Project Title: Soil and Plant Diagnostic Technology for Smart Nutrient Management

Report Type: Final report

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Project Duration: 2 Years

Total Project Request for Year 1 Funding: $17,812
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Agency Name: NSF USDA
Notes: We will leverage extension and outreach activities that fit both project goals, as well resources associated to internships to support summer activities.

Budget 1
Primary PI: Bernardita Sallato
Organization Name: Washington State University
Contract Administrator: Hollie Tuttle
Contract administrator email address: prosser.grants@wsu.edu

Item	2023	2024
Salaries		
Benefits		
Wages[1]	6400	6656
Benefits	640	666
Equipment		
Supplies[2]	10272	10272
Travel	500	500
Miscellaneous		
Plot Fees		
Total	$17812	$18094

Footnotes: [1] Wages: for sampling @ 16 USD/hour x 400 hours total + 10% benefits.
[2]Supplies: laboratory analyses of 384 samples @ $35.50/sample soil and @ $18 tissue samples x 2 sites, 4 areas, 3 reps and 8 dates.

OBJECTIVES

Our specific focus within the 'smart orchard project' has been to assess mapping technology for plant stress, vigor and fruit quality, soil mapping and plant testing methods and the correlation between indicators. The project started at 'Grandview smart orchard' (Washington Fruit & Produce) and WSU WA 38 Roza Farm as a demonstration site. In year 2 we incorporated the Mattawa Smart Orchard (NWFM).

1. **Assess soil variability mapping tools and soil testing methods that best reflect orchard conditions for effective management.**

2. **Evaluate plant nutrient test methods that can better predict nutrient status for effective management.**

3. **Develop outreach and extension activities; field days and durable products for continue learning, in English and Spanish.**

SIGNIFICANT FINDINGS

- SoilOptix mapping showed moderate correlation with calcium (Ca) and sulfur (S) ($r > 0.55$). Previously, it had also strongly correlated with magnesium (Mg), boron (B), and sand percentage. This suggests a need to calibrate soil sampling in areas with extreme values for these indicators.
- Standard nutrient testing aided to identify limiting conditions, deficiencies or excess. However, the correlation with plant indicators varied across sites and cultivars. For example, in Grandview Honeycrisp, where nutrient levels were within or above the optimal range, the number of fruits per tree correlated strongly and positively with leaf N%. In Mattawa, leaf N% and Mg% had a strong but negative correlation with fruit weight, fruit per tree, and productivity. While K% correlated positively with fruit weight, fruit per tree, and productivity.
- In the Grandview Honeycrisp orchard, bitter pit (BP) incidence increased exponentially with fewer than 50 fruits per tree. In Mattawa, fruit defects, including green spots and sunburn, were positively correlated with higher leaf N levels and negatively correlated with K levels. Additionally, green spot incidence correlated positively with higher leaf sulfur (S).
- Strong positive correlations were observed between leaf N% and Unmanned Aerial System (UAS) NDRE-derived data, as well as between Ca% and NDVI. Conversely, strong negative correlations were found between Fe% and RDVI and SAVI.
- Aerial and soil mapping technologies were helpful in identifying sampling areas, though no mapping technology alone provided reliable predictions for nutrient availability.
- The relationship between sap analysis and productivity and fruit quality parameters varied by orchard. In Grandview, sap levels of Mg, NH_4, and Mo correlated strongly with crop load; N, P, and Ca with fruit size; and NH_4 and S with BP incidence. In Mattawa, sap K levels correlated with the number of fruits per tree and total yield.
- The LAQUAtwin portable testing kit did not provide consistent or accurate values, making it unreliable as a diagnostic tool

METHODS

This project was conducted during 2023 and 2024, in two different orchards. In 2023, the trial was established on a commercial 'Honeycrisp' orchard near Grandview, managed by Washington Fruit and Produce (Grandview). In 2024, we change to a 4th year-old ‘WA 38’ orchard near Mattawa, managed by Northwest Farm Management. In both years, the WSU ‘WA 38’ Roza farm near Prosser has been a platform for workshops and demonstrations. This report will focus on the results from Mattawa 2024 season, and will include relevant data from Grandview when relevant for comparison purposes. For details on methods and Grandview orchard results please review (Sallato and Khot, 2023).

Site selection

In Grandview, four sites were selected; S1 to S4, where visual differences were evident in terms of tree vigor and fruit load. In Mattawa, seven sites were randomly selected across two blocks (Figure 2). Both orchards are under a semi-arid condition with mean annual precipitation of 7 inches (180 mm) during the winter. Summers are hot and dry with temperatures exceeding 100 F (38 C).

Figure 1. Site selection in Smart Orchard Grandview (2023) and Mattawa (2024)

Ground truth data

On each site, three to five representative trees for the selected area were labelled and monitored throughout the season for bloom density, fruit set, fruit yield, shoot growth, and fruit quality: size, firmness, color, and defects. From each site, 20 mature leaves were collected from three neighboring trees (n=12 in Grandiew and n=21 in Mattawa), throughout the season starting in May to determine plant nutrient levels, following Gavlak et al. (2005) methods. Soil ground truth data included soil physical and chemical characterization, including in-depth soil profile analysis. The soil profile analysis followed the USDA, NRCS Soil Survey 2017 guide, which includes texture, structure, infiltration, alkalinity (HCl test), color, porosity, effective depth, among others. For the standard soil test, three composite samples were collected on each site, at three depths (8, 12 and 24 inches) every month from May to September in Grandview, and once in April from Mattawa. The samples were sent to SoilTest Farm Consultants, Inc. in Moses Lake. The method used by the laboratory corresponds to the recommended test methods for western US (Gavlak et al. 2005) and soil health indicators Total N, C, POX, Microbial Respiration CO2, PMN 7-day anaerobic Nitrogen and water holding capacity (WHC).

