AGRICULTURAL RESEARCH FOUNDATION
FINAL REPORT
FUNDING CYCLE 2017 – 2019

TITLE: Establishing fertilizer guidelines for non-bearing hazelnut trees

RESEARCH LEADERS:

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COOPERATORS:

1. Matt Miller (Miller Farms, Donald), on-farm trial site
2. Matt Schuster (Chapin Farms, Keizer), on-farm trial site
3. Christensen Farms donated bare root trees, c.v. 'Jefferson'

SUMMARY:

Four research trials were established (one in 2017, three in 2018, and two in 2019). Trials were located at the North Willamette Research and Education Center (NWREC) in Aurora, and two were located on cooperator farms. We created a relationship between initial trunk diameter and the absolute quantity of nutrients in each tree. These data were used to calculate the nitrogen use efficiency for each fertilizer treatment. Two fertilizer were applied- urea only (Urea) and a commercial hazelnut blend (Blend) containing controlled release urea, P, K, S, and Mg at three N rates (4 rates for the trial established in 2017). Nutrients other than N and S added with the Blend (K, P, and Mg) did not show a clear or consistent difference in tissue nutrients compared to the Urea treatment or the unfertilized control. There was a consistent trend that trees receiving the Blend grew slightly faster (as measured by increase in trunk cross-sectional area) compared to Urea, though this was not always statistically significant. Calculated nutrient uptake efficiencies were low, but the blend resulted in better uptake than the urea alone. Adding urea alone caused excessive N:S ratio in the trees, leading to S deficiency symptoms poor growth. The highest uptake efficiencies were generally for the lower fertilizer rates.

OBJECTIVES:

The goal of this project is to provide farmers with guidance on fertilizing non-bearing hazelnut trees. To accomplish this goal, the project has the following objectives:

1. Identify the minimum N rate required to counteract nutrient immobilization from sawdust mulch and minimize fertilizer injury yet optimize tree growth and nutrient uptake in the short-term (2 years).
2. Measure nutrient uptake and nutrient use efficiency for non-bearing trees to better understand the nutrient requirements of young trees.
3. Determine if increased growth due to fertilizer applications in non-bearing years results in earlier, and larger yields in bearing trees (in years 3 and 4, beyond the timeline of this study).
4. Determine the relationship between root and shoot growth for newly planted trees receiving fertilizer.

Table 1. Fertilizer application rate treatments and nutrient content.

	Fertilizer rate			Nutrient addition				
Trt	oz/tree	g/tree	lb/acre[1]	N (g)	P (g)	K (g)	S (g)	Mg (g)
Control	0	0.0	0	0	0.0	0.0	0	0.0
Urea5	0.4	11.3	150	5.0	0.0	0.0	0	0.0
Urea10	0.8	22.7	300	10.0	0.0	0.0	0	0.0
Urea15	1.2	34.0	450	15.0	0.0	0.0	0	0.0
Blend5[2]	0.7	19.8	150	5.0	1.2	1.2	1.4	0.6
Blend10	1.3	36.9	300	10.0	2.2	2.2	2.8	1.1
Blend15	2.0	56.7	450	15.0	3.4	3.4	4.2	1.6

[1] based on a 12 inch application area; [2]27-6-6-7.5S-2.9Mg (commercial hazelnut blend of polymer coated urea, MAP, S°, ammonium sulfate, and sulfate of potash-magnesia)

PROCEDURES:

The trials were established (one in 2017, three in 2018, and two in 2019). Trials were located at the North Willamette Research and Education Center (NWREC) in Aurora, and two were located on cooperator farms. The variety 'Jefferson' was used in all trials and all trees were from the same source (Christensen Farms). At planting, the trees were sorted to remove small diameter trees and trees with weak root systems. This was done to minimize variability in growth due to these factors. A subset of trees was collected and cut to represent the height at which they are cut in the field following planting (~36 inches), and the trunk diameter was measured in two directions at 12 inches above the estimated soil surface, which is the method we use to measure calculate cross-sectional area and tree growth. A subset of trees were then separated into 2 components: wood and roots, and dried at 60°C, and sent to Brookside Laboratories, Inc. (New Bremen, OH) for total nutrient analysis. Based on this data, we were able to create a relationship between initial trunk diameter and the absolute quantity of nutrients in each tree. These data were used to estimate the starting nutrient content in each tree, allowing calculation of the nutrient use efficiency for each fertilizer treatment and rate.

Figure 1. Fertilizers were evenly applied in an approximately one-foot radius around the trees prior to sawdust application. Pictured is the Urea15 treatment (high rate-15 g N per tree).

Trunks of trees at three sites were painted to prevent sunburn, and one on-farm site used trunk guards. After planting, fertilizer treatments (Table 1) were applied evenly in an approximately 12-inch radius around each tree (Fig. 1). Figure 2 shows what 2 oz of fertilizer looks like, which is the recommended rate from the company. The experimental design was a randomized complete block design with 3 to 5 reps (depending on site). Following fertilizer application, each tree received a 5-gallon bucket of sawdust mulch (Fig. 3). At NWREC, rainfall was directly measured using a rain gauge and the

AGRIMET weather station (ARAO) located on station. Because both on-farm field sites are located ≤19 miles of NWREC, we assumed rainfall was similar at each field site. To assess the native soil fertility at each site, the top 12 inches was sampled on May 16 and analyzed for total available N (nitrate + ammonium) and S content (Table 3). Weeds were completely controlled through a combination hand weeding and the post-emergent herbicide, glufosinate. Complete weed control was necessary to prevent the weeds from uptaking soil nitrogen (native and applied). Suckers were not managed in 2018.

Figure 2. This is 2 oz (label rate) of the commercial fertilizer blend (Blend; 27-6-6-7.5S-2.9 Mg).

To monitor tree growth, the trunk caliper of each tree was measured in two directions 90° from each other at 12" above the soil line with calipers at planting, and then again at the end of each growing season. Mean caliper was converted to cross sectional area using the formula for the area of a circle.

Figure 3. Applying 5 gallons of sawdust mulch to each tree.

