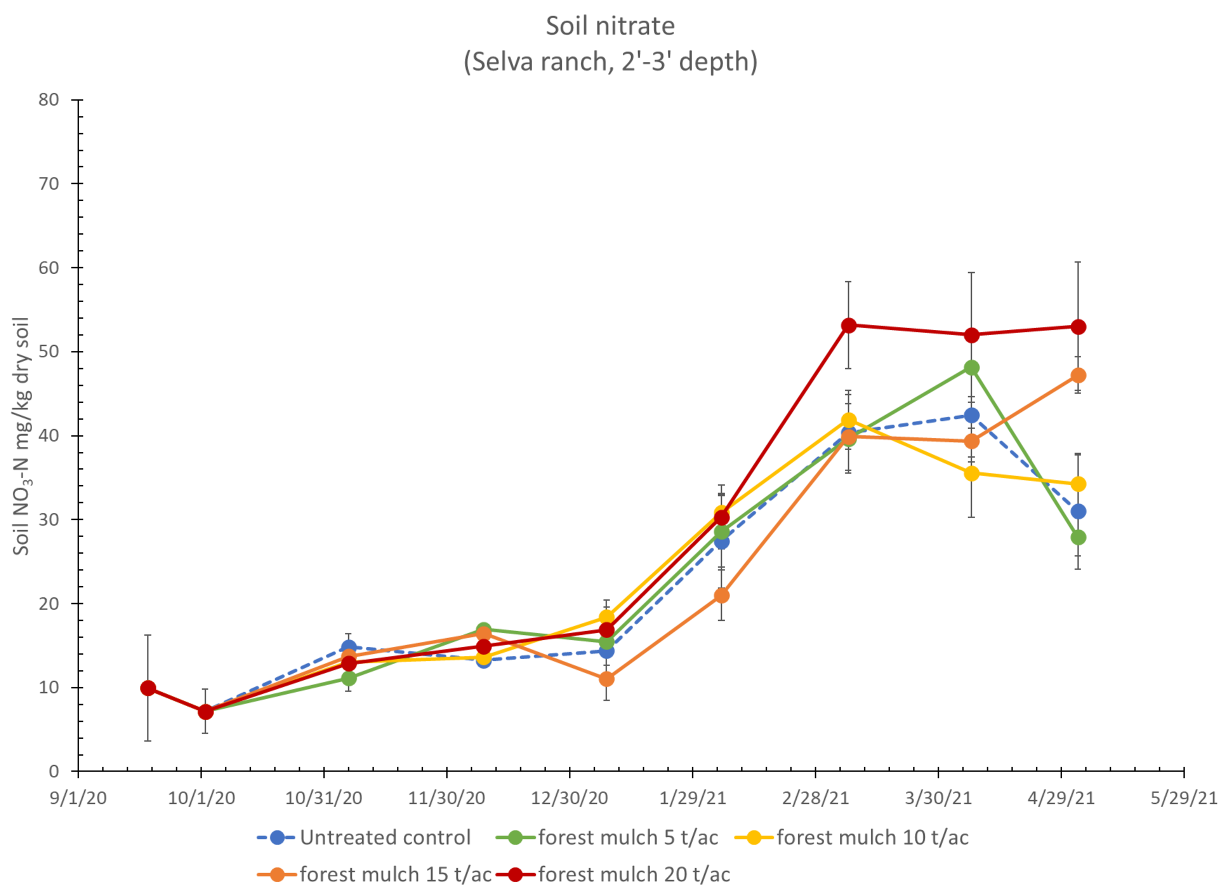

Figure 3. 2020-2021. Impact of various rates of high-carbon compost treatments on soil nitrate levels in the third foot of soil.

Table 2. 2020-2021. Subsequent lettuce crop rosette stage biomass evaluation on April 5

Forest Mulch T/A	Fresh wt lbs/A	Fresh wt tons/A	% solids	Dry wt lbs/A	Biomass Lbs N/A	Tissue N %
0	1,986	0.99	9.13	181.0	8.55	4.73
5	2,045	1.02	9.08	185.1	8.91	4.82
10	1,759	0.88	9.32	163.6	7.84	4.79
15	1,838	0.92	9.09	166.9	8.09	4.85
20	2,111	1.06	9.29	196.1	9.35	4.76

Table 3. 2020-2021. Subsequent lettuce crop harvest biomass evaluation on May 10

Forest Mulch T/A	Fresh wt lbs/A	Fresh wt tons/A	% solids	Dry wt lbs/A	Biomass Lbs N/A	Tissue N %
0	69,796	34.90	5.84	4,094	131.7	3.24
5	72,789	36.39	5.89	4,274	131.7	3.09
10	71,090	35.55	5.85	4,163	136.8	3.30
15	71,482	35.74	5.79	4,133	128.3	3.10
20	71,868	35.93	6.16	4,429	127.9	2.89

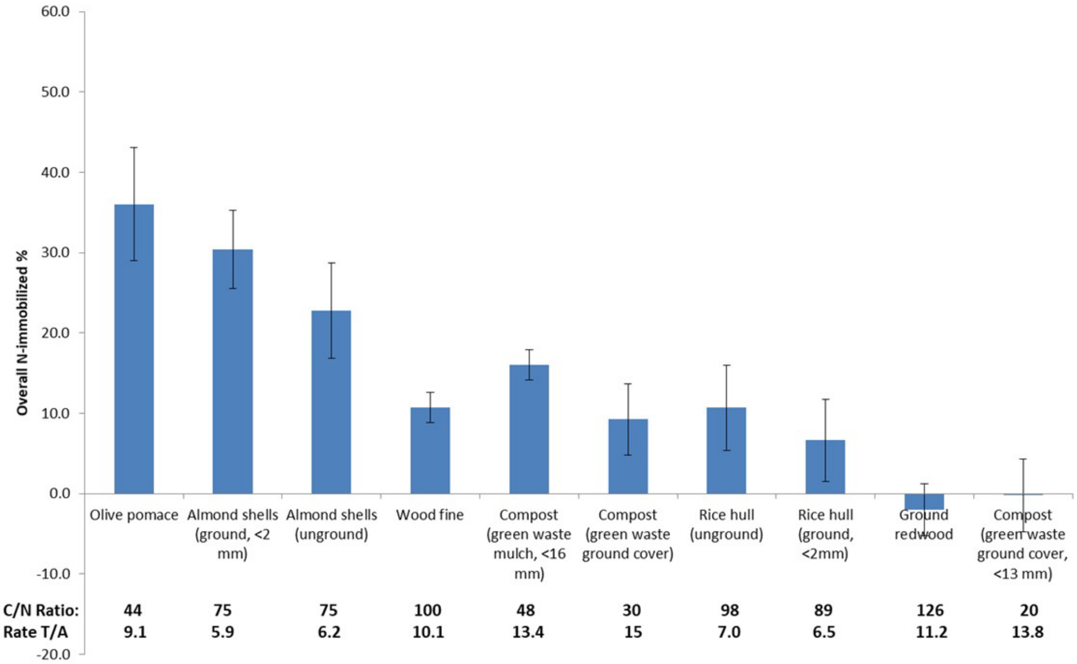

Figure 4. 2020-2021. Overall N-immobilization rate in a range of high carbon amendments at week 12.