Obj. 1. Assess soil variability mapping tools and soil testing methods that best reflect orchard condition for effective management.

Different mapping tools were deployed in both sites, including SoilOptix, E.C mapping, Satellite imaging, and several salient data products obtained with a small unmanned aerial system (UAS). The UAS method utilized five-band multi-spectral imaging sensors (RedEdge3, Micasense Inc., Seattle, WA) and thermal infrared sensor (Flir DUO Pro R, Flir systems, Wilsonville, OR). These images

were analyzed and we calculated several vegetation indices; Green Normalized Difference Vegetation Index (GNDVI), Modified Non-Linear Index (MNLI), Normalized Difference Red Edge (NDRE), Normalized Difference Vegetation Index (NDVI), Soil -Adjusted Vegetation Index (SAVI), Blue (B), Green (G), Red (R), Near Ifra Red (NIR), Simple Ratio (SR), Photochemical Reflectance Index (PRI), Structure Insensitive Pigment Index (SIPI), Plant Senescence Reflectance Index (PSRI), Ratio Vegetation Index (RVI), Enhanced Vegetation Index (EVI) and Chlorophyll Index (CI).
The maps were contrasted among each other, and alco correlated with standard soil methods and ground truth data.

Obj. 2. Evaluate plant nutrient test methods that can better predict nutrient status for effective management.

The aerial and ground-based mapping listed above were also contrasted with plant standard nutrient levels and plant productive variables (tree growth, fruit growth and quality, etc).
In addition, nutrient levels were monitored with two alternative methods; 1. sap analysis method offered by Advance Eco Ag (in-kind), and LAQUAtwin (Horiba). The sap analysis was conducted by Advance Eco Ag team and reported levels of pH, E.C, macro and micronutrients. The LAQUAtwin is a portable kit to measure soluble pH, Conductivity, Total Dissolved Solids (TDS), Na+, K+, NO3-, Ca2+ and Salt. Here we explore the feasibility to utilize with stem sap.

Obj 3. Develop outreach and extension activities; field days and durable products for continue learning, in English and Spanish.

RESULTS

Mattawa Smart Orchard

Fruit yield per tree varied between 9.9 to 38 lb, estimated in 9.8 to 23.1 tons per acre (equivalent to 25 to 59, 860 lb bin per acre). Site 1 had 2 to 3.8 times more fruit per trees when compared to all other sites, with no difference with S2 (Table 1). Fruit diameter ranged between 80 and 85 mm, and 271 and 323 g being larger in S6 but only compared with S4. Total yield was lowest in S3 (9.8 tons or 25 bins per acre), compared with S1 (22.8 tons) and S6 (23.1 tons) (Table 1). The proportion of undersized fruit (< 79 mm) was highest in S4 (38%), and lowest in S6 (8%) (Figure 2).

Table 1. Productive differences in Mattawa Smart Orchard, 2024. Different letters indicate significant differences within columns. Probability value computed utilizing Tukey Test.

Category	Yield Tree (Lbs)	Fruit count (n)	Weight (g)	Diameter (mm)	Tons/acre
S1	38.0 a	55.6 a	314.9 a	84.1 ab	22.8 a
S2	31.2 ab	43.0 ab	301.3 ab	82.0 ab	18.7 ab
S3	16.3 bc	22.2 bc	300.8 ab	82.3 ab	9.8 b
S4	16.3 bc	24.8 bc	270.9 b	80.1 b	19.5 ab
S5	9.9 c	13.4 c	295.8 ab	82.1 ab	11.8 ab
S6	19.3 bc	24.8 bc	323.2 a	84.9 a	23.1 a
S7	13.9 c	17.4 c	311.9 a	82.8 ab	16.7 ab
p value	<0.001	<0.001	0.009	0.040	0.042

Note: Tree density in S1, S2 and S3 is 1320 trees per acre, and 2640 in S4, S5, S6 and S7.

Two weeks after harvest, fruit color coverage was lowest in S6, which also had higher starch, suggesting slight delay in maturity compared to all other sites. Fruit firmness ranged between 19.7 and 21.2 lb, considered adequate for WA 38, with no differences across sites (Table 2). Among defect, green spot and sunburn were the most relevant in WA 38 2024 harvest season. Sites 6 and 7 had 15 and 3.5 times higher green spot, compared S1, S2 and S3 (< 2.5%), and S4 and S5, respectively (Table 2). Other defects included sunburn and fruit cracks, also with higher incidence in S6 and S7 (Table 2).

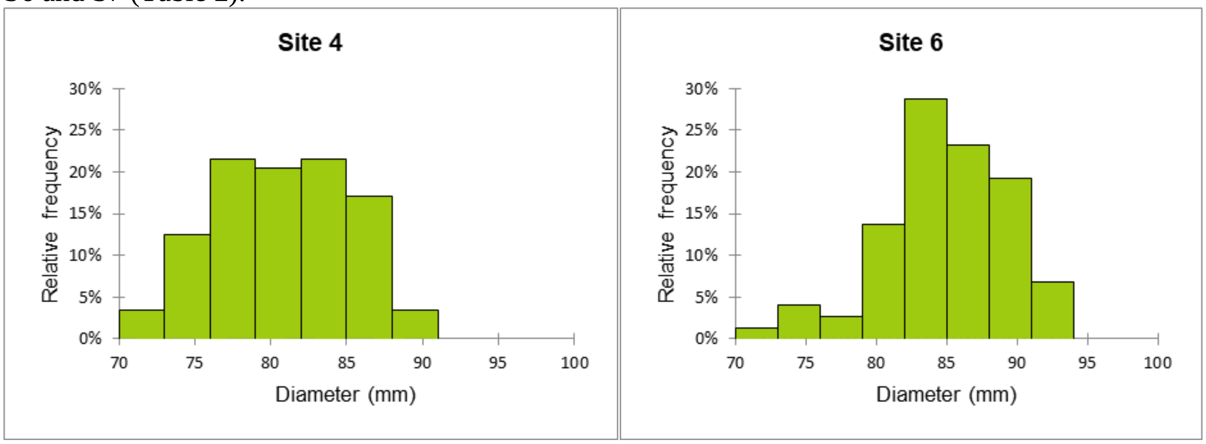

Figure 2. Fruit diameter (mm) distribution in site 4 and site 6.