In the winter of 2018-19, and winter of 2019-20, a portion of the trees were destructively harvested once leaves had dropped. At NWREC, a tree spader was used to dig up the plants. The trees were partitioned into two components: 1) below-ground (roots and crown) and above-ground biomass (trunk, branches, buds, and catkins). These components were weighed fresh, ground, and a subsample taken for moisture and total nutrient analysis. The NUE for N (and other nutrients) aka apparent recovery efficiency by difference was calculated according to Equations 1-3 in Appendix A, which also contains a more detailed description as well as an additional method for calculating uptake efficiency.

Table 2. Preplant soil analyses for each site.

Site	Est. CEC	pH	OM-LOI	Bray 1P	K	Ca	Mg
	meq/100g		%	ppm	ppm	meq/100g	meq/100g
NWREC 2017	11	5.1	3.3	208	298	4.0	0.8
NWREC 2018	13	6.2	3.4	173	252	8.6	1.0
Chapin	19	5.5	3.5	125	180	8.8	2.3
Miller	17	6.5	4.5	39	92	12.4	2.0

Table 3. Soil available N and S in the top 12-inches of soil sampled on May 16, 2018.

Site	NO3-N	NH4-N	Est. total available N	Sulfur
	ppm	ppm	lb/acre	ppm
NWREC 2018	7	5	40	11
Chapin	3	4	25	12
Miller	12	5	60	12

Site 1 (NWREC 2017):

This trial was established in 2017 on a soil mapped as a Willamette silt loam at the North Willamette Research and Extension Center (Aurora). Based on Google Earth imagery, the field has been in continuous minimally managed pasture since 2000 (some tillage, cover cropping, and vegetative management by mowing, but this site likely had no fertilizer additions). The trees were planted 5-ft apart in late May, and fertilizer and mulch were applied to the trees on May 10. This trial had five replicates per block. The fertilizer treatments were different than in 2018, but the same fertilizers were used. The fertilizer treatments were None, Urea8, Urea15, Urea30, Urea61, Blend8, Blend15, Blend30, and Blend61 (the number after the fertilizer is the g of N applied per tree). The trees were hand watered three times during the growing season a rate of 1 gal/tree each time. In 2018, the trees received no fertilizer or water.

On August 7, 2017 seven leaves per tree were collected (3rd fully expanded leaf from each branch- this represented growth from the middle of the branch) analyzed for total nutrients. On August 27, 2018, 10 leaves per tree were collected from the 4th to 6th fully expanded leaf and analyzed for total nutrients. In both 2017 and 2018, the trees exhibited Mg deficiency symptoms, which was corroborated with tissue testing. On July 16, 2018 the trees were rated for severity of Mg deficiency.

Site 2 (NWREC 2018):

The soil at this site is mapped as a Willamette silt loam. Based on Google Earth imagery, the field has been in continuous minimally managed pasture since 2004 (some tillage, cover cropping, and vegetative management by mowing, but this site likely had no fertilizer additions). This trial was planted on Feb. 27, fertilizer applied on March 26, and mulch applied on March 28. Trees were planted in a single row at an in-row spacing of 4.5 feet with 18 feet between row spacing. On October 5, 1 ton/acre of dolomitic lime was broadcast.

Prior to installation of a drip irrigation system, trees were hand watered (~1 gal per tree) on May 21 and June 13. On July 12, tubing was installed with a single 0.5 gal/hr drip emitter placed at the trunk of each tree, and the trees received weekly irrigations until September 7. The well water was sampled every two weeks and analyzed for nitrate, and a composite sample of all weeks was analyzed for total nutrients. Based on irrigation quantity recorded and the nutrient content of the well water, we were able to estimate the quantity of nutrients supplied by the irrigations.

On June 8, trees were evaluated for visual color rating and presence of interveinal chlorosis of young leaves (newly emerged to second fully expanded leaf). On June 25, a composite sample leaf sample (first fully expanded leaf) for each treatment in each block was collected, dried and ground, and sent to Brookside Laboratory for total nutrient analysis. On August 30, leaves from the high rate fertilizer treatments (1st to second fully expanded leaves) were sampled and sent for total nutrient analysis. This was done because the high rate urea treatment exhibited severe sulfur (S) deficiency early in the season, but disappeared later, and we wanted to see if the deficiency had truly disappeared or was not expressed even though tissue S was low.

In 2018, every other tree was destructively harvested December 5 using a spader (Fig. 4). Roots were washed using a high pressure hose to remove excess soil. Total biomass was weighed and then analyzed for nutrient content, keeping roots and total portion of tree above ground separate.


Figure 4. Spader used to harvest trees at NWREC winter of 2018.

Fertilizer was applied April 16, 2019 at the same rates as the year before for all trees except Treatment 8, which had not received fertilizer the first year, but were then given 1.2oz of urea per tree in spring. Trees received a significant amount of precipitation after fertilizer was applied, and were also irrigated three times with approximately 2 gallons of water during the growing season. Leaf samples were collected and pooled between paired trees August 9. Trees were measured December 30, and then every other tree was dug by hand for destructive harvest. Harvested are currently being processed using the same methods as the year before.

Site 3 (Miller): This trial was conducted on a commercial farm near Donald, OR, and the soil was mapped as a Concord or Woodburn silt loam. The field was in continual grass for seed for the three years prior, and 1 ton/acre of dolomitic lime was applied in the fall of 2017. The trees were planted on April 2 between the farmer's planting, and the final tree spacing was 9 ft On April 20, the sawdust mulch was applied. This site utilized plastic corrugated trunk guards instead of white paint. This site received no irrigation. On June 18 a visual evaluation was done to assess S and N deficiency. On July 19, a composite leaf sample (two trees per block) was taken from ~ the 1st to 2nd fully expanded leaf. Trees were pruned by the grower during the fall. Trees were dug by hand at this site for destructive harvest (Fig. 5).

Trees that had been harvested the year before and misprocessed were replanted in a single row, with 4.5 ft spacing March 25, 2019, and were measured, fertilized and mulched the next day. Two year old trees were fertilized April 18 using the same rates as the year before. Trees were not watered during the growing season, but did receive some rainfall after being fertilized. Leaf samples were collected August 9. Two-year old trees were pruned by the grower at some point during the fall. All trees were measured and then destructively harvested from both blocks December 16, and are still awaiting final processing and nutrient analysis..

