FINAL PROJECT REPORT

Project Title: How do we measure and manage soil health for productive orchards?

PI:	S. Tianna DuPont	**Co-PI**:	Lee Kalcsits
Organization:	Washington State University	**Organization**:	Washington State University
Telephone:	(509) 293-8758	**Telephone**:	(509) 663-8181
Email:	tianna.dupont@wsu.edu	**Email**:	lee.kalcsits@wsu.edu
Address:	1100 N. Western Ave	**Address:**	1100 N. Western Ave.
City/State/Zip:	Wenatchee/WA/98801	**City/State/Zip:**	Wenatchee/WA/98801

Cooperators: Clark Kogan, Washington State University, Department of Mathematics and Statistics

Orchardist site hosts: Hannah Walters, Bernardo Reyes, Stemilt; Tony Mena, Joe Gabriel, Rob Mc Graw, David Keller, Daniel Canales, Gilbert Orchards; Michael Burns, Zirkle Fruit; Keith Valeska, Harrison Ranch; Craig Obrien; Orlin Knutsen, Alamo Orchard; Keith Oliver, Olsen Bro; Lauren Gonzalez, Kershaw; Rolando Martin, WA Fruit; Jake Robison, Robison Orchards, Mark Gores; Rory Otte; Brian McMillon, Red Top Orchard; Steve Scheib, Highland Partnership; Suzanne Neiman, Alan Brothers; Chris and Paul Williams; Sam Godwin, Box Canyon Fruit; Geoff Thorton; Ray Fuller; Mike Brownfield; Jeff Cleveringa, Starr Ranch; Lee Pobst; Jim Baird; Mike Robinson; Columbia Fruit.

Total Project Request: Year 1: $48,884 **Year 2**: $51,258 **Year 3**: $51,686

Budget 1

Organization Name: WSU-TFREC **Contract Administrator:** Kim Rains/Katie Roberts

Telephone: 509.293.8803/509.335.2885 **Email:** kim.rains@wsu.edu/arcgrants@wsu.edu

Item	**2017**	**2018**	**2019**
Salaries[1]	$24,600	$25,584	$26,607
Benefits[2]	$9,740	$10,130	$10,535
Wages	0	0	0
Benefits	0	0	0
Equipment	0	0	0
Supplies[3]	$10,272	$11,272	$10,272
Travel[4]	$4,272	$4,272	$4,272
Miscellaneous	0	0	0
Plot Fees	0	0	0
Total	$48,884	$51,258	$51,686

Footnotes:

[1]Salaries for a 25% scientific assistant (Kalcsits) and a 33% scientific assistant (DuPont).

[2]Benefits at 44.1% for scientific assistant (Kalcsits) and 37% for scientific assistant (DuPont).

[3]Goods and services include soil nutrient analysis, soil quality analysis, plant tissues tests, fruit quality analysis, sampling and lab materials.

[4]Travel to collect soil, yield, and fruit quality samples from farm sites.

Acknowledgements: Thank you to technical support from Abigail Kowalski**,** Jared Dean and Hayley Mendez.

OBJECTIVES

1. Test the relationship between soil quality and fruit productivity.
2. Determine which of a suite of 21 soil quality indicators are appropriate for tree fruit production systems in the irrigated west.
3. Increase grower understanding of soil quality indicators, what they mean, and how to use the information they provide to improve management.

SIGNIFICANT FINDINGS

Indicators measured in Washington orchards had a wide range but with generally lower organic matter, lower available water capacity, higher % sand and lower wet aggregate stability than Midwest, Mid-Atlantic and Northeastern soils measured in other studies. Water related factors available water capacity and % sand had significant yield models, and root health factors *Pratylenchus* nematode and bean root health rating had consistent but not significant relationships with yield according to linear mixed models. The minimum dataset of soil health indicators for Central Washington orchards should include measurements of water availability (AWC, % sand) and of root health (bean root health rating, *Pratylenchus* nematodes*)* as well as fertility indicators to meet stakeholder management goals. High levels of mineralizable N in some orchards indicate the need to include a measurement of organic N availability in the minimum data set. With more than 25% of surveyed orchards with high subsurface penetration resistance values, a measurement of compaction should be included. While OM and active carbon (POXC) were not correlated with the stakeholder management goal of productivity, soil organic matter influences multiple soil functions including microbial activity, nutrient cycling, soil carbon accumulation and water relations, and as such should be included in the minimum dataset as indicators of environmental health.