Table 2. Difference in fruit quality parameters of 'WA 38' apple ground in different sites. Different letters indicate significant differences within columns (Tukey Test).

Category	Color (0 - 3)	Firmness (Lb)	Starch	Green spot %	Defect %
S1	3.0 a	19.7	4.0 bc	2.5 c	6.3 c
S2	3.0 a	21.2	4.3 abc	1.3 c	7.6 c
S3	3.0 a	21.2	4.5 ab	0.9 c	7.7 c
S4	2.9 ab	20.6	4.5 ab	6.6 b	13.3 c
S5	3.0 a	21.0	4.6 a	6.3 b	19.1 bc
S6	2.7 b	20.9	3.8 c	23 a	39.5 ab
S7	3.0 a	20.9	4.5 ab	23 a	51.2 a
p value	<0.001	0.28	<0.001	<0.001	<0.001

Shoot growth was 30% lower in S1 compared with S7 (Figure 3). Overall productivity, calculated as the total yield minus all defects, was doubled in S1 compared with S3 and S7 (Figure 3), with all other sites being in between.

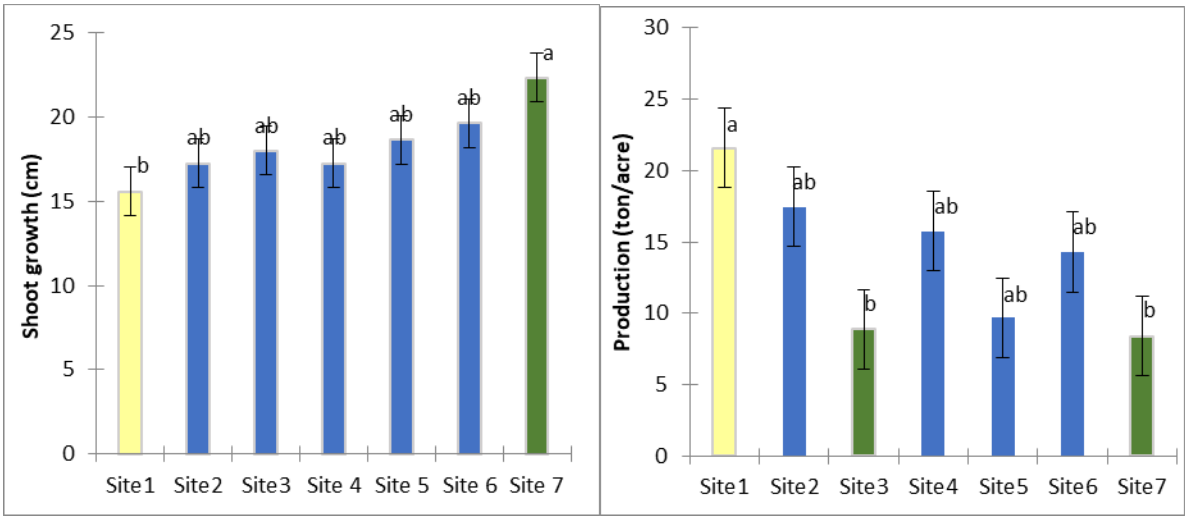

Figure 3. Shoot growth (left) and production (right) by site in Mattawa Smart Orchard, 2024. Different letters indicate significant differences among sites. Probability value computed utilizing Tukey Test.

Obj. 1. Assess soil variability mapping tools and soil testing methods that best reflect orchard condition for effective management.

Mattawa

The Mattawa orchard was associating to Burbank series, characterized by excessive drainage with reduced water holding capacity (8% at field capacity and 2% at wilting point). The parent material is eolian sands over gravelly glacial outwash (Figure 4).

0 to 16 inches; grayish brown (10YR 5/2) loamy sand; many roots; slightly alkaline (pH 7.4)
16 to 30 inches; light brownish gray (10YR 6/2) very gravelly loamy sand; loose; few roots; about 45 percent pebbles, CaCO3 - silica; strongly effervescent; slightly alkaline (pH 7.8); abrupt wavy boundary.
30 to 35 inches; light brownish gray (10YR 6/2) extremely gravelly; loose; about 85 percent pebbles and cobbles, some completely coated with lime-silica; violently effervescent; moderately alkaline (pH 8.3)

Figure 4. Soil profile representative of Mattawa Smart Orchard.

Soil pH ranged between 6.5 and 7.5 with no differences between sites (Table 3). Electric conductivity, as indicator of salinity, was below 0.4 mS/m and O.M ranged between 0.4% in S1 and

2.2% in S6. Soil available P (OlsenP) was within adequate range in all sites, except in S7 where P availability was 10.3 ppm. Soil K was adequate and highest in S1, while all other sites had K levels below optimum values. Soil Ca and B (not shown) were low with no differences between sites. Soil Mg was adequate, being higher in S2 and lowest in S1. Sulfur levels were low on S6 and S7 (Table 3).