Site 4 (Chapin): This trial was conducted on a commercial farm near Brooks, OR, and the soil was mapped as a Dayton/Woodburn silt loam. Two trees were planted on March 20 between the farmer's permanent trees, and the final tree spacing was 3 ft. In early June and late July, the farmer applied 2.5 inches of water per irrigation using overhead irrigation. Trees were replanted in a single row near the original plot, but in a location with less deer pressure March 25, 2019. Trees were measured, fertilized, and mulched the next day. Trees were not watered during the growing season, but did receive some rainfall after being fertilized. Leaf samples were collected August 9. All trees were measured, and then every other tree was destructively harvested December 16, and these are still awaiting final processing.

Figure 5. Hand-harvesting trees at Miller site in 2019.

SIGNIFICANT ACCOMPLISHMENTS:

- A preliminary trial (prior to ARF funding) was established in 2017 at NWREC. Three fertilizer trials were established in 2018, two on-farm with cooperative growers and one at NWREC, and additional trials were re-established in 2019 at the on-farm cooperator sites because trees harvested for destructive sampling from cooperators were accidentally processed incorrectly. Thus, this report can only cover uptake efficiency in destructively harvested trees from NWREC only.
- Prior to planting, a subsample of trees was dried down, shredded, and analyzed for total nutrient content in the wood. A strong positive linear relationship between the concentration of nutrients in the trees was found for most nutrients (Fig. 6). These regression equations were used in the calculation of nutrient uptake efficiency (see Appendix A) for the nutrients represented in the fertilizer treatments.
- Two fertilizer formulations were applied to bare root hazelnut trees after planting: urea only (Urea; 5, 10, and 15g) and a commercial hazelnut blend (Blend) containing controlled release urea (Blend; 5, 10, and 15g), P, K, S, and Mg at three N rates per (56 g/2 oz) of fertilizer (Table 1).
- Growth response to the treatments depended on the site (Fig. 7). With all data pooled, there was not a significant difference in growth as measured by stem caliper between untreated and treated trees. At the Miller orchard, there appeared to be a slight numeric response of declining growth with the addition of Urea, with slightly more growth from the Blend treatments compared to the Urea, but no treatments appeared to improve growth over the untreated trees and the response was not significant at the $\alpha = 0.05$ level. At the Chapin orchard, it also appeared that increasing N tended to reduce growth numerically, but again differences from the untreated control were not significant. At NWREC, which was also the only irrigated site, there was a significant growth response from the Blend fertilizer. Both the Blend5 and Blend10 treatments significantly increased growth of trees as measured by trunk caliper ($P < 0.05$). Increasing the N in the blend up to 15 g had no further effect on tree growth, suggesting the N above 10 g was surplus and could not be taken up by the trees.

- In terms of biomass at NWREC, the blend fertilizer treatment had a significant impact on growth (*P* < 0.05; Fig. 8). The Blend15 treatment increased aboveground and belowground biomass compared to unfertilized trees. The Blend 5 treatment had a significant effect on root growth at the $\alpha = 0.10$ level.
  - The benefit from the Blend vs. straight urea on growth was likely due to: 1) Polymer coated urea preventing N leaching losses, 2) Polymer coated urea reducing fertilizer damage, 3) Addition of S, which is critical to support the addition of N (Fig. 9). S defficiency was apparent on young trees with a N:S ratio higher than 18.

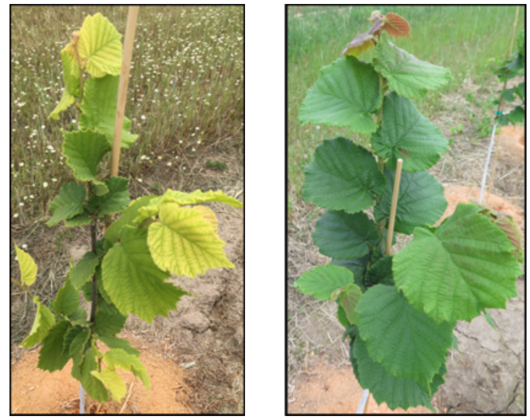

Figure 9. The tree at right received the Blend fertilizer (27-6-6-7.5S-2.9 Mg) and showed no signs of sulfur (S) deficiency, while the tree at the left received the high urea rate and is exhibiting S deficiency symptoms (June 14, 2018).

- All trees that received fertilizer showed significantly elevated levels of N in within-season foliar tissue samples (Fig. 10), however the elevated levels were no longer apparent by the second growing season. The addition of S in the Blend10 treatment resulted in higher within-season S levels.
- Increasing the urea application to 10 and 15 g per tree resulted in significantly increased N:S ratios in within-season foliar tissues (Fig. 11). At N:S ratios of 18 and above, S deficiency symptoms became apparent in the leaves midseason. This clearly illustrates an advantage of the Blend fertilizer, because it provided S to support the growth stimulated by the addition of the N. The addition of P in the Blend fertilizer tended to cause a drop in within-season foliar P (Fig. 11).
- Fertilizers had no significant effect on the K or the Mg content of leaves within-season. This suggests there was minimal uptake of these nutrients despite their addition in the Blend fertilizer treatments (Fig. 12)
- Fertilizers had no significant effect on the Zn or the Ca content of leaves within-season (Fig. 13). It did appear that the addition of Urea tended to lower Zn numerically within-season. Similarly, there was no effect of fertilizer addition on the levels of B (data not shown).
- Nutrient uptake efficiency (UE) was calculated for trees planted in winter of 2017/2018 and harvested in winter of 2018/2019 at NWREC only (Table X). Remaining destructively harvested trees are still being analyzed by the laboratory. At NWREC, nutrient uptake efficiency was calculated using equations 1-3 (Appendix A). Overall, UE was poor for all