METHODS

Site description: To date 101 orchard plots have been soil sampled. Of these plots 60 plots (30 matched pairs) were well matched with available/measured yield data. A subset of 32 plots (16 matched pairs) were sampled for fruit yield and fruit quality. Matched plots were on the same general soil type with matching variety, tree age and training system. One plot in each pair was high performing based on grower description and the other site in the matched pair was underperforming.

Soil sampling: Fifty to one hundred soil probe subsamples to an 8-inch depth just inside the drip line of the canopy were taken for nutrient, soil health and nematode analysis. Four four-inch deep intact soil cores were taken for bulk density analysis. Five intact cores two inches deep by two-inch diameter were taken for micro-arthropod analysis. Water infiltration was measured by timing the length of time for water to fully infiltrate when one inch of water was added to a 10-inch diameter ring pounded 2 inches into the ground.

Soil health analysis: Soil health indicators measured included water availability: available water capacity (AWC), water infiltration, and % sand; indicators of root health: apple root health rating, bean root health rating, *Pratylenchus spp.* nematodes; indicators of soil structure: surface and subsurface penetration resistance (PR), bulk density (BD), and wet aggregate stability (WAS); chemical fertility factors: P, K, Mg, Ca, Fe, Mn, Zn, pH; microbially available fertility factors: autoclaved citrate-available protein (ACE), potentially mineralizable N (PMN); and OM and biological activity indicators: organic matter (OM), permanganate oxidizable active carbon (POXC), microarthropods, soil food web structure and enrichment indices (SI, EI), and respiration.

Fruit yield and quality: Fruit yield and quality were determined by collecting grower reported packing house yield data for the previous two to four years where possible. For orchards where packing house data was not collected, a subset of five representative trees were selected for each orchard. At harvest, fruit per tree were counted and 20 fruit per tree collected to determine mean fruit weight and to estimate total yield. To assess the proportion of high-quality fruit free of sunburn, bitter pit, or poor color, 60 fruit were collected from the three representative trees in each orchard. Fruit quality assessments included sunburn analysis following the Washington Tree Fruit Research Commission sunburn scale for bi-color fruit based on Schraeder et al. (2003). Red overcolor was graded based on <25% coverage, 25-50% coverage, 50-75% coverage, or 75-100% coverage. Bitter pit, lenticel breakdown or other external disorders were also assessed on all fruit. If fruit contained less than 50% red over color, bitter pit, or sunburn incidence that was greater than YII, fruit was classified as a cull. From this, packout % and total packout (packed boxes per acre) was calculated for each orchard.

RESULTS

Indicators of water availability varied widely across Central Washington orchards where 11 sites had limited water availability. Available water capacity ranged from 0.2 g g^{-1} in coarse and medium texture soils to 0.3 g g^{-1} in fine textured soils. Almost half of the soils sampled had coarse soil texture with an average of 66% sand. Water infiltration varied by site with a range of 10 seconds to 5 minutes for 1-inch of water to infiltrate.

Indicators of root health function showed disease potential in 50% of Central Washington apple orchard fields sampled according to apple root health ratings (values <50%), 29% of fields according to bean root health ratings (values 5-9), and 15% based on *Pratylenchus* nematode counts. Twenty-nine percent of orchard fields showed moderate damage to advanced decay in bean root health ratings used to detect disease potential for common plant pathogens.