Table 3. Soil pH and available nutrients (ppm) in Mattawa Smart Orchard, 2024. Different letters indicate significant differences within rows with probability value < 0.05 (Tukey Test)

Parameter	Optimum range	S1	S2	S3	S4	S5	S6	S7
pH	5.0 – 7.5	7.00	7.10	7.23	6.90	6.73	7.33	7.33
Olsen P	15 - 40	23.3 bc	31.0 b	41.7 a	32.0 ab	33.7 ab	19.3 cd	10.3 d
K	150 - 250	191.3 a	101.7 b	117.0 b	122.7 b	132.3 b	120.3 b	77.7 b
Ca	820 - 4000	600.0	680.0	686.7	673.3	680.0	773.3	600.0
Mg	60 - 300	157.3 c	221.8 a	193.6 abc	213.8 ab	193.6 abc	197.6 ab	177.5 bc
S	9 - 20	15.9 cd	28.0 a	28.4 a	26.0 ab	18.2 bc	5.4 e	7.4 de

Differences in physical and chemical characterization were present, however within a small range of variability. Generally, S1 had better conditions for apple growth, with balanced and adequate nutrient levels. S1 also had deeper effective soil depth, higher root volume and less gravel, compared to the southernmost sites (S2, S7 and S5) (Figure 5)

Figure 5. Soil profile of S1, S7 and S5. Mattawa Smart Orchard.

Soil mapping Mattawa

SoilOptix mapping correlated moderately with Ca and S (r > 0.55) (Figure 6). In our previous work, SoilOptix had a strong correlation, not only with Ca, but also with Mg, B and Sand %. These correlations were weak at the Mattawa orchard (Figure 6). These lack of consistency regarding the correlations with soil test levels could be associated with different soil types and the ranges in soil nutrient concentration. While the standard protocol requires three samples for calibration, we recommend additional sampling of areas that suggest extreme conditions.

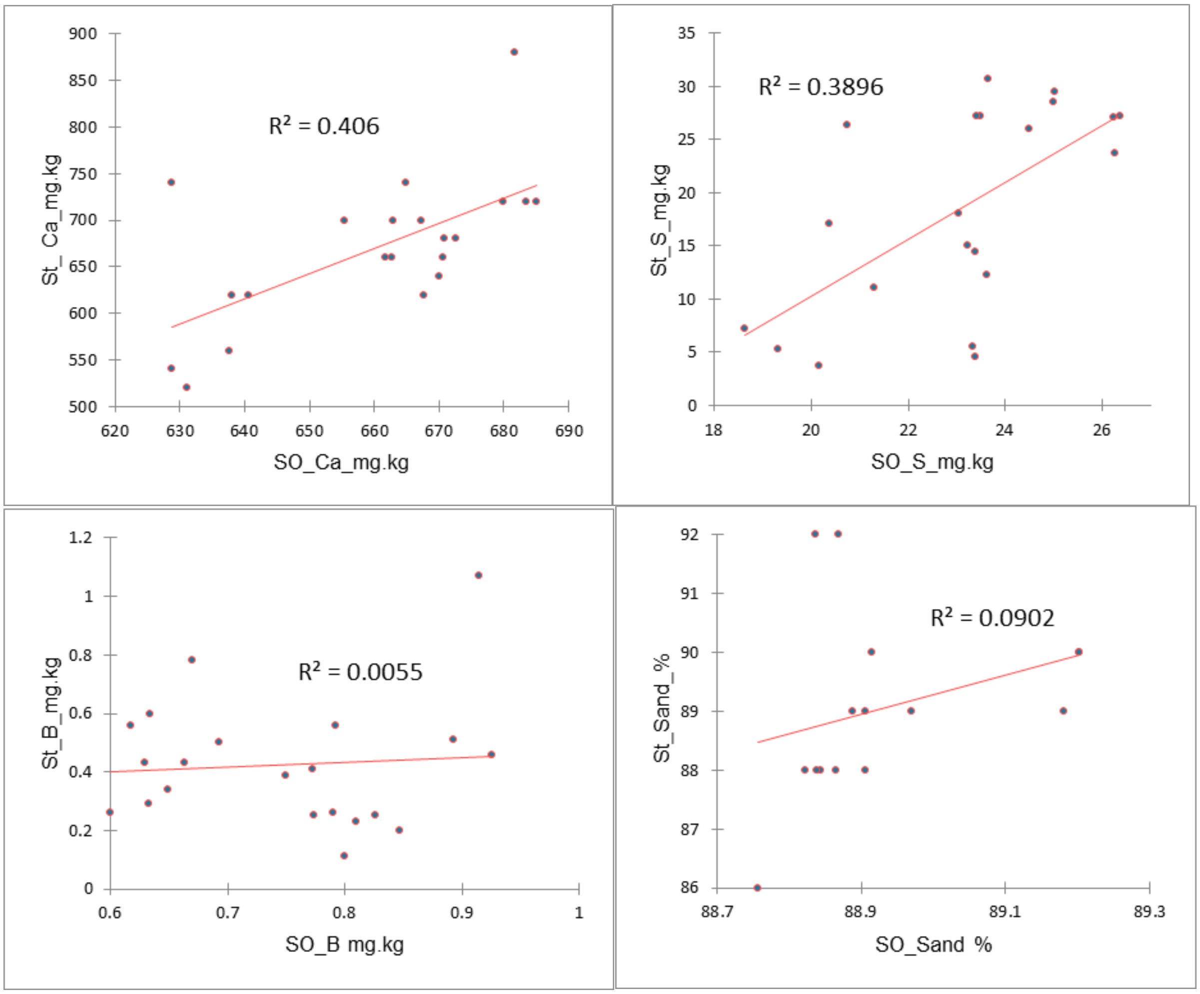

Figure 6. Correlation between standard soil test and SoilOptix for Ca (top left), S (top right), B (bottom left) and sand (bottom right).

Obj. 2. Evaluate plant nutrient test methods that can better predict nutrient status for effective management.

Grandview

At Grandview, fruit number correlated strongly and positively with leaf N% ($r = 0.86$) (Figure 7), and moderately with leaf P, Ca and Fe ($r > 0.55$) (data not shown). While BP incidence did not correlate with any leaf nutrient concentration. Here we found that BP incidence increases exponentially with less than 50 fruit per tree.