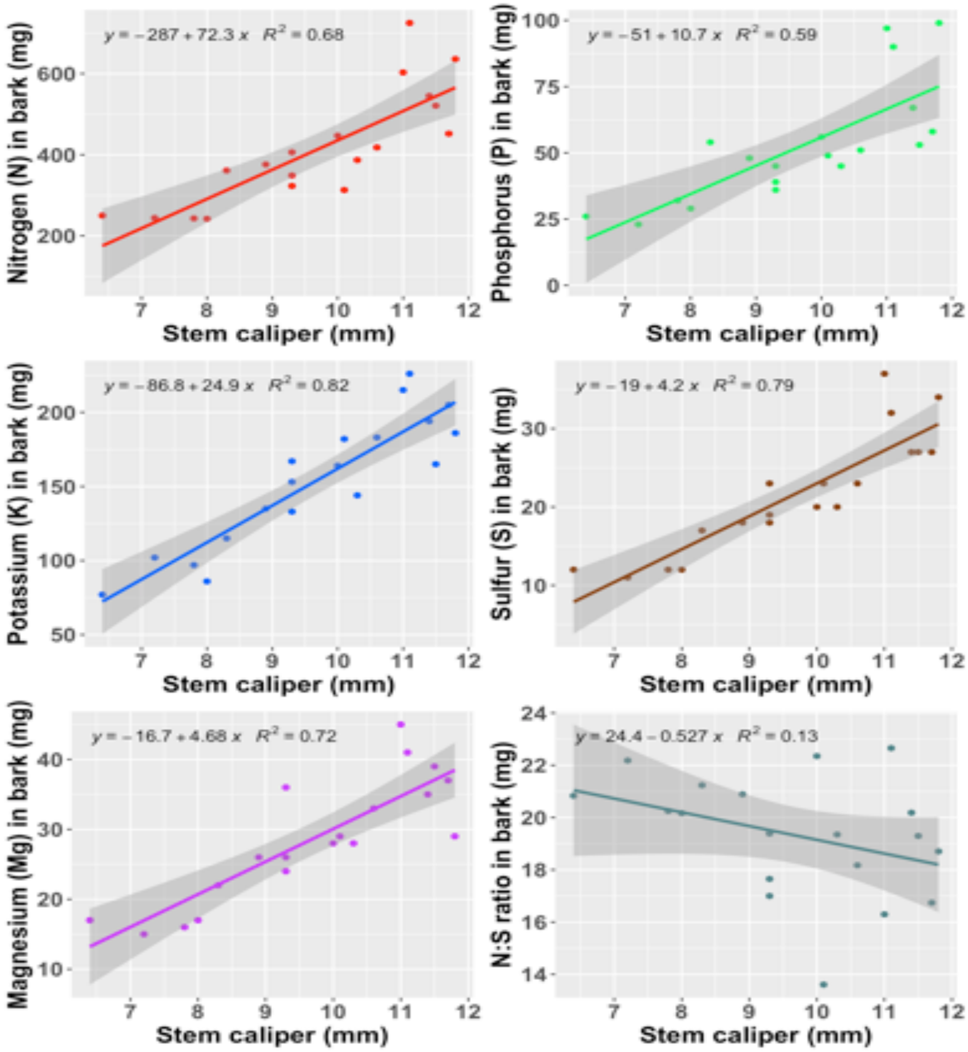

Figure 6. Pre-plant nutritional status of bare-root 'Jefferson' trees. Strong relationships between nutrient content and size of stem were apparent, all regressions had significant slopes ($P < 0.05$), with the exception of N:S ratio.

treatments. For N, maximum UE occurred with the Blend 5 treatment and minimum UE occurred with the Urea15 treatment. At all rates of N, UE was higher in the Blend because of the slow-release formulation. For P applied in the Blend, no more than 5% of the total amount of applied P was taken up into the tree, and the efficiency decreased as the rate of fertilizer increased. UE for S was even lower although S uptake was critical to increased growth. Very little of the applied Mg was taken up into the tree, although a slightly higher Mg efficiency was observed with the higher rates.

- Additional results and discussion can be found in Appendix A.

Table 4. Mean uptake efficiency (standard error of the mean) for nutrients applied in fertilizer to trees after one growing season at NWREC. Uptake efficiencies were calculated from equations 1-3 (Appendix A) utilizing the regression equations from Fig 6 to estimate original nutrient content of trees based on their caliper.

Treatment	**N (SEM)**		**P (SEM)**		**K (SEM)**		**S (SEM)**		**Mg (SEM)**	
Urea5	7.0	(3.40)	0	--	0	--	0	--	0	--
Urea10	4.17	(1.68)	0	--	0	--	0	--	0	--
Urea15	1.60	(0.80)	0	--	0	--	0	--	0	--
Blend5	12.69	(2.97)	5.15	(2.09)	5.39	(3.06)	1.93	(0.54)	0.99	(1.69)
Blend10	4.81	(2.34)	1.28	(0.88)	2.94	(2.16)	1.13	(0.45)	1.20	(1.38)
Blend15	5.73	(1.38)	1.33	(0.55)	2.11	(0.67)	1.30	(0.30)	1.20	(0.51)