Central Washington orchards surveyed generally had optimum macro and micronutrient levels. pH levels were generally within the optimum range of 6.0 to 7.5 with one site at a limiting level of 5.5 where macronutrients would be less available and 28 sites above 7.5 but below 8.0. Only 12% of sites had P levels below 10 ppm considered limiting for tree fruit and two sites had excessive levels (>50 ppm). Potassium levels generally were equal to, or greater than, optimum (150-250 ppm) with the exception of four sites that had soil K concentrations of less than 100 ppm and 11 sites were between 100 and 150 ppm. However, 47 sites had greater than 300 ppm K.

Measurements of microbially available N in Central Washington orchards showed a range of levels with many orchards where substantial organic N pools should be accounted for when nutrient applications are made. Washington orchards measured had average potentially mineralizable nitrogen of 21.1, 15.1 and 6.5 µ N g^{-1} $week^{-1}$ for coarse, medium and fine soils, respectively. ACE soil protein was relatively low with 6.7, 4.3 and 4.5 mg g^{-1} for coarse, medium and fine soils, respectively. The soil food web Enrichment Index varied widely with 82% of sites showing an EI rating of 50 or higher indicating soil fauna with a large capacity to respond to and mineralize N additions.

Soil structure in Central Washington orchards surveyed had moderate to low wet aggregate stability (average 19% medium, 27% fine and 30% coarse), bulk density averaging 1.1 to 1.3 g cm^{-3} for fine and medium-coarse soils and moderate surface and subsurface penetration resistance (PR) with the exception of 26 sites where subsurface PR exceeded 2070 kPa (300 psi) (Figure 4). On average, bulk density was 1.1 g cm^{-3} in fine texture soils and 1.3 g cm^{-3} in medium and coarse texture soils and lower than levels proposed to impact root growth and yield. Five orchard fields had bulk density of 1.5 g cm^{-3} indicating a potential limitation in some sites. Compaction measured as penetration resistance is considered to limit root growth as well as access to water and nutrients when levels exceed 2070 kPa (300 psi) Twenty-six of the sites had subsurface PR higher than 2070 kPa with five sets of matched pairs where subsurface PR was higher in low yielding orchard sites compared to high yielding sites indicating a potential limiting effect.

Indicators of soil biological activity and food web structure were on average moderate too low in this study but were highly variable. Microbial activity measured by respiration varied from 0.01 to 1.25 mg CO^2 g^{-1}. These respiration levels were generally low with 78% of samples below the scoring curve average of 0.6 mg CO^2 g^{-1}. Soil food web structure was also low on average with 78% of sites scoring less than 50% as calculated by the soil food web Structure Index. Micro arthropods including fungal feeding and predatory mites and collembolan in the surface soils were highly variable from 0 to 90,000 counts m^{-2}.

Washington orchard soils surveyed had a wide range of organic matter, but levels were generally lower than those documented in other regional surveys. Organic matter in Central Washington orchards ranged from 1.0 to 5.5%, with active carbon (POXC) ranging from 191 to 1145 ppm. Fifty seven percent of soils had less than 2% OM and scored less than 50% on the scoring curve for active carbon indicating relatively low carbon availability.

In order to identify a minimum dataset for a soil quality index for Washington orchards several methods were employed to relate soil factors to management factors important to stakeholders: fruit yield and fruit quality. Statistical methods included lasso regression, linear mixed effects models, principal components analysis and nonlinear Bayesian modeling.

Using an integration of biological knowledge of the system we looked for trends to see at what thresholds yield trended to decrease between matched pairs (sets of two orchards with matching scion, rootstock and location) as a factor increased or decreased. *Pratylenchus* nematode has a known threshold where 20-70 *Pratylenchus* 500 g^{-1} may cause crop damage and 80 + is likely to damage young trees. All six matched pairs with values over 80 *Pratylenchus* 500 g^{-1} have a downward slope indicating potential reduced yield capacity at high *Pratylenchus* nematode densities. The bean root health rating is on a scale of 1 to 9 where 1 is healthy and values over 4 generally show root damage. In this dataset all the fields with values over 5 have a negative slope where percent yield goal decreases as bean root health rating values increase. Available water capacity (AWC) of 0.1-0.15 g g^{-1} is thought to create moderate water limitation with AWC less than 0.1 g g^{-1} severely limiting water availability. In exploratory analysis AWC showed negative slopes for matched pairs where low yielding sites had less than 0.15 g g^{-1} AWC. Additionally, in soils with over 70% sand, a downward trend for percent yield goal was apparent.