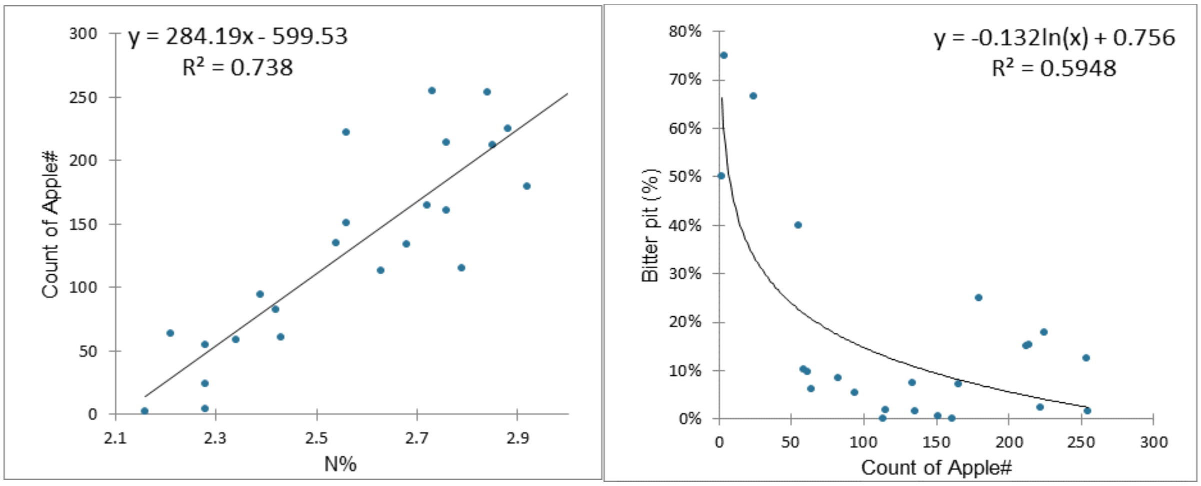

Figure 7. Correlation between fruit count and leaf N concentration (left) and Bitter pit incidence (right).

Mattawa

Leaf N was lowest, but within range in S1, S2 and S3, compared to excessive in S4, S5, S6 and S7 (Table 4). Leaf P differences have no agronomic significance and were within adequate range in all sites. Leaf K was highest in S1, in agreement with a higher soil K in S1. Leaf Ca were low (S1) or at deficiency levels (all other sites), also in agreement with soil Ca levels. Leaf Mg and S were above recommended level across all sites, but not at toxicity level (Table 4). Micronutrient Zn and Mn were not different across sites, and within adequate range (data not shown).

Table 4. Leaf nutrient concentration in WA 38 Mattawa Orchard by site. Different letters indicate significant differences within nutrient (column).

Site	N	P	K	Ca	Mg	S
			%			
Site 1	2.0 c	0.3 ab	2.7 a	1.5 a	0.40 d	0.21 c
Site 2	2.2 c	0.4 a	2.2 b	1.4 ab	0.44 cd	0.21 c
Site 3	2.3 bc	0.3 abc	1.6 d	1.3 abc	0.52 a	0.22 bc
Site 4	2.8 a	0.3 c	1.8 cd	1.3 abc	0.49 ab	0.25 a
Site 5	2.7 ab	0.3 bc	1.7 cd	1.1 c	0.49 abc	0.26 a
Site 6	2.5 ab	0.3 abc	2.0 bc	1.2 bc	0.47 abc	0.24 ab
Site 7	2.6 ab	0.3 abc	1.9 bcd	1.2 bc	0.46 bc	0.22 bc
p value	<0.0001	<0.0001	<0.0001	0.005	<0.0001	<0.0001

While correlation between leaf and soil standard nutrient levels were weak (data not shown), both methods distinguished between extreme conditions of low and high nutrients, which also correlated with differences among sites.

Leaf N and Mg levels correlated strongly (r < -0. 59) and negatively with fruit weight, fruit per tree and productivity (Figure 8). In contrast, leaf K correlated positively with fruit weight (r = 0.78), fruit per tree (r = 0.74) and productivity (r = 0.64). Frut defects were positively correlated with leaf N (r = 0.61) and negatively with K (r = -0.60). All other correlations were weak or not significant (data not shown).