Table 4. 2020-2021. Composite of compost treatments (including all fertilizer treatments) and composite
of fertilizer treatments (including all compost treatments) and effect on soil N, N uptake by lettuce and mean head weight

Forest Mulch Tons/A	Starter fertilizer Lbs N/A	Starter fertilizer Gallons/A	February 26		May 10		
			NH_4-N	NO_3-N	Percent N in heads	lbs N/A in lettuce	Mean head weight lbs
0	---	---	0.7	13.4	3.1	127.8	2.6
5	---	---	1.3	13.3	3.0	122.6	2.6
10	---	---	1.2	11.9	2.9	114.9	2.6
15	---	---	0.9	13.8	2.9	112.5	2.4
---	0.0	0	0.6	8.8	3.0	121.1	2.5
---	7.8	15	1.4	12.1	2.9	125.2	2.5
---	15.5	30	0.8	15.3	2.9	123.6	2.5
---	31.2	60	1.3	16.2	2.9	122.9	2.6

1 – Compost 36.7% moisture (net solids applied: 5 tons/A = 3.2, 10 = 6.3; 15 = 9.5); compost C:N ratio = 186:1

2 – Fertilizer applied post planting 6-16-0 (7.8 lbs N/A = 15 gallons/A; 15.5 = 30 gallons/A; 31.2 = 60 gallons/A)

Table 5. 2020-2021. Cost/ton of immobilization materials

Expense	Forest mulch	Ground almond shells	Unground almond shells
Material	0.00	15.00	15.00
Trucking	0.00	37.50[1]	37.50[1]
Grinding	20.00[2]	20.00[2]	0.00
Spreading	8.00	8.00	8.00
Total Costs	28.00	80.50	60.50

1 – Trucking from Central Valley (2022 cost) ; 2 – ground to 0.5 inch screen

Table 6. 2021-2022. High carbon amendments analysis

		Total - Percent					
	C:N	N	C	P	K	Ca	Mg
Almond Shells	84.4	0.481	42.5	0.052	1.49	0.25	0.08
Forest mulch	96.5	0.318	30.7	0.041	0.21	0.80	0.17

	ppm					mg/L	meq/L
	Na	Zn	Mn	Fe	Cu	B	Cl
Almond Shells	62	7	24	892	6	9.4	3.5
Forest mulch	592	19	78	2236	4	0.5	8.7

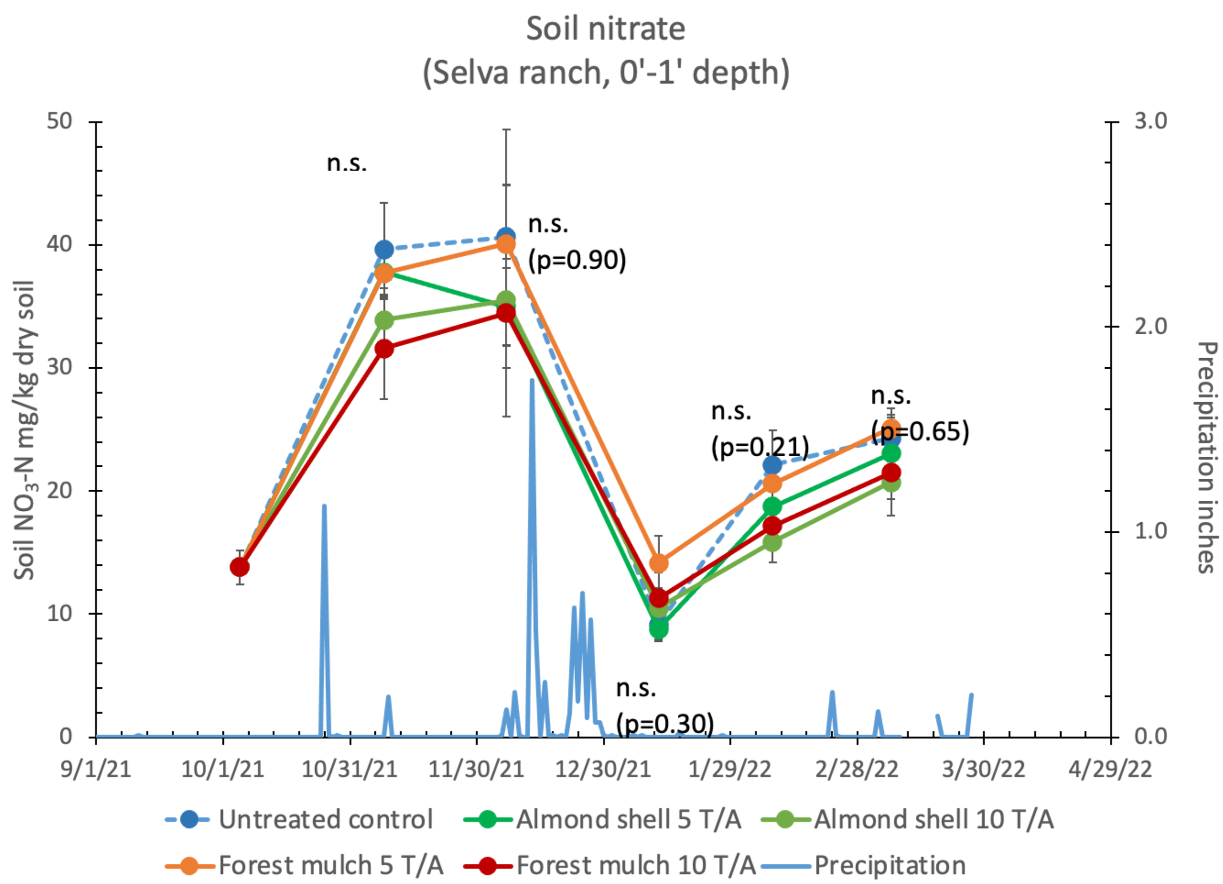

Figure 5. 2021-2022. Soil nitrate levels in the first foot of soil in the carbon amendment treatments over the course of the fallow period and the subsequent lettuce crop cycle.