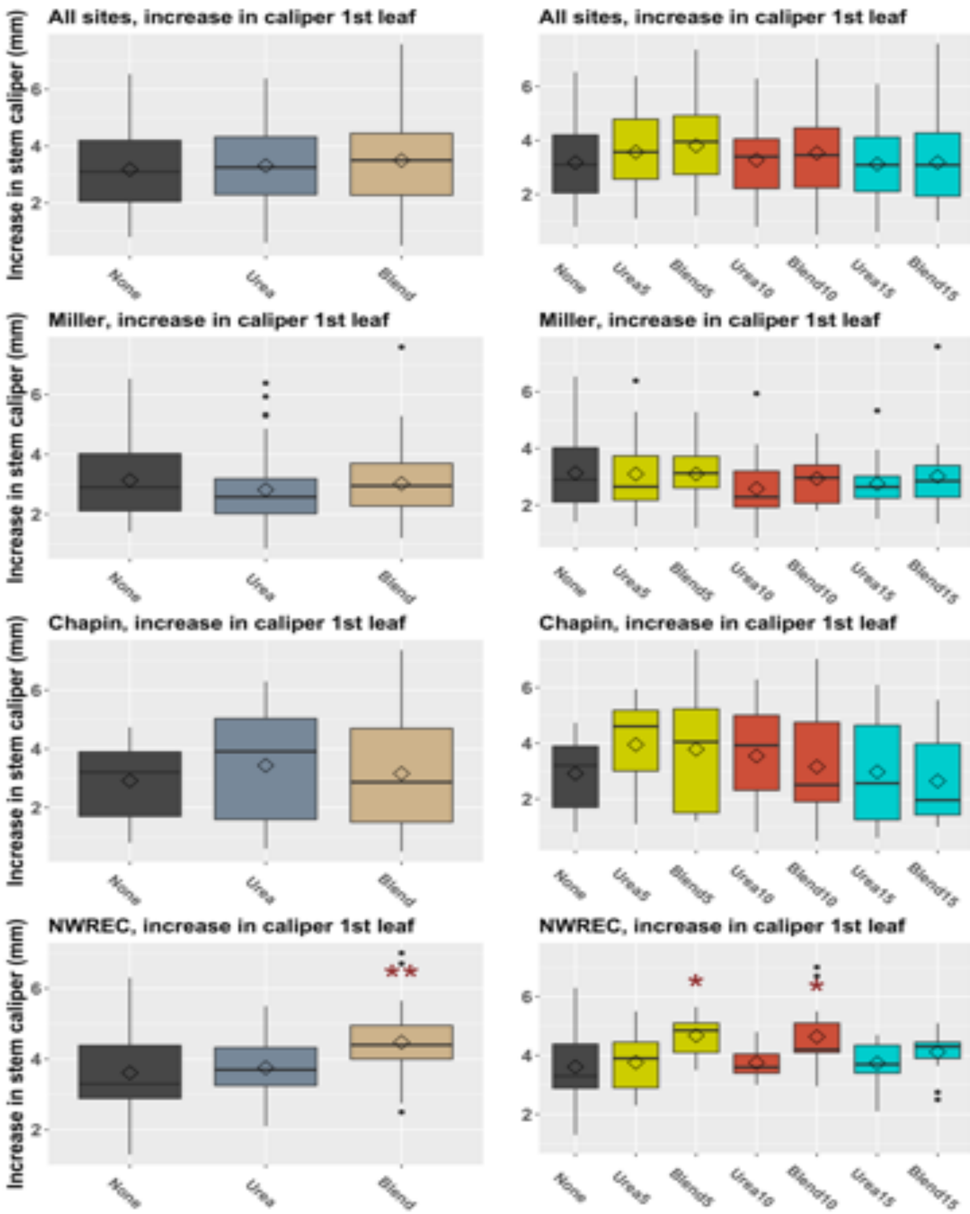

Figure 7. Growth represented by trunk caliper increase from planting to the end of the first growing season. Asterisks indicate significant differences from the control treatment “None” (Dunnett’s Test; $P < 0.10$ = •, $P < 0.05$ = *, $P < 0.01$ = **, $P < 0.001$ = ***).

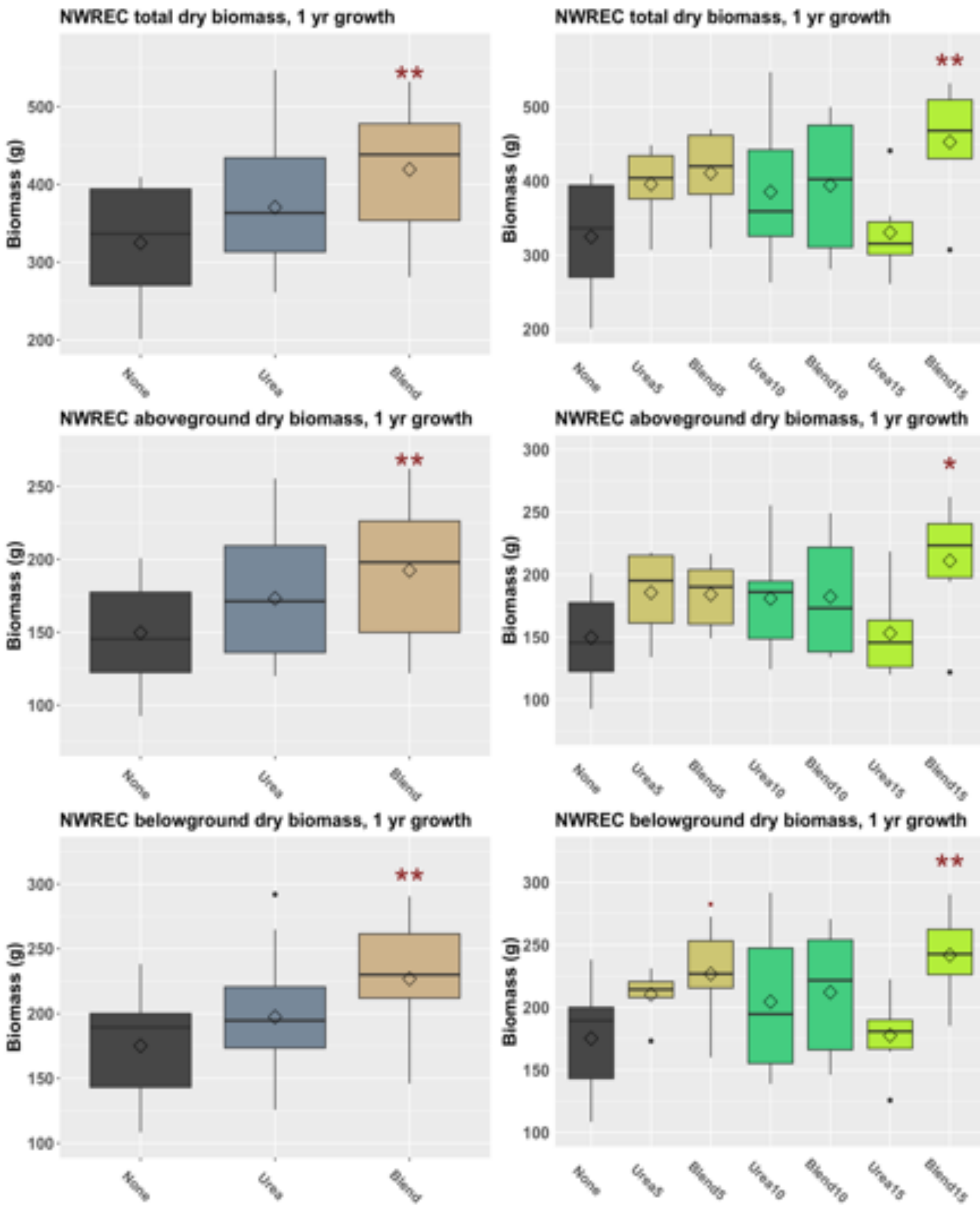

Figure 8. Aboveground, belowground and total biomass of trees destructively harvested at NWREC after one year of growth. Significant differences between individual treatments and the control (None) are indicated by asterisks (Dunnett's Test; $P < 0.10$ = •, $P < 0.05$ = *, $P < 0.01$ = **, $P < 0.001$ = ***).