We then used a linear mixed effects model to characterize the association between yield (percent goal) and each of the selected soil health factors which showed strong trends in exploratory analysis. *Pratylenchus* nematode with a threshold of 80 and bean root health rating with a threshold of 4 had consistent but not significant yield (percent goal) models (P=0.24, P=0.08), with similar results for packout (P=0.19, P=0.17). AWC with a threshold of 0.15 and % sand with a threshold of 70% had significant yield (percent goal) models (P=0.009; P=0.03), with non significant results for packout (P=0.09; P=0.20).

A nonlinear Bayesian model was computed to discern association between soil health components and tree fruit productivity. The model coallates available water capacity and percent sand into one factor for water relations, pratylenchus nematode numbers and bean root health ratings into a second factor representing a root health function and macro and micronutrient levels to a factor for nutrient availability. We hypothesize that the Bayesian model will better serve to represent nonlinear interdependence of the soil health variables and outcomes.

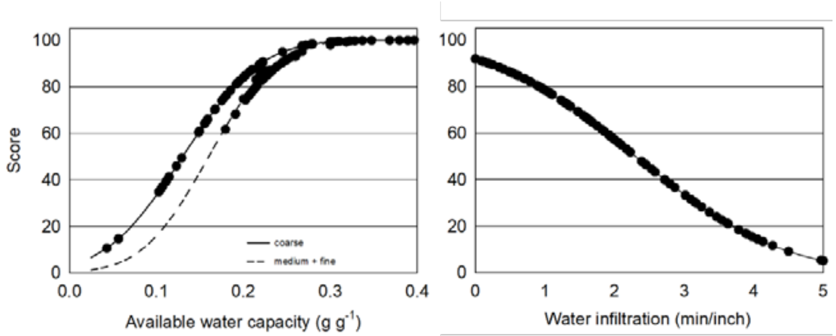

Figure 1 Soil water indicators: available water capacity (g g^{-1}) and water infiltration (min/inch).

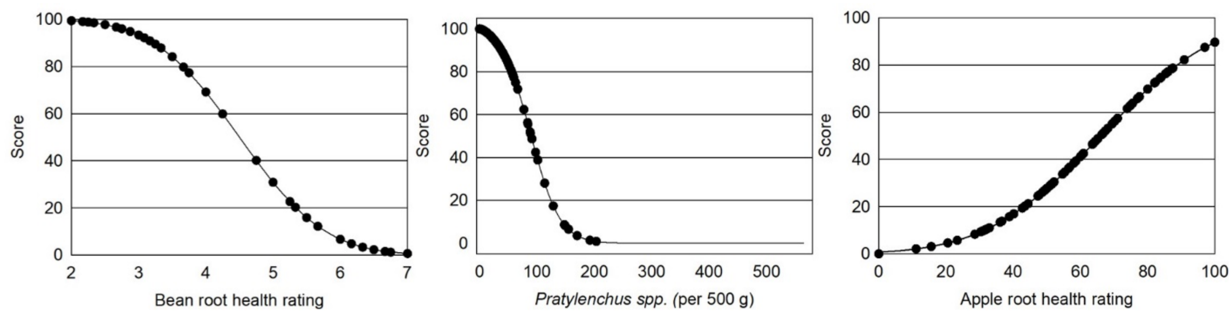

Figure 2 Indicators measuring the root health function of soil including bean root health rating, numbers of Pratylenchus spp. nematodes*, and apple root health rating.*