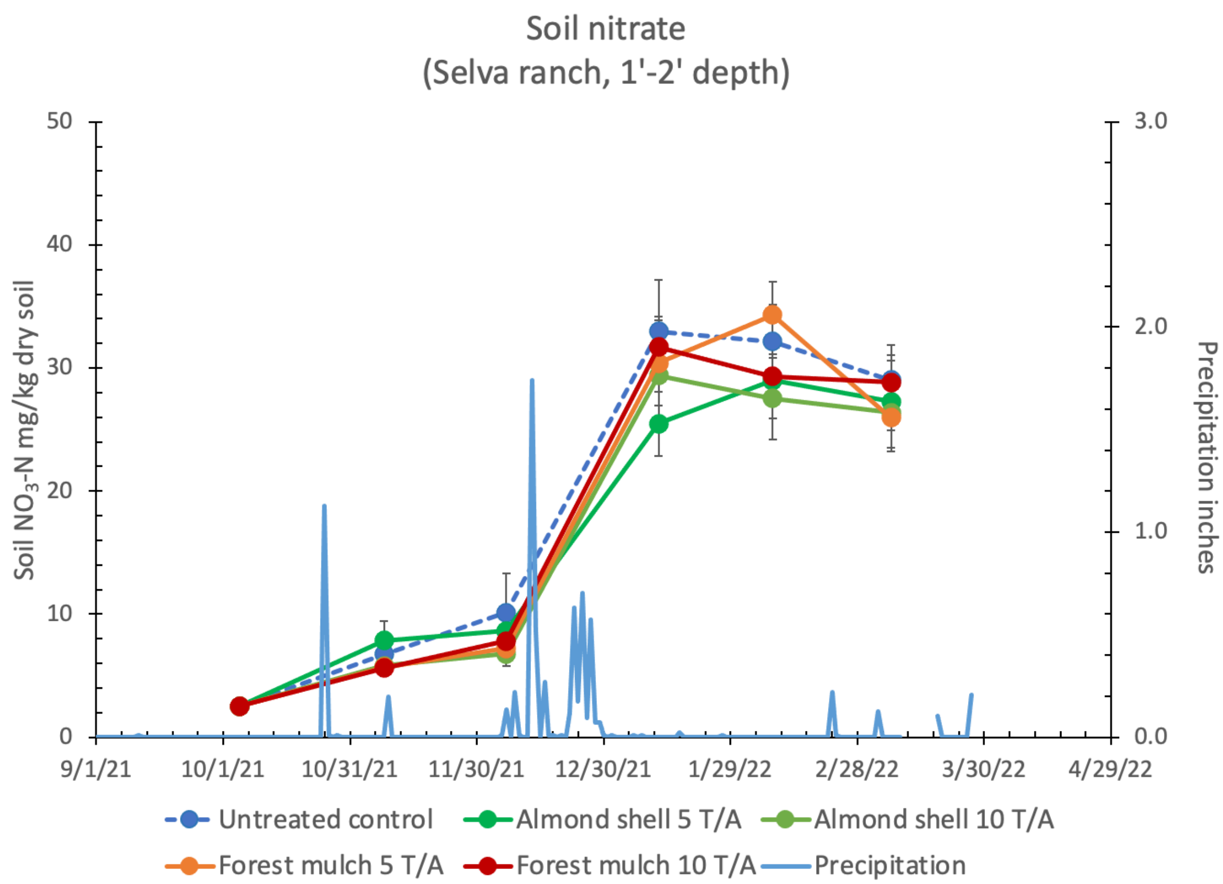

Figure 6. 2021-202022. Soil nitrate levels in the second foot of soil in the carbon amendment treatments over the course of the fallow period and the subsequent lettuce crop cycle.

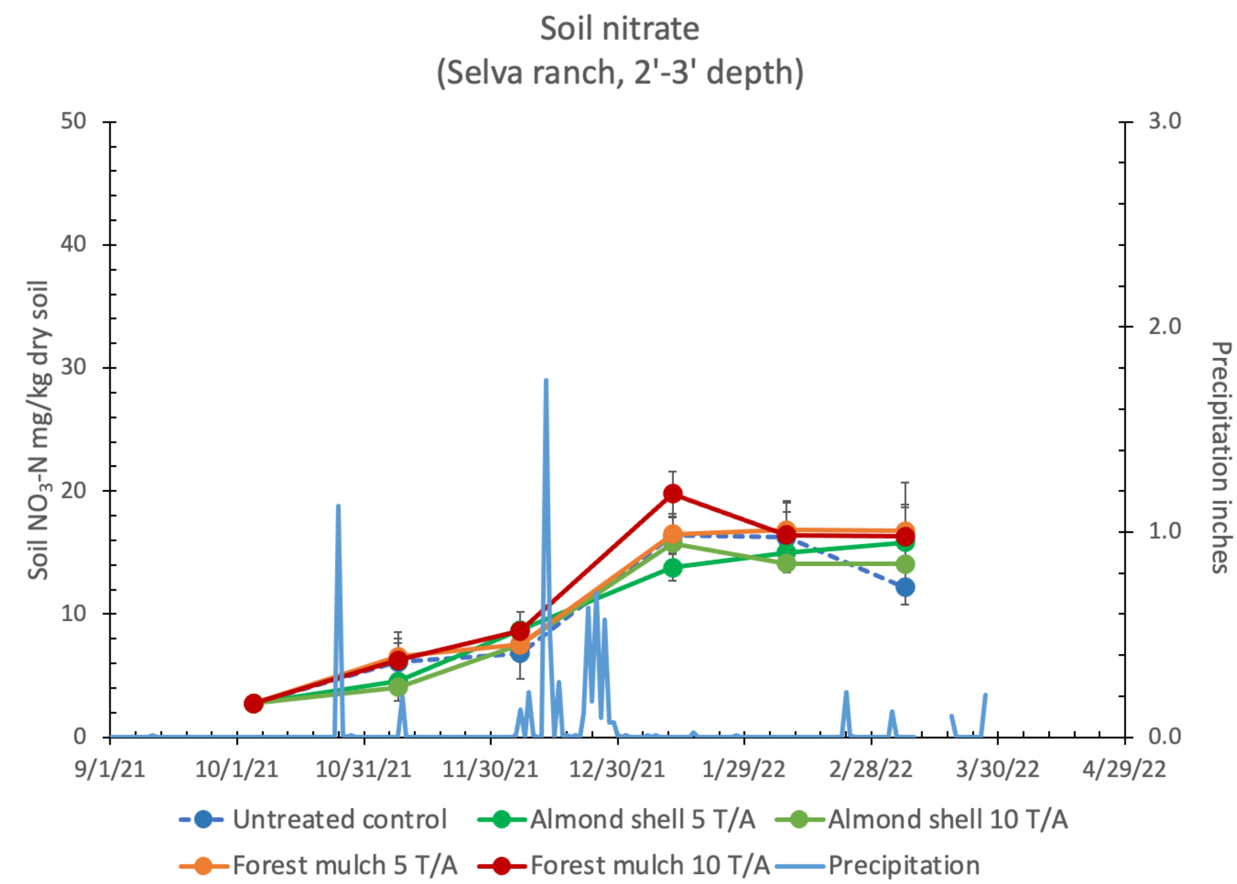

Figure 7. 2021-2022. Soil nitrate levels in the third foot of soil in the carbon amendment treatments over the course of the fallow period and the subsequent lettuce crop cycle.