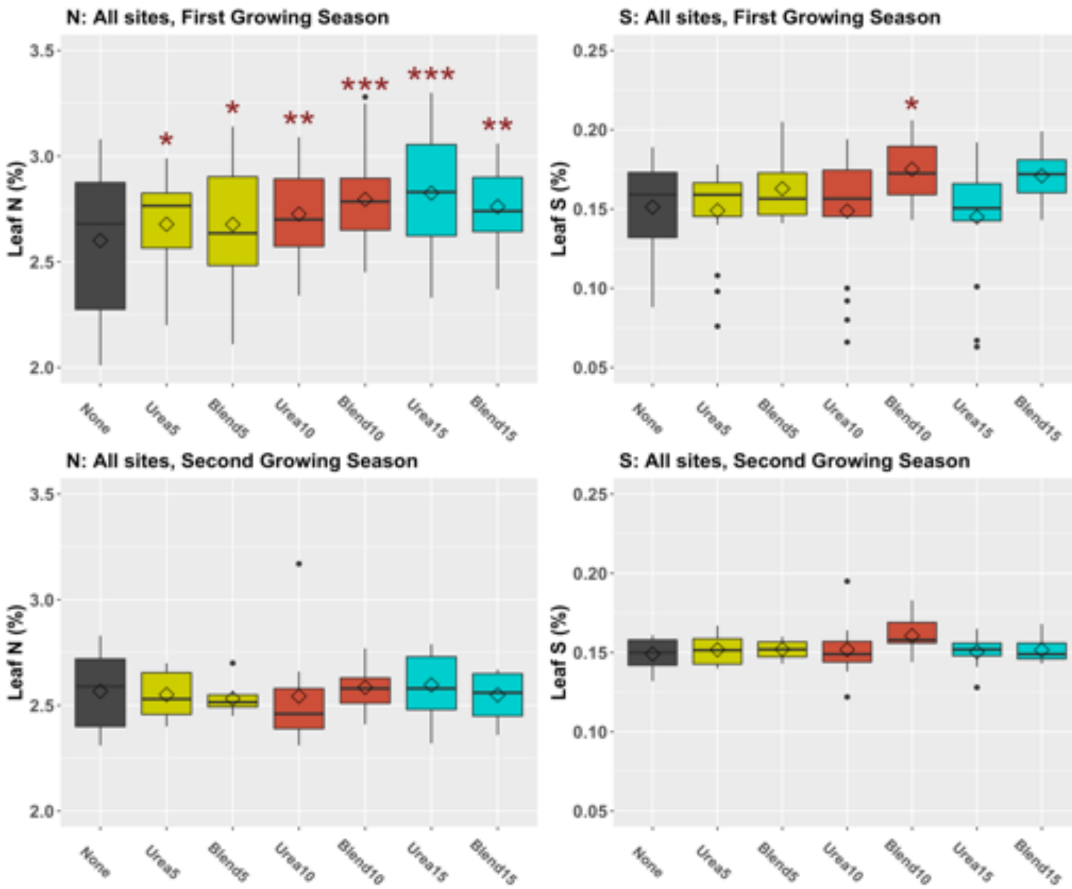

Figure 10. Nitrogen and Sulfur concentration in leaves during the first year of growth. Significant differences between individual treatments and the control (None) are indicated by asterisks (Dunnett's Test; $P < 0.10$ = •, $P < 0.05$ = *, $P < 0.01$ = **, $P < 0.001$ = ***).

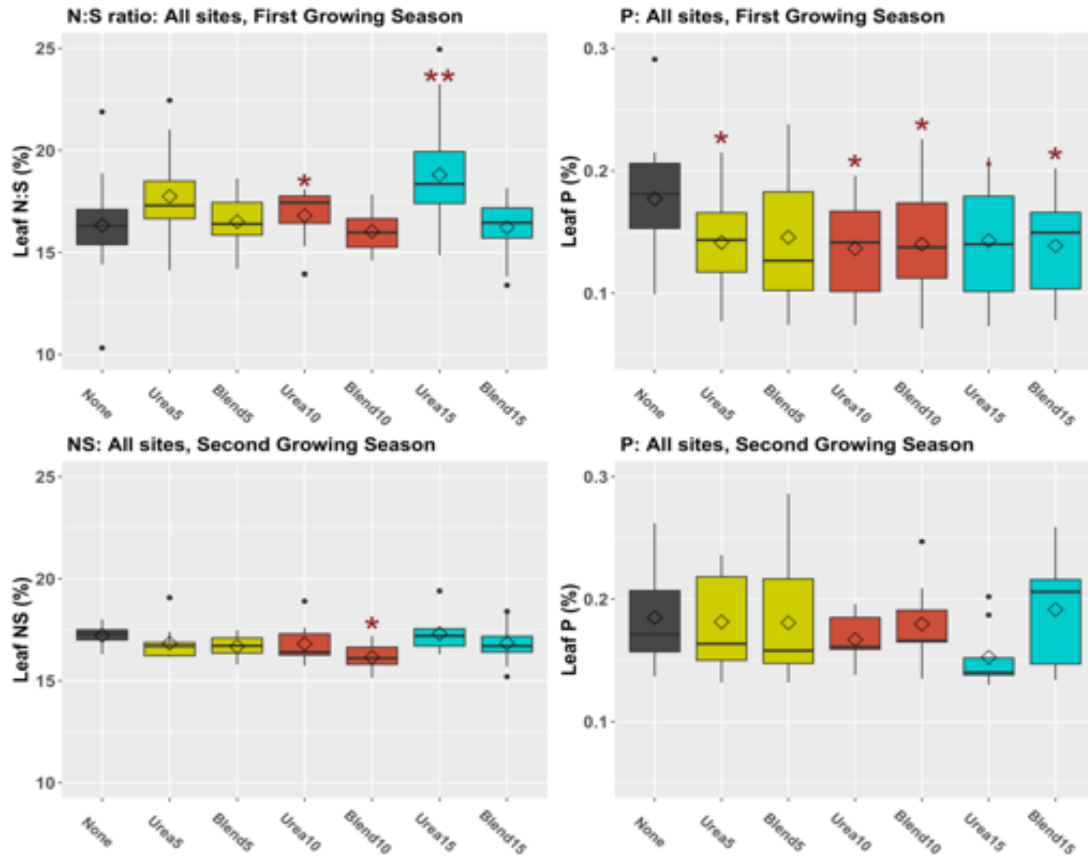

Figure 11. Nitrogen: sulfur ratio and phosphorus in leaves during the first year of growth. Significant differences between individual treatments and the control (None) are indicated by asterisks (Dunnett's Test; *P* < 0.10 = •, *P* < 0.05 = *, *P* < 0.01 = **, *P* < 0.001 = ***).