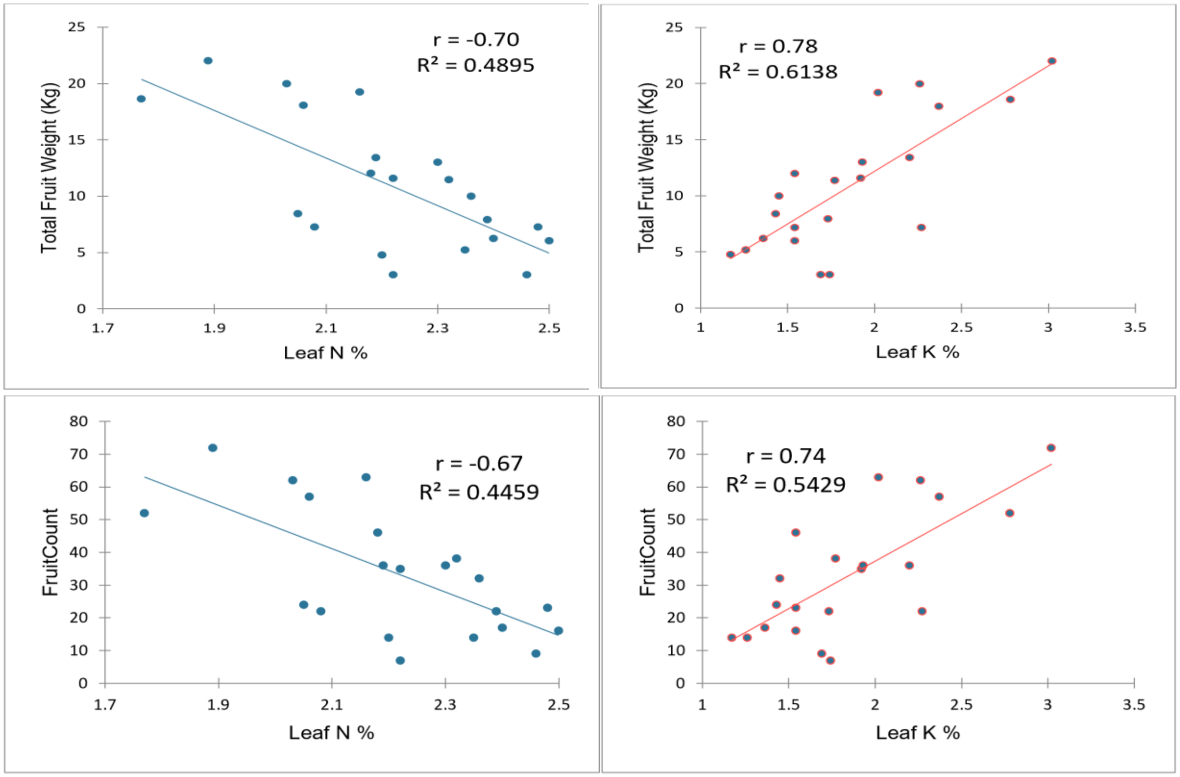

Figure 8. Correlation between total fruit weight per tree (Kg) (Top) and fruit per tree (bottom) with leaf N (left) and leaf K (right).

Green spot incidence varied between 0 – 35%, being significantly higher in S6 and S7, intermediate in S4 and S5, and lowest in S1, S2 and S3. There was a significant and moderate correlation between green spot incidence and leaf S levels (r = 0.65) (Figure 9). The relation between green spot and leaf N fitted an exponential model (Green spot % = 2.28754e-06*exp(4.50008*N). The relationship with green spot and high N, high N:Ca ratio and higher vigor has been reported previously (Sallato et al., 2021).

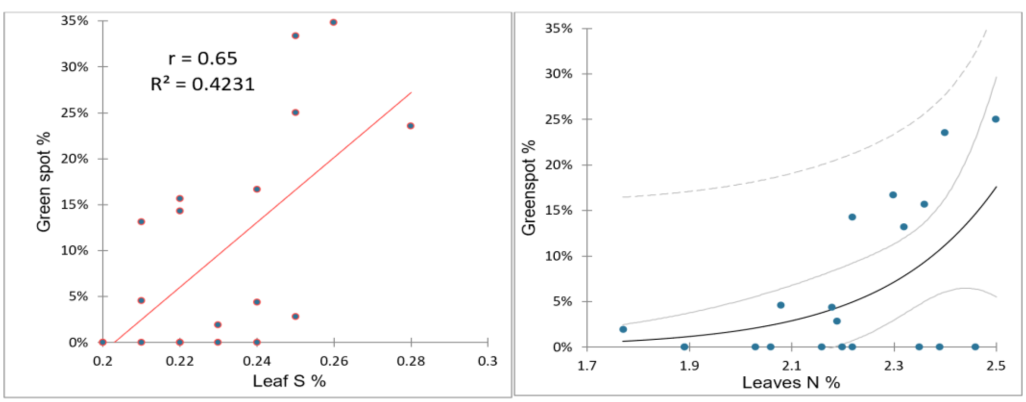

Figure 9. Green spot incidence in WA 38 versus leaf S% (left) and leaf N (right).

Sap analysis

In 2023 Grandview orchard, standard Ca and sap Ca correlated strongly with Cl (r = 0.83 and r = 0.95, respectively), which might relate to foliar CaCl sprays, commonly used in WA orchards. Sap Mg, NH4 and Mo levels in older leaves correlated strongly with crop load (r > 0.70), and Ca with fruit size (r = 0.80) (data not shown). Sap N and P levels in young leaves correlated strongly with fruit size (r > 0.85), while NH4 and S correlated strongly with BP incidence (r > 0.81) (Figure 10).