Table 7. 2021-2022. Large-scale trial. Subsequent lettuce crop rosette stage biomass evaluation on April 6

Amendments Tons/A	Fresh wt tons/A	Dry matter %	Dry wt lbs/A	Tissue N lbs/A	Tissue N percent
Untreated	4.23	7.15	598	26.5	4.43
AS[1] 5	4.70	6.87	645	28.6	4.43
AS 10	4.47	7.33	653	27.8	4.26
FM[2] 5	4.68	7.11	666	29.0	4.36
FM10	4.71	6.98	662	28.5	4.36
Pr>F	0.7556	0.8043	0.8726	0.8962	0.9879

1 – Almond Shells; 2 – Forest Mulch

Table 8. 2021-2022. Large-scale trial. Subsequent lettuce crop harvest evaluation on May 10

Amend-ments Tons/A	Mean head wt lbs	Fresh wt tons/A	Dry wt lbs/A	Tissue N lbs/A	Tissue N %	Tissue P lbs/A	Tissue P %	Tissue K lbs/A	Tissue K %
Untreated	1.36	24.49	2911	103.7	3.58	10.8	0.372	192	6.60
AS 5	1.46	26.36	3019	108.0	3.59	11.8	0.391	201	6.68
AS 10	1.50	26.74	3255	107.5	3.31	11.9	0.367	210	6.45
FM 5	1.39	25.37	2974	102.3	3.46	11.9	0.401	196	6.68
FM10	1.41	25.60	2946	109.5	3.77	11.4	0.393	197	6.79
Pr>F	0.3459	0.5426	0.7941	0.9904	0.5523	0.7818	0.6157	0.8299	0.9421

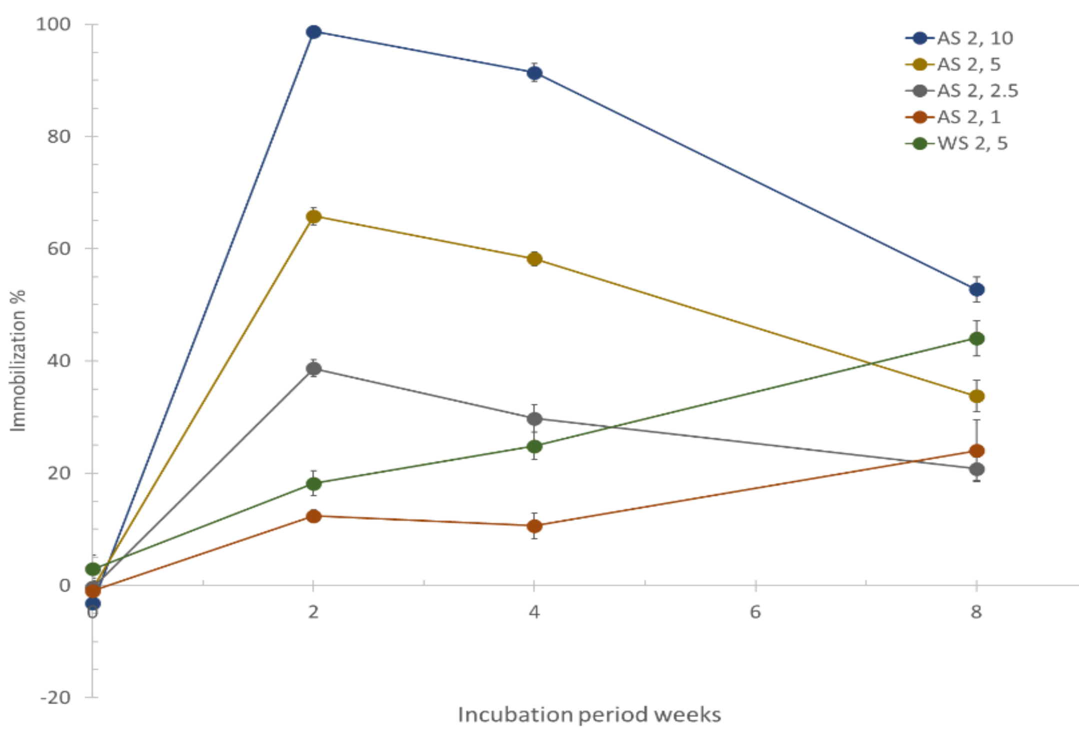

Figure 8. 2021-2022. N immobilization by 2 mm particle size almond shells: 1.0 T/A (AS 2, 1). 2.5 T/A (AS 2, 2.5), 5.0 T/A (AS 2, 5.0), 10.0 T/A (AS 2, 10.0) and 2 mm particle size walnut shells: 5.0 T/A (WS 2, 5.0)

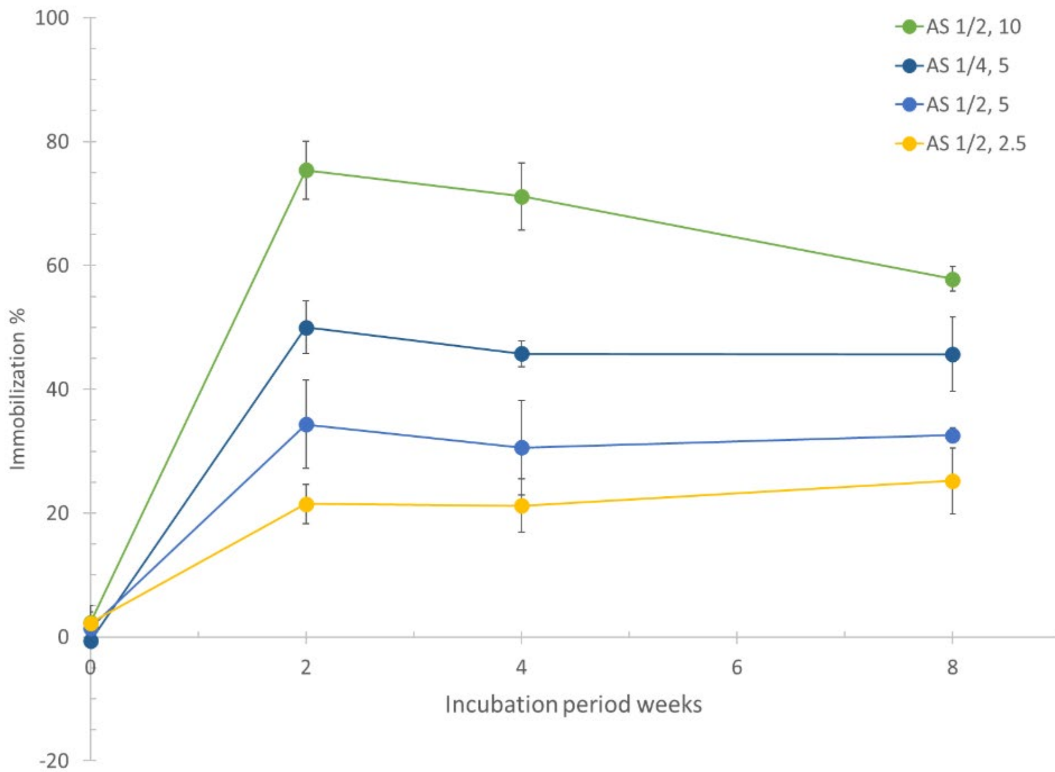

Figure 9. 2021-2022. N immobilization by ½" or ¼" particle size almond shells: 2.5 T/A (AS ½, 2.5), 5.0 T/A (AS ½, 5.0 or AS ¼, 5.0) and 10 T/A (AS ½, 10)