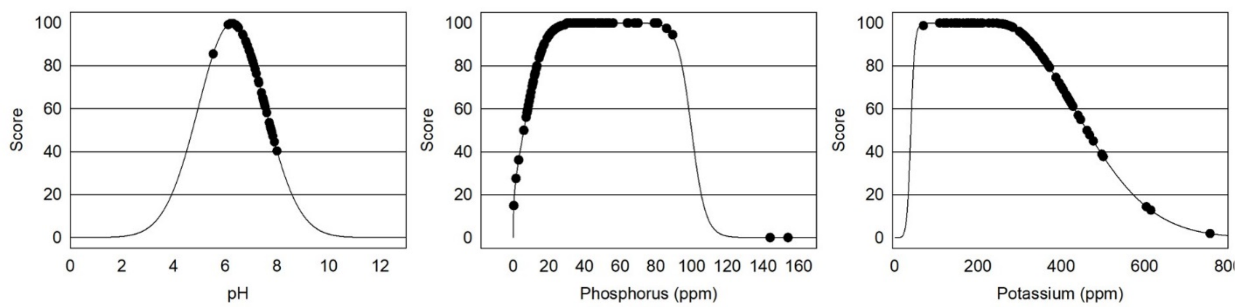

Figure 3 Soil fertility indicators: pH, P and K in 101 Central Washington orchards surveyed.

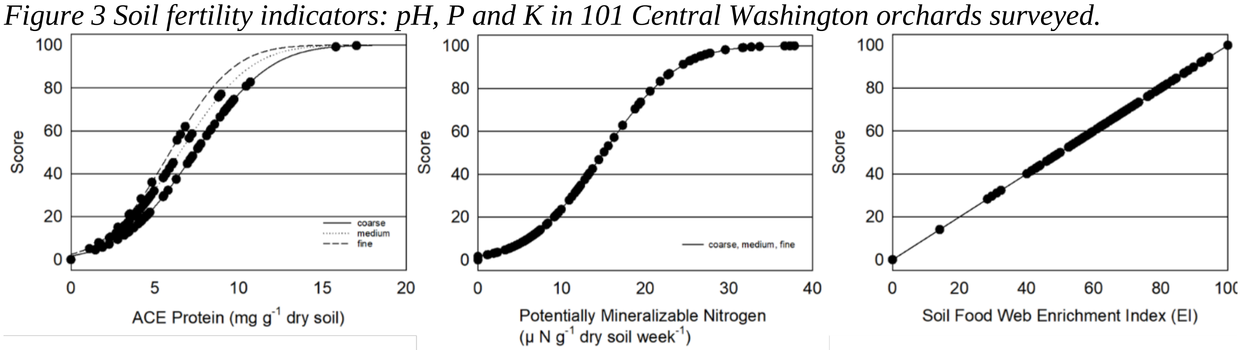

Figure 4. Indicators of microbially available N: ACE Protein (mg g^{-1} dry soil), Potentially Mineralizable N (μ N g^{-1} $week^{-1}$), and Soil Food Web Enrichment Index for 101 Central Washington orchard field soils.

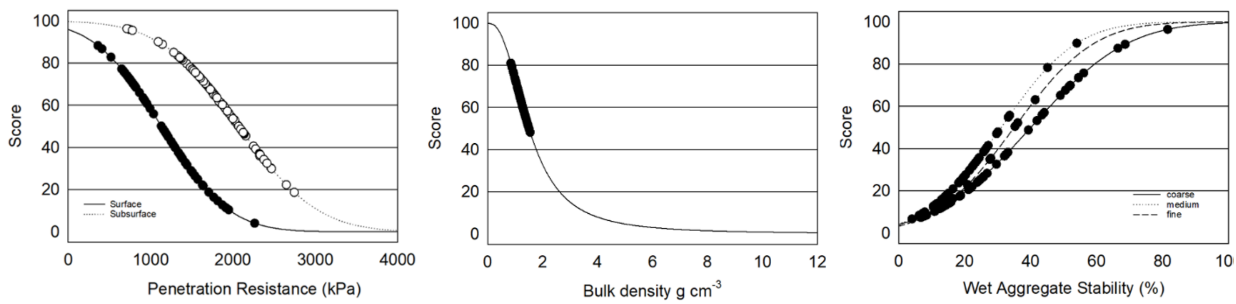

Figure 5. Indicators of soil structure: penetration resistance, bulk density, and wet aggregate stability in 101 Central Washington orchards field soils.