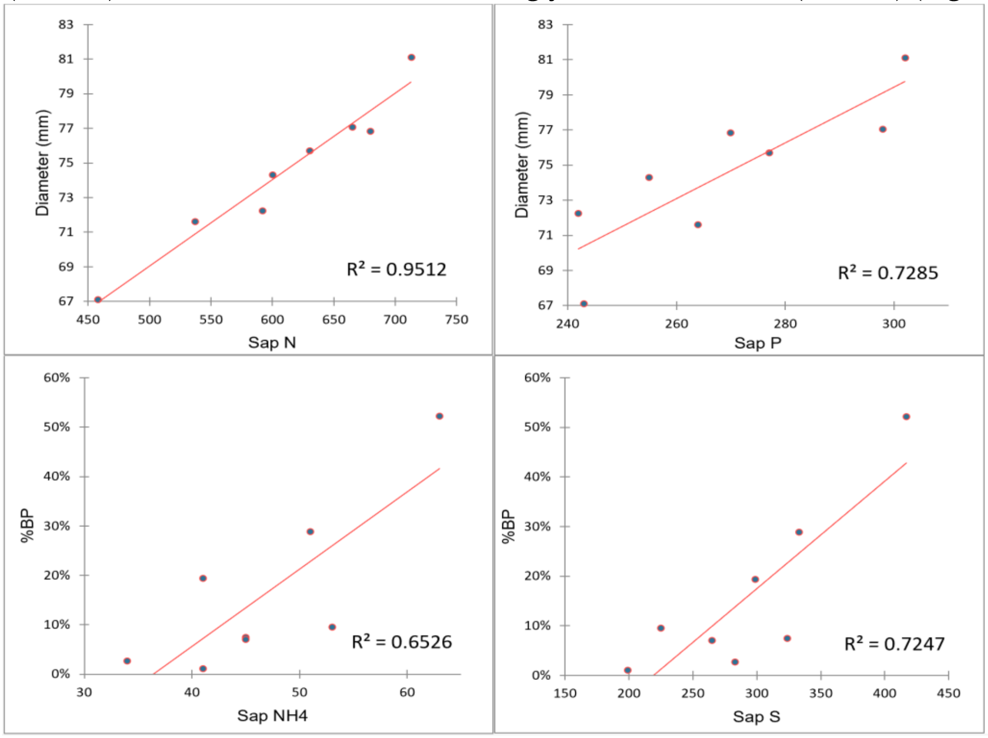

Figure 9. Correlation between sap mineral analysis of young leaves during August and fruit diameter (top) and bitter pit (BP) incidence (bottom).

In Mattawa, differences across sites were only observed in P, K and Mg sap in old leaves and P and K of spur leaves. All other elements show no differences across sites (Table 5).

Table 5. Sap analysis of shoot old leaves (Shoot_Old) and young spurs leaves (Spur Young) with significant differences across sites.

	Shoot_Old_P	Shoot_Old_Mg	Shoot_Old_K	Spur_Young_P	Spur_Young_K
Site 1	1259.3 a	1122.6 c	9516.9 a	1511.7 a	9407.7 a
Site 2	930 ab	1358.3 abc	7647.8 b	841.3 b	8218.7 ab
Site 3	800.8 b	1345.4 bc	7326.0 b	650.3 b	7249.3 ab
Site 4	779.5 b	1558.0 ab	6645.0 b	602.3 b	6220.7 b
Site 5	721.6 b	1698.2 a	6859.6 b	656.3 b	5758.0 b
Site 6	883.6 ab	1676.8 ab	7116.2 b	764.0 b	6915.0 ab
Site 7	756.6 b	1671.4 ab	6828.0 b	736.3 b	6709.7 b
p value	0.015	0.000	<0.0001	<0.0001	0.017

Sap K levels in old shoot leaves and young spur leaves correlated with total yield (total fruit weight), and fruit per tree (Figure 10).

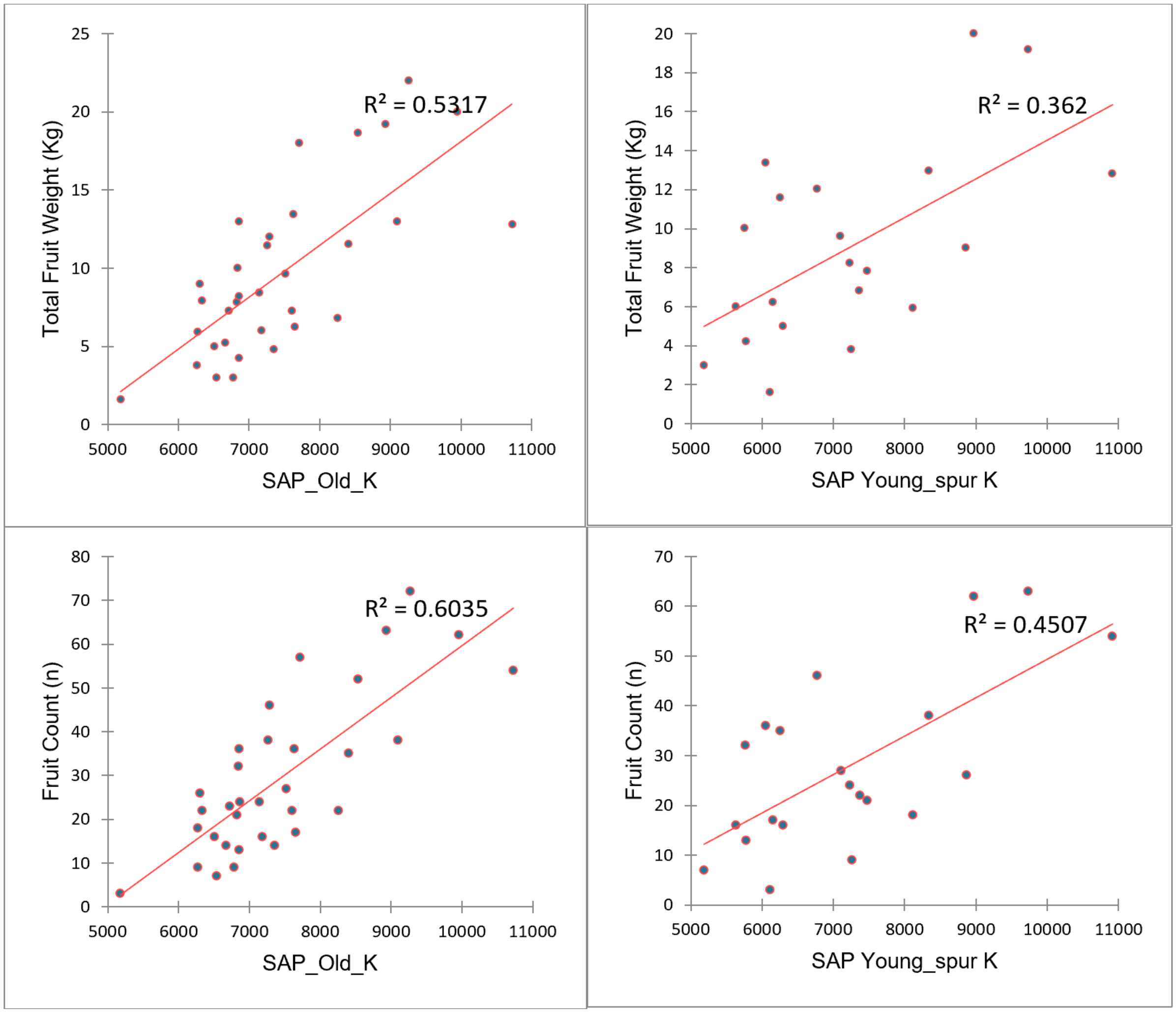

Figure 10. Correlation between total fruit weight per tree (Kg) (Top) and fruit per tree (bottom) with K sap in old shoot leaves (left) and young spur leaves (right).