Table 9. 2021-2022. Small-plot trial. Impact of starter fertilizer on immobilization of an application of 20 tons/A of almond shells

Starter Fertilizer lbs N/A	Starter Fertilizer Gals/A	April 11	May 6		May 23	
		Total Mineral N ppm	Biomass weight lbs/plant	Percent Nitrogen in biomass	Mean head weight Lbs/head	Percent nitrogen in heads
0	0	11.1	0.13	4.64	0.80	3.97
31	60	19.1	0.17	4.34	0.95	4.02
62	120	28.7	0.21	4.46	1.21	4.04
$Pr>F_{treat}$	---	0.0008	0.0537	0.3086	0.0775	0.9576
$LSD_{0.05}$	---	6.5	0.06	ns	0.36	ns

Table 10. 2022-2023. Almond shell analysis

	Percent					
C:N	N	C	P	K	Ca	Mg
107.2	0.451	48.1	0.041	1.03	0.25	0.07

PPM						meq/L
Na	Zn	Mn	Fe	Cu	B	Cl
103	6	17	425	5	31.8	10.1

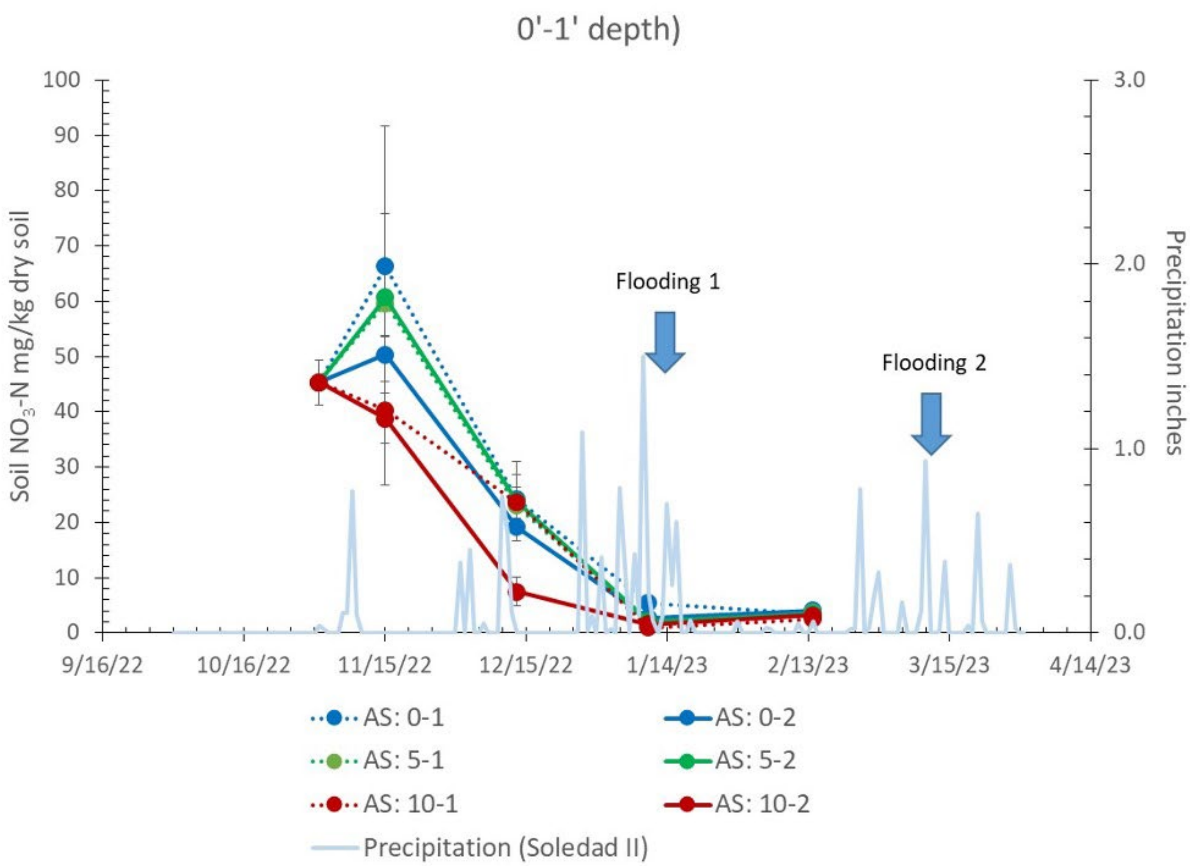

Figure 10. 2022-2023. Soil nitrate levels in the first foot of soil in the almond shell treatments until flooding terminated the trial.