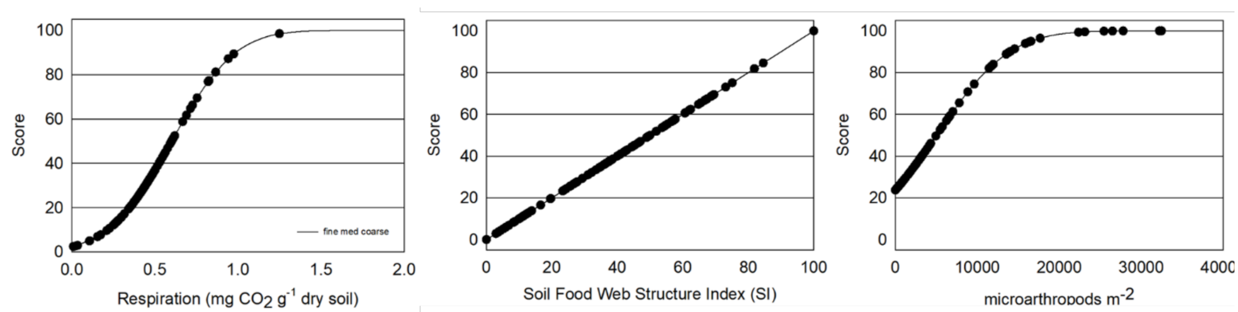

Figure 6. Indicators of soil biological activity and food web community structure: respiration (mg CO^2 g^{-1}), soil food web structure index (0-100 scale) and micro arthropods (m^{-2}) in 101 Central Washington orchards fields.

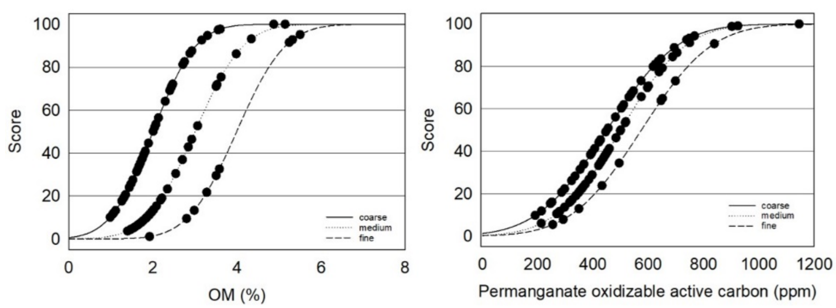

Figure 7. Soil organic matter (OM %) and permanganate oxidizable active carbon (POXC ppm) in 101 Central Washington orchards fields.

Table 1. Data from individual orchards for yield and packouts for 32 orchards sampled from 2017-2019.

