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Soil health and *Verticillium* disease of potato Part II: Soil Health Indicators and Comprehensive Soil Health Assessment

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Executive Summary

1.) We identified several indicator values that are significantly related to the incidence of Verticillium wilt in potato fields of the Pacific Northwest

2.) The Comprehensive Assessment of Soil Health, which scores indicators and whole fields on a scale from 0-100, is particularly useful for applications within farm operations, because it allows for the identification of site-specific, beneficial management practices and their no-cost transfer to other fields within the same farm

Introduction

Verticillium wilt is a common limiting factor of potato production in the Pacific Northwest. It has become the predominant pathogen of potatoes because its microsclerotia can survive in soil for over a decade. It is difficult to eradicate from soils using rotation management techniques due to its ability to use numerous weeds and crops as alternative hosts. Conventional disease control has focused on reducing the populations of microsclerotia in soil using broad spectrum fumigants. But, the high costs and potential regulatory restrictions in the future are strong incentives to find non-chemical control methods for managing this soilborne disease.

An ideal solution to the problem would be if the soil could be made resistant or better, suppressive to the disease through targeted management practices with the ability to put pressure on the pathogen. That this is fundamentally possible has been known for some time. In a benchmark study conducted at Aberdeen, Idaho, Davis et al. (1996) found the effect of certain green manure treatments to be equivalent to that of soil fumigation, with up to 81% reduction in disease severity and a 35% increase in tuber yield. Certain organic amendments may reduce the incidence of Verticillium wilt and potato scab, as well as populations of plant pathogenic nematodes to near zero (Conn and Lazarovits 1999). Unfortunately, the disease control efficacy of these treatments was often limited to a specific site and/or product (Lazarovits 2010). Apparently, what works at one site does not necessarily work in another.

Hence, to select the most efficient management option for strengthening disease suppressiveness at a given site, we need to know what the deficits of that site are. For example, at one site it may be vital to improve soil structure to give antagonistic microbes a better chance to get at microsclerotia, while at another site it may be more important to promote the degradation of potato tissues through additions of biologically active carbon, accelerating the release of microsclerotia into the soil where they are more prone to be killed by microbial activity.

The connection to soil health

The 1970s witnessed a widespread development in agricultural industry in the Pacific Northwest. New irrigation techniques, particularly center pivot sprinklers, led to the farming of much land formerly deemed unsuitable for agriculture. The region now includes more than 500,000 acres of irrigated soils, the majority of which are relatively coarse textured (sandy). While sandy soils typically show good water infiltration, an increasing number of growers farming these soils are experiencing soil-wetting problems, restricted infiltration and soil erosion with associated reductions in yield and product quality. Because of the high permeability of these soils, both water and fertilizer application rates are high to meet the requirements of crop growth, and contamination of groundwater wells with nitrate has been observed (20 % of domestic wells in Morrow county testing above 10 ppm NO_3^-, DWSP 2019). Issues with soilborne pathogens result when soils are even modestly over-watered (Johnson and Dung 2010). Generally speaking, soils have been **stressed** for several decades and are now showing indications of a decline in soil quality that must be stopped and reversed to ensure the continued economic success of the agricultural industry in the region.

The desire to attend to declining soil resource quality raises several questions and challenges. For instance, we find that the concept of soil quality itself has been extended by the insight that soil microorganisms are critically involved in all aspects of successful crop production. In the past, grower activities were focused on providing for crop needs while soil microbiota were largely left out of immediate management concerns. With the realization that soil microorganisms are behind many of the mechanisms that actually make a soil productive, a need to treat the soil microbiota as a vital part of the system and a subsequent necessity to develop respective technology is increasingly acknowledged. This is the practitioners view of "Soil Health": the idea that the microbes must be actively recruited and well-supplied in order to allow the production system to be driven at its maximum performance level. There is one additional component that sets the soil health concept apart from the concept of soil quality. This is the intent to drive the system in a way that it will maintain unrestricted productivity in the future. This objective is reflected in the concept of "**sustainable Ag intensification**", which is a central part of the USDA Science Blueprint for the years 2020 -2025.