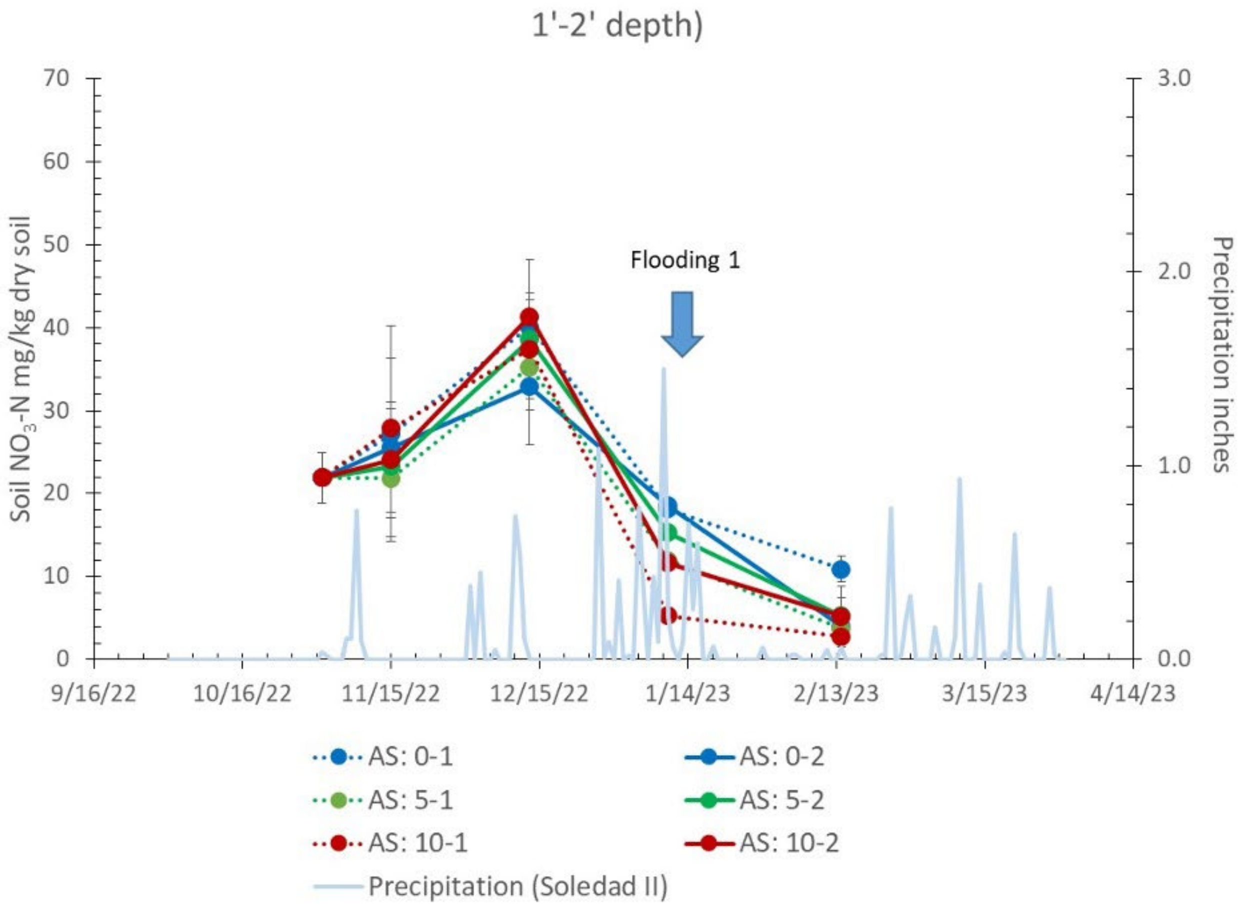

Figure 11. 2022-2023. Soil nitrate levels in the second foot of soil in the almond shell treatments until flooding terminated the trial.

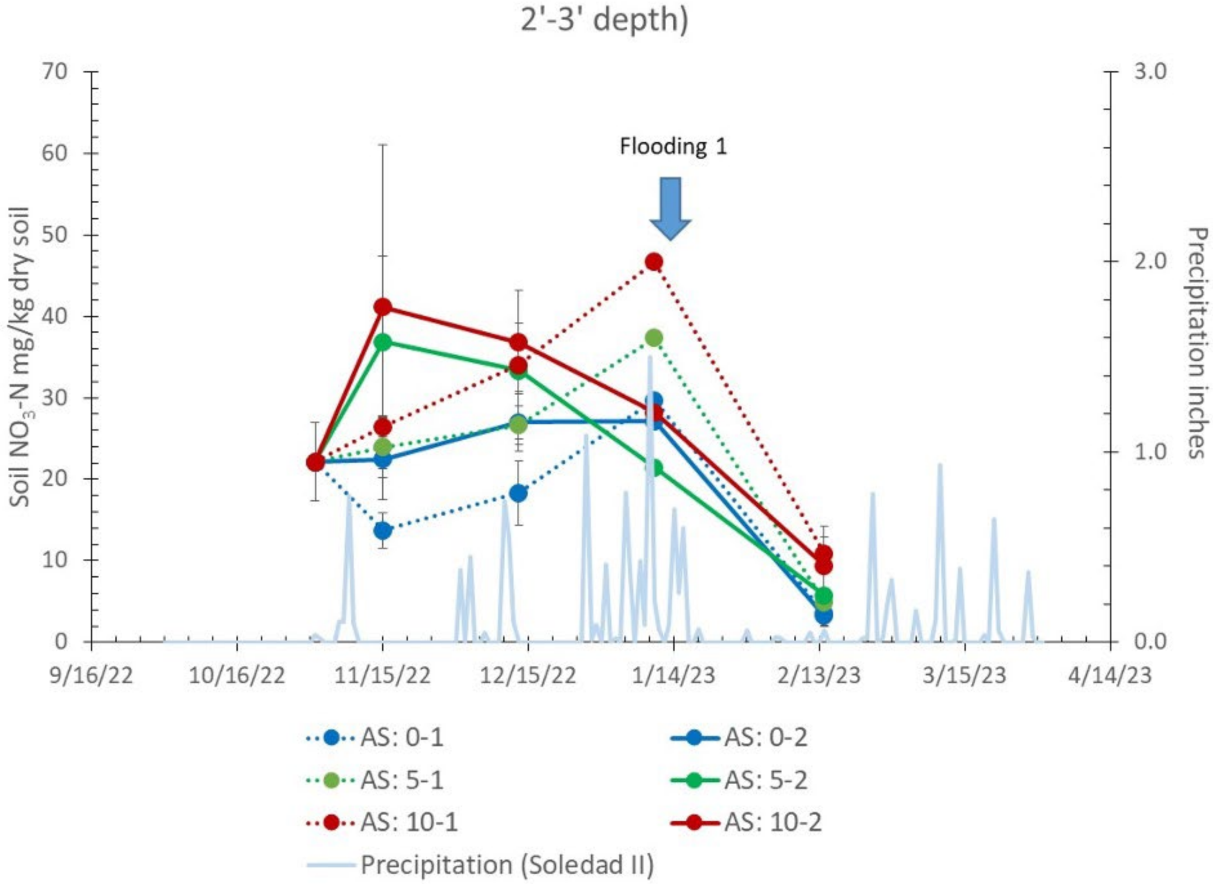

Figure 12. 2022-2023. Soil nitrate levels in the third foot of soil in the almond shell treatments until flooding terminated the trial.