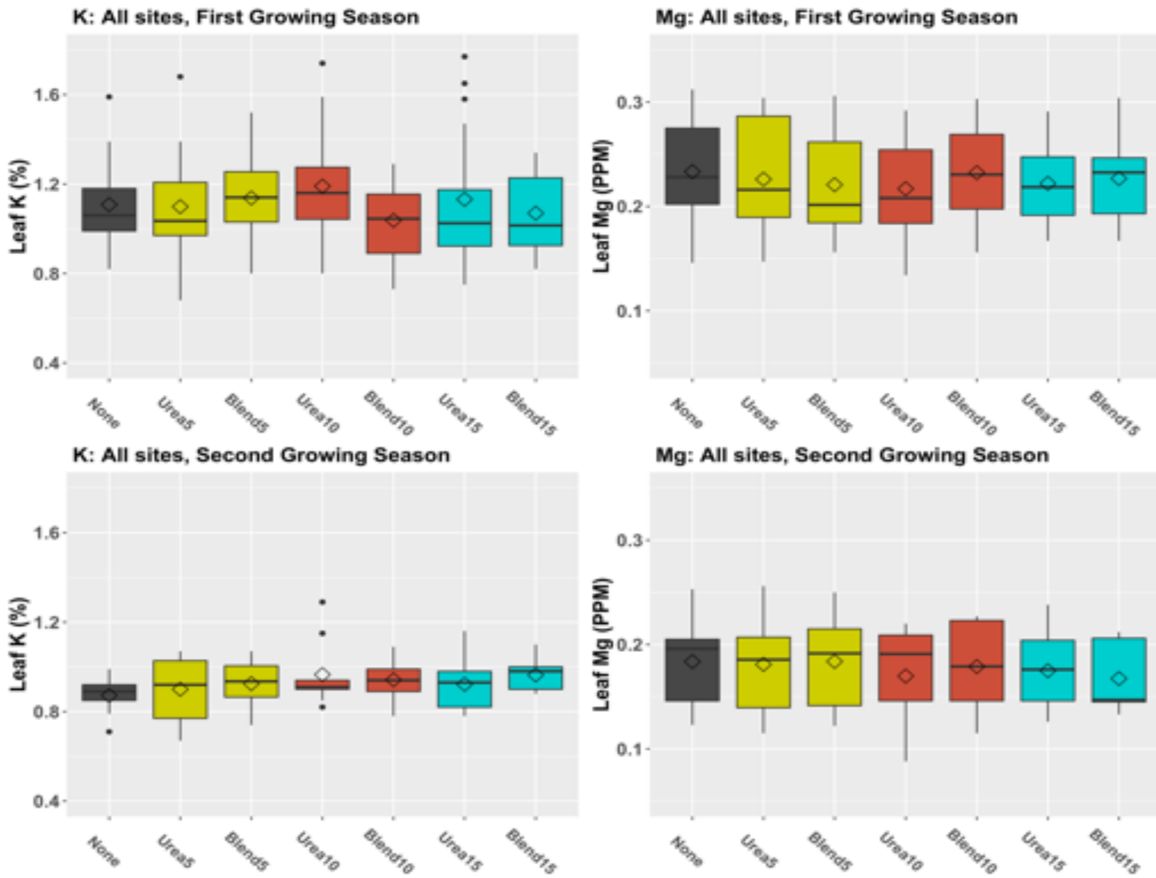

Figure 12. Potassium and magnesium in leaves during the first year of growth. There were no significant treatment differences $P > 0.05$.