These considerations bring us to the topic of this contribution. How do we know whether the soil at a given site is at its full production potential, i.e., healthy, or whether it is somewhat encumbered? Yield data alone cannot answer this question because they depend on numerous factors beyond soil quality. What, then, do we have to measure to diagnose eventual deficiencies of the soil system? And can we be sure that soil health actually translates to plant health? These questions need to be answered before we can suggest technical solutions for the improvement of soil system performance.

Assessing soil health

There have been various suggestions to measure soil health, some of which are focused on directly assessing the performance of the soil microbiota in processing soil carbon and nitrogen, such as the Haney Soil Health Tool (Haney et al. 2018). This approach recognizes the importance of soil biology but leaves out vital information about soil physics and soil chemistry. For instance, much of crop success is dependent on a good physical structure of the soil. Equally important is the chemical status of the system, including its pH but also potential imbalances between mineral nutrients. The recognition of the complexity of the task has given rise to so-called "comprehensive soil health assessments", where the word comprehensive is used to indicate the joint consideration of physical, biological, and chemical indicator values to arrive at an overall, numerical health status score.

At present, there are two main variants of comprehensive soil health assessments. The older one is the Soil Management Assessment Framework (SMAF) developed by the USDA-ARS (Andrews et al. 2004, Wienhold et al. 2009), which aims to provide site-specific interpretations for crop and pasture lands. The other is the more farmer-oriented Comprehensive Assessment of Soil Health (CASH) developed by a group of researchers at Cornell University (Idowu et al. 2008, Moebius-Clune et al. 2016). CASH was initially based on SMAF, but as CASH moved into a high-throughput lab setting, it shifted to indicators with faster procedures, reducing cost and sample processing time. When compared with each other, both methods showed good agreement in their diagnostic capabilities (Karlen et al 2017).

There is one major difference between the two assessment philosophies that can be understood by remembering that soils differ between growing regions as much as athletes differ between sports disciplines: while they may both excel in their disciplines, it would be foolish to have a gymnast compete with a marathon runner in an endurance race, because the outcome could be predicted off-hand. Hence there is a need to bin soils into groups where comparisons of soil performance are actually meaningful. The SMAF procedure achieves this by grouping soils into soil suborders according to US Soil Taxonomy, while the CASH assessment groups soils by texture classes (Figure 1).

What makes a soil suppressive to Verticillium wilt?

The purpose of the work reported here was to identify the factors that are involved in making a soil suppressive to Verticillium wilt. The general idea was to compare potato fields that had not been affected by Verticillium wilt in the 2017 growing season with such fields that had suffered moderate to severe damage. Growers throughout ID, OR, and WA supported the effort by identifying and granting access to 20 potato fields that had produced a healthy crop (no disease detected or only very minor damage, based on grower assessment) and 20 fields that had produced a diseased crop (moderate to severe damage, based on grower assessment). We then subjected all these fields to the full suite of CASH tests (Moebius-Clune et al. 2016). This protocol combines physical, chemical, and some biological indicators and uses them to derive an overall score which indicates the health status of the soil. It was chosen over the SMAF protocol because it is cheaper and faster while generating similar insights. We hypothesized that the "healthy" soils should have stronger health scores compared to diseased soils. We also performed detailed analyses of some microbial parameters that are not part of the routine CASH assessment. Results for microbial community composition will be reported separately.