Year	Orchard	Cultivar	Crop Load (fruit cm^{-2} TCSA)	Fruit $Tree^{-1}$	Mean Fruit Weight	Yield $Tree^{-1}$ (kg)	Trees Ha^{-1}	Yield (T Ha^{-1})	% cull	Packed boxes Ha^{-1}
2017	BR27+	Gala	1.76	270	176	47.4	1621	76.8	6.7	3271
2017	BR28-	Gala	3.51	49	175	8.7	2928	25.3	18.3	1043
2017	AB42+	Honeycrisp	3.77	87	161	14.0	3194	44.7	1.7	1358
2017	AB43-	Honeycrisp	5.47	60	179	10.7	3194	34.1	1.7	1928
2017	AB40+	Honeycrisp	2.80	421	126	53.0	651	34.5	5.0	3798
2017	AB41-	Honeycrisp	0.77	71	179	12.7	1505	19.1	1.7	4047
2017	KG48+	Granny Smith	6.06	46	260	12.0	2197	26.3	1.7	1806
2017	KG49-	Granny Smith	7.73	72	217	15.5	2197	34.1	1.7	1047
2017	H38+	Granny Smith	8.68	120	169	20.3	3758	76.2	0.0	2479
2017	H39-	Granny Smith	8.28	110	174	19.1	3758	72.0	16.7	1587
2018	z52+	Gala	6.40	441	144	63.5	1256	79.7	1.7	3951
2018	Z53-	Gala	4.45	137	153	20.9	1621	33.8	6.7	1500
2018	Z66+	Gala	3.16	332	141	46.8	1256	58.8	1.7	2976
2018	Z67-	Gala	2.10	133	151	20.0	1621	32.4	16.7	1433
2018	RB58+	Gala	2.61	143	163	23.4	2928	68.5	0.0	3722
2018	RB59-	Gala	3.52	91	204	18.6	2928	54.4	3.3	2283
2018	K54+	Gala	3.84	474	152	72.1	823	59.4	3.3	3318
2018	K55-	Gala	4.35	125	190	23.6	2197	51.9	3.3	2307
2018	WA56+	Honeycrisp	2.55	121	235	28.4	2928	83.1	10.4	3613
2018	WA57-	Honeycrisp	3.68	77	258	19.9	2928	58.2	29.2	1996
2018	O50+	Gala	2.98	237	178	42.1	1350	56.9	1.7	2518
2018	O51-	Gala	4.51	221	174	38.4	1350	51.9	1.7	2352
2019	Al88+	Gala	6.59	121	185	22.4	3514	78.8	1.7	3694
2019	Al89-	Gala	5.26	53	113	6.0	3514	21.1	20.0	913
2019	Gil76+	Gala	9.31	92	133	12.2	4392	53.7	26.7	1972
2019	Gil77-	Gala	7.99	44	139	6.1	4392	26.9	13.3	1116
2019	S70+	Honeycrisp	4.72	139	194	27.0	2928	79.0	0.0	5082
2019	S71-	Honeycrisp	5.00	27	232	6.3	2928	18.4	8.6	820
2019	Zi82+	Honeycrisp	8.74	75	226	16.9	4392	74.4	10.4	3685
2019	Zi83-	Honeycrisp	3.61	79	216	17.1	1505	25.7	27.3	981
2019	KMO68+	Pinata	5.65	352	202	71.2	968	68.9	10.0	3481
2019	KMO69-	Pinata	4.21	233	216	50.2	968	48.6	8.3	2198

DISCUSSION

Indicators measured in Washington orchards had a wide range but with generally lower organic matter, lower available water capacity, higher % sand and lower wet aggregate stability than Midwest, Mid-Atlantic and Northeastern soils measured in other studies. Water related factors available water capacity and % sand had significant yield models, and root health factors *Pratylenchus* nematode and bean root health rating had consistent but not significant relationships with yield according to linear mixed models. A high percentage of sites with subsurface compaction and high organic nitrogen content suggest these factors are important to track in Washington orchards.

Root health and available water were the most common limiting factors in the orchards we studied. Almost half of the soils sampled had coarse soil texture with an average of 66% sand. Available water capacity is a measure of the porosity of soil and indicates the amount of plant available water a soil can hold where below 0.15 g/g available water is considered moderately to severely limiting. Of sites surveyed 11% had available water capacity indicating moderate water limitation and 5% levels indicating severe water limitation. For example, consider matched granny smith on M9.337 blocks where the high productivity block yielded 64 bins per acre and the low yielded 34 bins per acre on average. Available water capacity was 19 g/g (56% sand) in the high yielding block compared to 15 g/g in the low yielding block (75% sand).