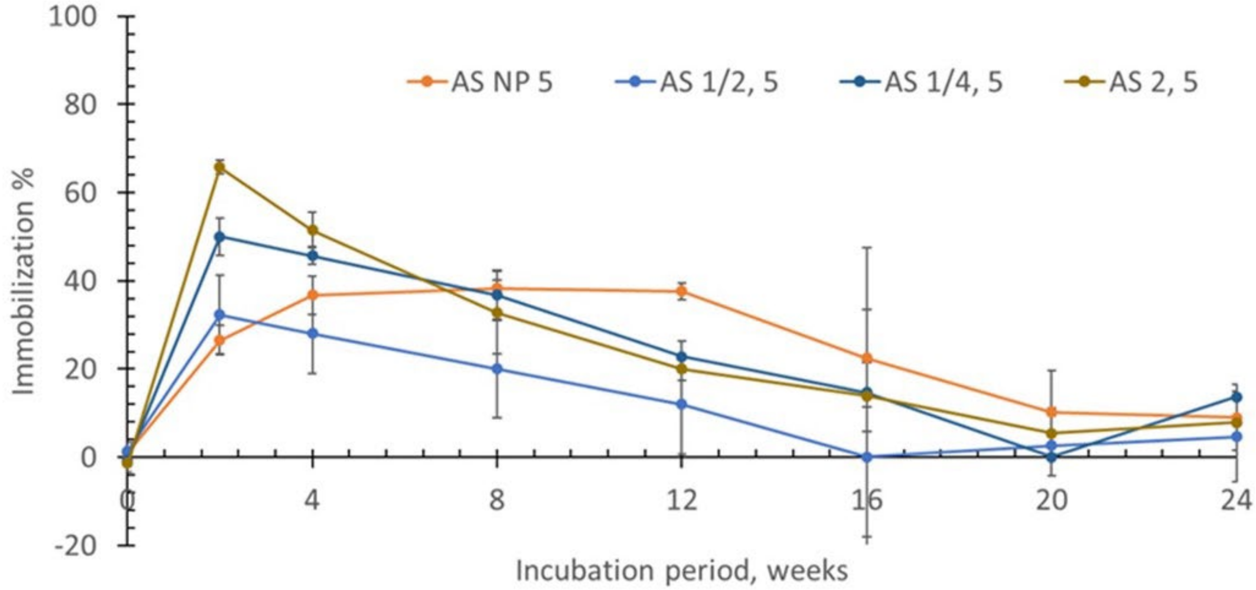

Figure 13. 2022-2023. N immobilization by almond shells with different particle sizes at 5 tons/ac rate: AS NP 5 - unground shells; AS ½, 5 - ½" particles; AS ¼, 5 - ¼" particles; and AS 2, 5 - 2 mm particles.

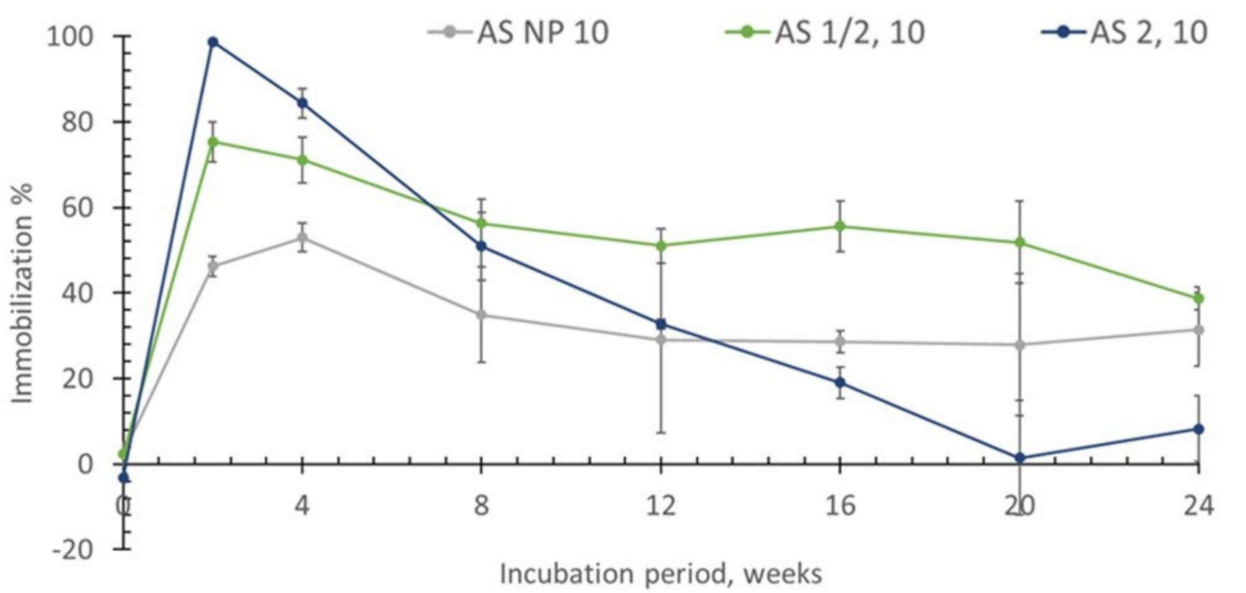

Figure 14. 2022-2023. N immobilizaton by almond shells at 10 tons/ac rate: AS NP 10 - unground shells; AS ½, 10 – ½" particles; and AS 2, 10 - 2 mm-particles.

G. DISCUSSION AND CONCLUSIONS

Forest Mulch applied at 0, 5, 10, 15 and 20 T/A was applied in a commercial scale trial but did not immobilize nitrate effectively. Incubation studies confirmed this observation. We then decided to reevaluate the use of almond shells. They are highly effective and abundant (but expensive to truck to the Salinas Valley). In years 2 and 3 we observed in field and laboratory incubation studies that unground and ¼ and ½ inch almond shells are effective at immobilizing nitrate. Small particle sizes immobilize a greater quantity of nitrate more rapidly, but also begin to remineralize it more quickly. The optimal particle size seems to be ¼ to ½ inch and applications need to be 5 to 10 T/A. Residual immobilization may be a problem, but higher rates of starter fertilizers can be used to offset this issue. We surveyed a trucking company and the cost of almond shells and trucking from the Central Valley to the Salinas Valley was $60.00/T. Grinding adds an additional $20.00/T. If a grower budgets $150/A to the use of this practice, these current costs allow the use of 2.5 T/A of unground and 1.9 T/A of ground almond shells. This is probably not sufficient to effectively immobilize the residual soil nitrate left by a broccoli crop at these current prices.

H. CHALLENGES

The original objective of this project was to identify an affordable and local source of high-carbon amendment. We initially evaluated an abundant material from the green waste stream – Forest Mulch which is made from tree limbs and ground to pass through a 3/8 inch screen. This material was not sufficiently labile to effectively immobilize the large pool of residual soil nitrate in winter fallow beds following a broccoli crop. As a result we decided to reevaluate the use of almond shells that were either unground or partially ground to ¼ to ½ inch particle size in order to reduce grinding costs. The use of almond shells as the preferred carbon source to immobilize soil nitrate is justifiable in terms of their efficacy but the cost of this material may limit the quantities of this material that a grower can apply at present.

I. PROJECT IMPACTS

We had extensive conversations and meetings with staff and members of the board of the Central Coast Regional Water Quality Control Board and educated them about the potential for high-carbon amendments in providing a best management practice that can reduce nitrate leaching in winter fallow beds in vegetable production. As a result, this practice was included in Ag Order 4.0 as a nitrogen removal credit. Growers that follow the guidelines outlined in the Ag Order (application of 10 T/A of almond shells with a C:N ratio >40) can receive a credit of 30 lbs N/A credit on the R side of the A-R equation (Applied minus Removed N from a field). This project helped us to identify almond shells as the best high-carbon source. It contains carbon that is sufficiently labile to interact with soil microbes to initiate the immobilization process. There are also abundant quantities available in the state. The main obstacles are transportation and grinding costs.