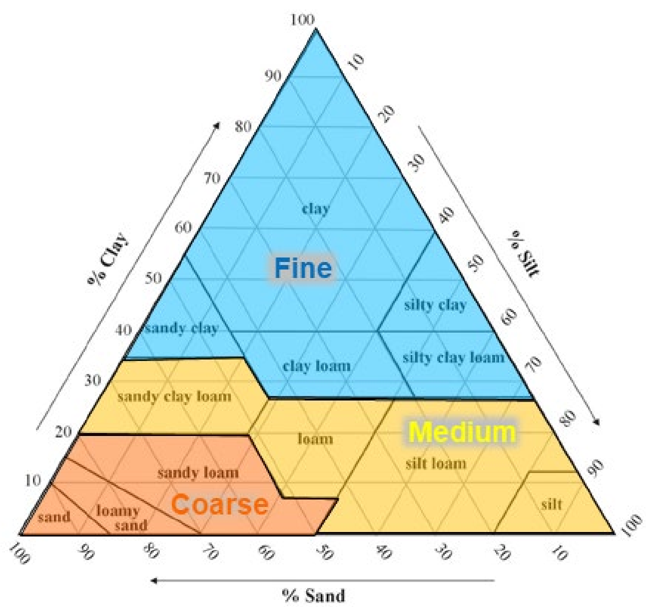


Figure 1: Textural groupings used by the CASH soil health assessment procedure. Three classes are recognized: **coarse**-textured (sand, loamy sand, sandy loam); **medium**-textured (sandy clay loam, loam, silt loam, silt) and **fine**-textured soils (sandy clay, clay loam, silty clay loam, silty clay, clay).

The comparison of 20 “diseased” soils with 20 “healthy” soils revealed several trends in physical, biological, and chemical health indicator values. Table 1 lists mean indicator values grouped into physical, biological, and chemical categories.

Strong and statistically significant differences between healthy and diseased fields were observed for one physical (Clay content), one chemical (pH) and two biological indicators (Permanganate oxidizable Carbon [PoxC] and the decline in respiration over 4 days; [ΔRespiration]). Other parameters also differed between healthy and diseased fields, but not to the extent that the difference could be considered statistically significant. For instance, healthy fields had at least a 10 % probability for more magnesium, a lower Potassium/Magnesium ratio and a higher ACE protein index compared to diseased fields (orange fonts in Table 1). A weaker trend (yellow fonts in Table 1) was seen for Available Water Holding Capacity and Soil Organic Carbon and Nitrogen (both elevated in healthy fields), while sand content trended higher in diseased fields.

The data allow us to accept the hypothesis that soils growing healthy crops are different from soils where Verticillium wilt had an outbreak. Apparently, having more clay and a lower pH as well as having greater values for "biologically active carbon” contribute to disease suppressiveness. The latter finding is particularly noteworthy, because it is near impossible for the grower to change clay content, and quite costly and time consuming to drive pH lower, but an increase in biologically active carbon is entirely within the scope of affordable management options.

Table 1: Properties of "healthy" and "diseased" soils. Grey shades identify indicator values used by the Comprehensive Assessment of Soil Health (CASH). Mean (n=20), SD = Standard deviation (n=20) and probability of error (*p*) for the assumption that means are different (Student's t-test.). Indicators are sorted by significance level. p-Values below 0.05 (red) indicate statistically significant differences (probability of error less than 5%) between healthy and diseased soils. Orange (probability of error less than 10%) and yellow fonts (probability of error less than 20%) are used to identify notable trends that are not statistically significant.