Note that while we collected samples for sap analysis for contrast, we did not apply nutrient recommendations based on sap analysis. Specific recommendations, based on sap analysis included foliar Ca for 1,2,3,5,7 during May due to general lower calcium levels. Potassium foliar application during August 5th due to inverted relationship between old and new leaf in site 3. Micronutrient spray from May 24 through June 14, consisting of Fe, Mn, Zn, Cu, and Mo in site 5.

LAQUAtwin Kit test.

The LAQUAtwin portable testing kit did not provided consistent or accurate values to use as a diagnostic tool (data not shown). For example, LAQUAtwin NO3 was strongly but negatively correlated with the standard N in leaves (r = -0.97), thus is not recommended for stem or leaf nutrient testing.

3. Develop outreach and extension activities; field days and durable products for continue learning, in English and Spanish.

We conducted several WSU extension and outreach efforts. In 2023 we share initial findings at the WFTRC Apple review (January 25th, 2023), Apple Day, Chelan Tree Fruit Day, and Okanogan meeting. We provided a summary report on soil mapping technology published in our WSU Tree fruit newsletter "Fruit Matters" (Jan 2023). We conducted a "spring Drone Day" in May demonstrating mapping technology inviting different providers, a summary of the field day was published by Good Fruit Grower and in Fruit Matters. On June 21, 2023, we hosted the Western Ag Leadership tour, comprised ~60 Deans and extension professionals from Universities in the Western US in the WA 38 site, showcasing heat and irrigation technology of the smart orchard project. In July, we coordinated a field day in Spanish at the WA38 Roza farm to update participants on heat stress mitigation technology, irrigation and the smart orchard initiative. In collaboration with our collaborators (Innov8Ag and WSU AgAID), we conducted two field days (August 2nd and September 16th) where the PI's and their interns' shared findings. The August field day was attended by over 200 people and close to 30 growers attended the September Smart Orchard + AgAID field day. In Dec, Sallato presented about the smart orchard project at the ISHS meeting on rootstocks and orchard systems, Australia.

In 2024, we coordinated a Spanish field day on irrigation, plant physiology, sensors and automation. We had 70 participants, four educators and three private companies (Wilbur Ellis, Phytech and Wiseconn).

Field day on irrigation technology at WSU WA 38 Roza farm. Photo credit: Good Fruit Grower.

EXECUTIVE SUMMARY

Title: Soil and Plant Diagnostic Technology for Smart Nutrient

Key words: Soil mapping, WA 38, SoilOptix, Sap analysis, Nutrient relations

Abstract:

Effective nutrient management in tree fruit production requires a comprehensive understanding of multiple interacting factors, including soil conditions (physical, chemical, and biological), plant health and demand, water availability, and environmental conditions. Current methods like soil and plant tissue testing, standardized by the Soil Science Society of America (SSSA), remain underutilized among growers due to a perceived lack of correlation between test results and outcomes in crop growth, yield, and quality. Growers and service providers are exploring new technologies to better predict plant nutrient status and inform management practices.

In 2023 and 2024, we evaluated new and existing nutrient management tools across two orchards: A commercial 'Honeycrisp' orchard near Grandview in 2023, and a 'WA 38' orchard near Mattawa in 2024. Technologies deployed included advanced mapping tools: SoilOptix, E.C. mapping, satellite imaging, and unmanned aerial system (UAS) data products. Derived data was correlated with plant nutrient levels and productivity parameters (e.g., tree and fruit growth, fruit quality). Additionally, two alternative nutrient monitoring methods—sap analysis (Advance Eco Ag) and LAQUAtwin (Horiba)—were tested.

SoilOptix mapping, though useful, requires additional calibration for reliable nutrient management recommendations. It demonstrated strong correlations for calcium (Ca) across both sites and years, and for sulfur (S), magnesium (Mg), boron (B), and sand in two of the three orchards. Tools such as SoilWeb Survey, Google Earth, and UAS also aided in guiding sampling decisions. Leaf nutrient levels showed correlations with productivity metrics like fruit count, weight, yield, and disorders. However, these correlations varied by cultivar and site. In Honeycrisp, low nitrogen (N) was linked to smaller fruit size, given the site was overcropped. In WA 38, higher N levels were associated with green spot and higher shoot growth, given the block is young and still filling the space. UAS imaging data revealed useful correlations with nutrient levels. Positive correlations between leaf N% and NDRE, and Ca% with NDVI. And negative correlations between Fe% with RDVI and SAVI. These findings suggest that UAS imaging data could support variable-rate nutrient application for micronutrients. Sap nutrient correlations varied by orchard: For example, in Grandview: Mg, NH_4, and Mo levels in sap correlated with crop load; N, P, and Ca correlated with fruit size. In Mattawa: Sap K levels correlated with fruit count and yield. The LAQUAtwin portable kit did not yield reliable results for nutrient diagnostics.

Precision nutrient management in apple orchards demands a holistic approach, integrating diverse data sources and insights into plant physiology, soil chemistry, and environmental interactions. Standard soil and tissue testing remain valuable but require context-specific understanding for optimal use. While mapping technologies and UAS imaging provide new opportunities to assess nutrient variability, further refinement is needed to enhance precision and develop actionable recommendations for variable rate nutrient application.