J. OUTREACH ACTIVITIES SUMMARY

Meetings:

- February 23, 2021; 2021 Irrigation and Nutrient Management Meeting; Virtual; Using high-carbon compost for reducing nitrate leaching during the winter fallow; 150 attendees; R. Smith, CCA credits provided.
- February and March, 2021 (two meetings); Sustainable Conservation Ag Order 4.0 Committee Meeting; Virtual; Sequestration of nitrate in winter fallow: cover crops and high carbon amendments; 14 attendees; R. Smith and M. Cahn.
- February to March, 2021; Board members of the Central Coast Regional Water Qualtiy Control Board; Virtual; Discussion of the R side of the A (applied) minus R (removed N) metric and the role of cover crops and high carbon amendments; 5 attendees; R. Smith and M. Cahn.
- February 22, 2022; 2022 Irrigation and Nutrient Management Meeting; Salinas; Factors affecting the R side of the A-R metric equations in Ag Order 4.0; 100 attendees; R. Smith, CCA credits provided.
- August 25, 2022; 2022 Irrigation and Nutrient Management Meeting for Vegetables and Berry Crops; Ventura; Use of high-carbon amendments to reduce nitrate leaching during rainy winters; 60 attendees; R. Smith, CCA credits provided.

Publications:

Smith, R.F., J. Muramoto and P. Love. 2021. Summary of the use of high carbon compost to immobilize soil nitrate in winter fallow beds. UCCE Monterey County Blog: https://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=45542 January 4.

Smith, R.F. and M. Cahn. 2021. Ag Order 4.0 Finalized: Implications for Nitrogen management on the Central Coast. UCCE Monterey County Blog: https://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=46578. May 1

Smith, R. and M. Cahn. 2022. New water quality regulations will change how vegetables are grown on the Central Coast. Progressive Crop Consultant Magazine. 7(4): 10-15 July/August.

K. REFERENCES

N/A

L. APPENDIX:

N/A

M. FACT SHEET/DATA BASE TEMPLATE

1. Immobilization of nitrate in winter-fallow vegetable production beds to reduce nitrate leaching
2. Contract 19-0955-SA
3. Project Leaders:
   - Richard Smith, UCCE Emeritus Vegetable Crops Farm Advisor, Monterey, San Benito and Santa Cruz Counties
   - Mike Cahn, UCCE Irrigation Farm Advisor, Monterey, San Benito and Santa Cruz Counties
   - Joji Muramoto, UCCE Organic Specialist, Dept of Environmental Studies, UC Santa Cruz
   - Daniel Geisseler, Associate CE Specialist, Dept of Land, Air and Water Resources
4. January 1, 2020 to December 31, 2023
5. Conducted in Muramoto and Geisseler labs and commercial production fields.
6. Monterey County
7. Highlights:
   - Large-scale evaluations were conducted in commercial production fields examining high-carbon amendments as a best management practice to reduce nitrate leaching from fallow winter beds following broccoli production. Initial studies indicated that 2 mm particle size almond shells as well as glycerol effectively reduce leaching. However, these materials were too costly to be widely used by growers.
   - This project evaluated an alternative high-carbon amendment, Forest Mulch, made from tree limbs and ground to 3/8 inch particle size. However, an initial field trial and laboratory incubation evaluations showed that this material was too recalcitrant and did not quickly reduce nitrate leaching.
   - Incubation studies showed that almond shells contain sufficient labile carbon and in the second and third year of this project we evaluated unground almond shells, and almond shells ground to ¼ and ½ inch particle size to reduce grinding costs and make them more affordable for growers. Unground almond shells immobilize nitrate at a lower rate than smaller particles and remineralize nitrate more slowly than smaller particle sizes.
   - Incubation studies showed that almond shells ground to ¼ and ½ inch particle sizes immobilize soil nitrate effectively and remobilize them at a rate that is useful to reduce nitrate leaching during the winter fallow.
   - No reduction in the yield of the subsequent lettuce crop was observed following winter application of high-carbon amendments due to reduced nitrogen from immobilization. However, in trials where immobilization in the subsequent lettuce crop was created by application of high rates of high-carbon amendments, immobilization could be offset by increasing the rates of starter fertilizer applied over the seedline at planting and prior to the first germination irrigation.

- The costs of this practice are an issue for growers. The cost of almond shells and trucking from the central valley to the Salinas valley are about \$60.50/ton. Grinding the almond shells adds an additional \$20.00/ton. If a grower budgets \$150/acre this practice they can afford 2.5 T/A for unground shells and 1.9 tons/A of ground almond shells. In these studies, 5-10 T/A are the effective rates of ground shells.

8. Introduction: Prior studies showed that 2 mm particle size almond shells effectively immobilize residual soil nitrate left by a prior broccoli crop during the winter fallow. However, this material is too expensive for widespread adoption by growers. This project evaluated a local source of C made from trees limbs ground to pass a 3/8 inch screen. However, this material was not sufficiently labile to immobilize soil nitrate. We decided to continue evaluating almond shells given their abundance and ability to effectively immobilize nitrate. To reduce the cost, we evaluated unground and partially ground (1/4-1/2 particles) almond shells. Based on our initial evaluations the CCRWQCB granted a nitrogen removal discount of 30 lbs N/A credit for the use of high carbon amendments
9. Methods/Management: In year one of this project a locally sourced material called Forest Mulch which was made from tree limbs and ground to pass a 3/8 inch screen was tested in large scale trials in a commercial vegetable production field in which the previous crop was broccoli. Each year of the project a commercial scale trial was conducted in the fall and the soil was sampled to three feet deep each month during the winter fallow and through the first crop cycle of lettuce (October to May). In year one, the woody material did not immobilize soil nitrate sufficiently so we changed our focus in years two and three of the project and evaluated almond shells that were unground or ground to ¼ to ½ inch particle sizes. Laboratory incubations of almond shells were conducted to examine immobilization and subsequent remineralization studies conducted of almond shells of different particle sizes and rates. Evaluations were conducted to evaluate the use of starter fertilizer to overcome residual immobilization at the start of the subsequent lettuce crop cycle. An economic evaluation of the costs of materials, trucking and grinding was conducted.
10. Findings: Forest Mulch applied at 0, 5, 10, 15 and 20 T/A was applied in a commercial scale trial but did not immobilize nitrate effectively. Incubation studies confirmed this observation. We then decided to reevaluate the use of almond shells. They are highly effective and abundant (but expensive to truck to the Salinas Valley). In years 2 and 3 we observed in field and laboratory incubation studies that unground and ¼ and ½ inch almond shells are effective at immobilizing nitrate. Small particle sizes immobilize a greater quantity of nitrate more rapidly, but also begin to remineralize it more quickly. The optimal particle size seems to be ¼ to ½ inch and applications need to be 5 to 10 T/A. If residual immobilization may be a problem higher rates of starter fertilizers can be used to offset this issue. We surveyed a trucking company and the cost of almond shells and trucking from the Central Valley to the Salinas Valley was \$60.00/T. Grinding adds an additional \$20.00/T. If a grower budgets \$150/A to the use of this practice, these current costs allow the use of 2.5 T/A of unground and 1.9 T/A of ground

almond shells. This is probably not sufficient to effectively immobilize the residual soil nitrate left by a broccoli crop at these current prices.

N. COPY OF THE PRODUCT/RESULT
None available as of this writing