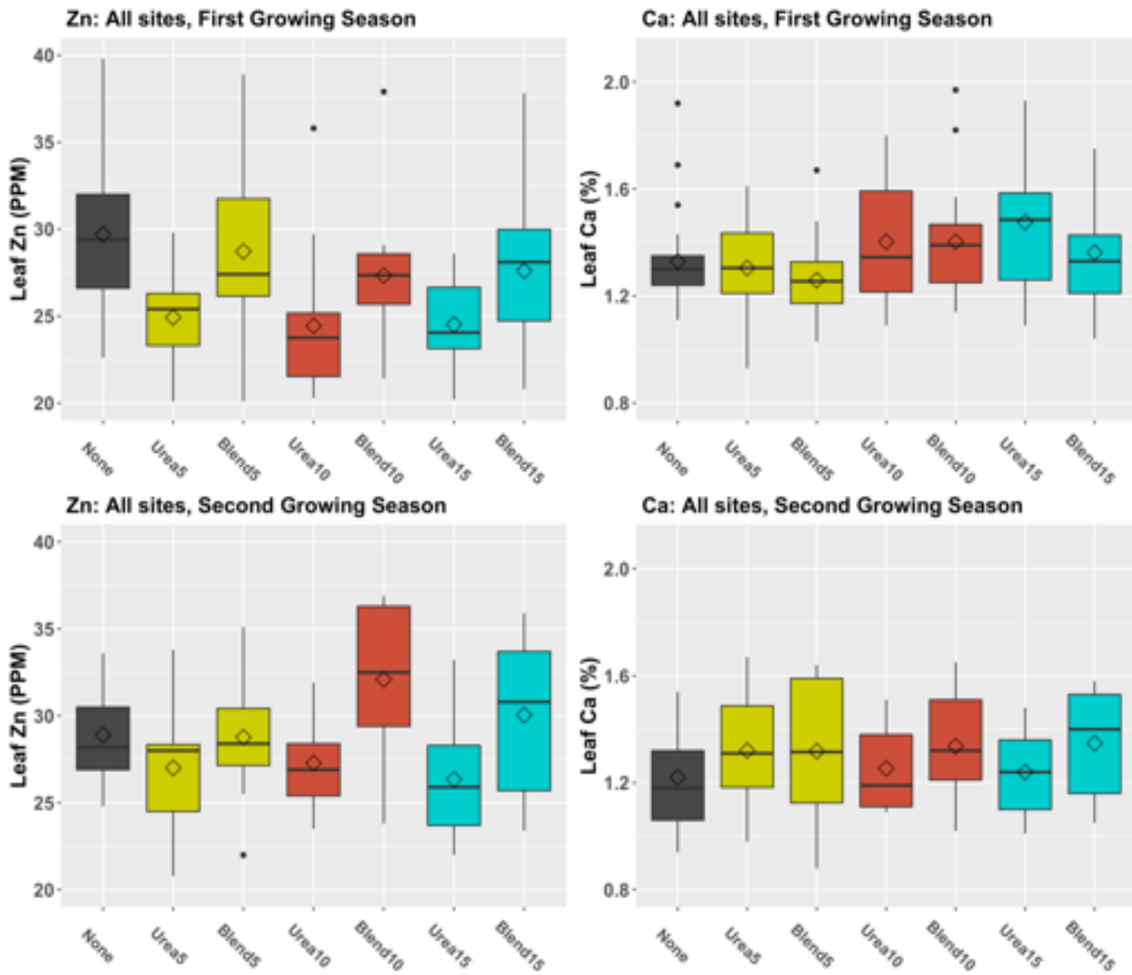

Figure 13. Zinc and calcium in leaves during the first year of growth. There were no significant treatment differences $P > 0.05$.

BENEFITS AND IMPACT:

There have been no previous published data on the effect of fertilizing new hazelnut trees at planting. The most current OSU fertilizer recommendations (Olsen 2013) state that bare root trees have enough nutrients to supply growth for the first growing season. This study did confirm that there are substantial stored nutrients in bare-root trees at planting, but whether this is enough to supply the first year of growth probably varies quite within and between planting stock. Nonetheless, most growers disregard the advice and add fertilizer to new plantings. Occasionally, growers damage new trees by applying too much urea. Injury occurs from temporary high ammonia/ammonium concentrations as the result of urea hydrolysis. Ammonium may accumulate in the spring due to cold soil temperatures which slows nitrification (the conversion of ammonium to nitrate). The danger for urea injury is greatest when applied in a concentrated area (a pile dumped by the tree). This can be avoided by spreading the fertilizer out or using a controlled release urea. In this study, the urea in the Blend was polymer coated (ESN Smart Nitrogen® produced by Nutrien, Ltd.). ESN's polymer membrane allows moisture to diffuse into the granule, creating a nitrogen solution. The solution moves out through the membrane at a rate that is controlled by soil temperature. By slowly releasing the urea, a large, potentially phytotoxic doses of ammonia/ammonium is avoided. Also, leaching may be minimized due to high spring rainfall.

In this study, application of straight urea did not acutely burn trees. However, there is little to recommend applying straight urea to young hazelnut trees. We found that while urea application may moderately benefit to the tree when applied at a low rate, at times, it appeared to inhibit growth at higher rates perhaps due to minor root injury. It also increased the N:S ratio, resulting in S deficiency. Furthermore, application of urea was very inefficient as the maximum uptake we measured was only 7%. Thus, most of this applied urea is wasted and can be considered potential pollution.

The Blend had a higher N uptake efficiency (12% for 5 g of the blend) compared to urea thanks to the slow release mechanism, but it was still rather low efficiency. The addition of the S in the blend was definitely beneficial for the tree, but no other nutrients in the blend had any benefit. When the analysis is completed for the remaining trees, we will be able to more conclusively recommend an improved blend might include S and slow-release N but exclude the other nutrients.

The irrigation at NWREC may have greatly increased the uptake efficiency of nutrients, as the two dryland sites did not show as much response to treatments in terms of trunk caliper increase. However, this remains to be seen and illustrates the importance for future studies to examine nutrient uptake efficiency for different irrigation regimes as well as fertigation.

When fully complete, we will be able to recommend optimal fertilization for new hazelnut plantings that maximize growth of trees while minimizing cost and waste. With current results it is apparent that bare root trees of good stock must contain most of the nutrients required for the first year of growth, and most likely many growers are wasting money and fertilizer on new hazelnut plantings. This is of critical importance to protect water resources and reduce the carbon footprint of hazelnut orchards.

ADDITIONAL FUNDING RECEIVED DURING PROJECT TERM:

In 2018, we received a 3-year ODA fertilizer grant to study the relationship between irrigation and N delivery method on N uptake for young, bearing hazelnut trees. This work will complement the scope of this grant, which is looking at fertilizer requirements for non-bearing trees.

FUTURE FUNDING POSSIBILITIES:

Oregon hazelnut commission: uptake efficiency for fertigation
USDA-NIFA-Organic Transitions (ORG) organic fertility sources and uptake efficiency.

Appendix A.

Preplant nutrients and calculating nitrogen use efficiency

The trees used in this study were bare-root 'Jefferson' trees (not micro-propagated). Unlike seeds, the trees start with a relatively large storehouse of nutrients. The relationship between N content and initial caliper size for the batch of trees we planted is given in Fig 4. The roots contained 2.2% or less of the total N in a bareroot tree. Using this relationship, we can estimate starting N content for each tree and use this to calculate how much of the applied fertilizer N was taken up by the tree using the following equations:

$$N_{s,c} = N_{i,c} - N_{t,c} \quad \text{[Eq. 1]}$$

$$N_{F,f} = N_{t,f} - N_{s,c} - N_{i,f} \quad \text{[Eq. 2]}$$

$$NUE = 100 * N_{F,f}/(R_f + I) \quad \text{[Eq. 3]}$$

Where $N_{s,c}$ is the N uptake from the soil (s) by the unfertilized control (c) in mg, N_i is the initial (i) N content for c or each fertilizer treatment (f) using the equation from Figure 4 in mg, N_t is the total N content from the destructively harvest trees (above and belowground) at the end of each growing season in mg, N_F is the N in the tree from applied fertilizer, R_f is the N rate applied in mg for each fertilizer treatment and I is the amount of N applied to each tree with the irrigation water (for NWREC2018 only), and NUE is the N use efficiency (% of applied N that was taken up by the tree). This equation can be used to calculate nutrient use efficiency for any nutrient,

The NUE can also be calculated using the following equation:

$$NUE = 100 * (N_{t,f} - N_{t,c})/(R_f + I) \quad \text{[Eq. 4]}$$

The benefit for calculating the NUE using equations 1 to 3 is that it takes into account the initial tree size (and thus different starting N content). However, this method also estimates starting N concentration using Table 4, which adds in some variability.