Root health was an important factor in Central Washington orchards. Plant pathogens *Phytophthora* and *Pythium*, *Ilyonectria robusta*, *Rhizoctonia solani* as well as the lesion nematode *Pratylenchus penetrans* are known to negatively impact growth and production in young apple trees. Root health ratings measured negative impacts in 29% of orchards surveyed according to bean root health ratings and 15% based on lesion (*Pratylenchus*) nematode counts. The impacts of poor root health can be significant. For example, in two matched Gala on M9 rootstock orchards the orchard with 33 bin/A average versus 60 bin/A in the productive block had high lesion nematodes numbers (129 per 500 cc) well over the 80 per 500 cc threshold.

Soils with high bulk density and compaction limit root growth and root access to water and nutrients. Twenty-six of the surveyed orchards had high subsurface penetration resistance indicating compaction and limited rooting area. Five of the matched sets of orchards had higher compaction in low-yielding compared to high-yielding sites. For example, in Ultima gala on Nic.29 rootstock orchards planted the same year with the same training system, the orchard yielding 15 bin/A less (55 bin/A vs 70 bin/A) had a deep compaction layer at an 18 inch-depth. While neither penetration resistance nor bulk density had significant effects on yield in mixed model analysis, trends indicate that this factor should continue to be tracked in order to measure potential effects that may be confounded by the limited number of sites analyzed.

Many orchards surveyed had high organic N content. Including a measurement of organic nitrogen in the minimum dataset for soil health assessment in orchards could be critical to avoid nitrogen over applications. For example, the average PMN for sites measured was 21 μg^{-1} $week^{-1}$ which would supply 2.45 lb/A per week reducing N needs by 49 lbs/A over the 20-week season. Assuming an 80 bin/A yield goal and N recommendations of 70 lb/A per season the N needs may be only 21 lbs/A. Unfortunately, while extractable organic N fractions are generally positively correlated with mineralizable N, they often only partially explain the variation in mineralizable N and there is disagreement about which test provides more usable information.

The minimum dataset of soil health indicators for Central Washington orchards should include measurements of water availability (AWC, % sand) and of root health (bean root health rating, *Pratylenchus* nematodes*)* as well as fertility indicators to meet stakeholder management goals. High levels of mineralizable N in some orchards indicate the need to include a measurement of organic N availability in the minimum data set. With more than 25% of surveyed orchards with high subsurface PR values, a measurement of compaction should be included. While OM and POXC were not correlated with the stakeholder management goal of productivity, soil organic matter influences multiple soil functions including microbial activity, nutrient cycling, soil carbon accumulation and water relations, and as such should be included in the minimum dataset as indicators of environmental health.

EXECUTIVE SUMMARY

Project title: How do We Measure and Manage Soil Health for Productive Orchards?

Key words: soil health, organic matter, available water capacity

Abstract:

Soil health assessment has been recognized as a critical soil testing tool. But what does soil health mean in perennial orchards in the irrigated west? Our group set out to identify a set of soil health indicators that are useful to track in Central Washington orchards. Specifically, we were challenged to track which factors may be limiting to yield and fruit quality. This study measured twenty-one soil health indicators in 101 Central Washington apple orchards. To determine the relationship between soil health indicators and fruit yield and quality we used 30 sets of matched sites with high and low productivity orchards of the same or similar variety, rootstock, age, and training system. Fruit yield and packout were determined using two-to-four year grower averages and fruit measurements from five representative trees per orchard. The soil health indicators we measured had a wide range across Washington orchards surveyed but overall organic matter, available water capacity, and wet aggregate stability were lower, and % sand higher than soils measured in other Midwest, Mid-Atlantic and Northeastern studies. Water related factors (available water capacity and % sand) had a significant relationship with yield according to linear mixed model analysis and root health factors (*Pratylenchus* nematode and bean root health rating) had consistent but not significant relationships. A high percentage of sites with subsurface compaction and high organic nitrogen content suggest these factors are important to track Washington orchards. The minimum dataset of soil health indicators for Central Washington orchards should include measurements of water availability (AWC, % sand) and of root health (bean root health rating, *Pratylenchus* nematodes*)* in addition to standard fertility indicators to meet stakeholder management goals.