			Healthy		Diseased		
	INDICATOR	*unit*	**Mean**	**SD**	**Mean**	**SD**	***p*-VALUE**
Physical	**Clay**	%	**17**	11	**11**	3	0.04
	Sand	%	**52**	20	**60**	18	0.17
	AWHC	% (Vol)	**13**	7	**10**	6	0.19
	Subsurface Hardness	psi	**394**	27	**380**	555	0.33
	Wet Aggregate Stability	% of total soil mass	**17**	14	**15**	7	0.51
	Silt	%	**31**	18	**29**	19	0.62
	Surface Hardness	psi	**171**	72	**167**	64	0.86
Biological	**Δ Respiration**	% of day 1 value	**39.3**	7.8	**47.6**	3.9	0.0002
	PoxC	$mg\ kg^{-1}$	**287.2**	163.9	**159.3**	107.7	0.01
	ACE Protein Index	$mg\ g^{-1}$	**0.95**	0.26	**0.8**	0.28	0.08
	N	%	**0.14**	0.15	**0.09**	0.03	0.13
	OM	%	**2.7**	3.1	**1.6**	0.5	0.14
	C	%	**1.33**	1.55	**0.79**	0.23	0.14
	Respiration, Day Four	$\mu g\ CO_2\text{-}C\ g\ dry\ soil^{-1}\ day^{-1}$	**6.3**	2.7	**5.5**	1.3	0.25
	β-Glucosidase	$nmol\ g\ soil^{-1}\ h^{-1}$	**152.4**	50.8	**137.9**	47.9	0.36
	Mineralized Nitrogen	$mg\ kg^{-1}$	**1.08**	0.33	**1.2**	0.58	0.44
	Respiration, Day One	$\mu g\ CO_2\text{-}C\ g\ dry\ soil^{-1}\ day^{-1}$	**10.7**	5.1	**10.5**	2.5	0.90
	C/N	ratio	**9.0**	0.9	**9.1**	1.1	0.93
Chemical	**pH**	$-log_{10}[H+]$	**6.7**	0.8	**7.3**	0.7	0.02
	Mg	$mg\ kg^{-1}$	**410**	355	**250**	73	0.06
	K/Mg	ratio	**1.14**	0.6	**2.02**	1.53	0.06
	K	$mg\ kg^{-1}$	**375**	192	**484**	367	0.25
	Mn	$mg\ kg^{-1}$	**60**	17	**67**	19	0.26
	K/Mg+Ca	ratio	**0.18**	0.08	**0.28**	0.29	0.26
	Fe	$mg\ kg^{-1}$	**137**	54	**120**	57	0.34
	Cu	$mg\ kg^{-1}$	**5.6**	8.4	**4.0**	1.4	0.41
	P	$mg\ kg^{-1}$	**111**	53	**122**	47	0.47
	Zn	$mg\ kg^{-1}$	**9.3**	5.9	**9.9**	3.6	0.67
	Ca	$mg\ kg^{-1}$	**2124**	1654	**1939**	932	0.67

We also note that it is not the immediate biological activity (= the 'Respiration day one value') but the ability of the microbiota to sustain their activity over several days (= the ΔRespiration value) that distinguishes healthy from diseased soils. This observation motivates us to look closer into the factors that may be responsible for microbial resilience and to investigate options to increase such resilience.

Interpreting numbers for the assessment of soil health

So far, we just presented a plain comparison of mean values from healthy fields with mean values from diseased fields. This turned out to be very informative, revealing insights that can be used to improve disease management. But Table 1 does not attempt to interpret individual numbers or identify if a given value is particularly good or bad, such as extension publications do when they offer fertilizer recommendations for certain crops. Table 2 is an example of the traditional process of interpreting test results from soils according to crop need:

Table 2: Phosphorus (P) soil test categories and suggested fertilizer rate recommendations. From Horneck, D.A. et al. 2011. Soil Test Interpretation Guide. OSU Extension Publication EC 1478.

	West of Cascades Bray P1 test P (ppm)	East of Cascades Olsen test P (ppm)	Recommendation (lb P_2O_5/acre)
Low	<20	<10	0–300
Medium	20–40	10–25	0–200
High	40–100	25–50	0–30
Excessive	>100	>50	0

However, recommendations of this kind have the purpose of addressing immediate nutrient and fertilizer needs of the subsequent crop. In order to detect if a soil is showing a physical or biological deficiency that may evolve into a management problem in the future, it would be desirable to have a way to assign a grade or score that stands for the overall status (or 'health') of the soil. This is what a soil health assessment aims to do: find the position of individual indicator values among all the values within the pool of available data. To this end, a soil health assessment does not simply report the result of an analysis, it also interprets the value observed by scoring it on a scale from 0 (very low = poor health) to 100 (very high = excellent health). It is immediately apparent that such a scoring procedure must involve the comparison of an individual value with the values seen in other soils.

In the study presented here, the pool of available data was 40 values for each indicator since we investigated 40 soils. For our attempt to develop soil health assessments, this number defines the data pool against which we can compare individual soils and indicators. However, following the rules of the CASH procedure, this pool had to be split into coarse (22 soils), medium (15) and fine (3) textured soils (compare Figure 1). Why doing this is important is demonstrated in Figure 3 for the indicator "Available Water Holding Capacity (AWHC)".

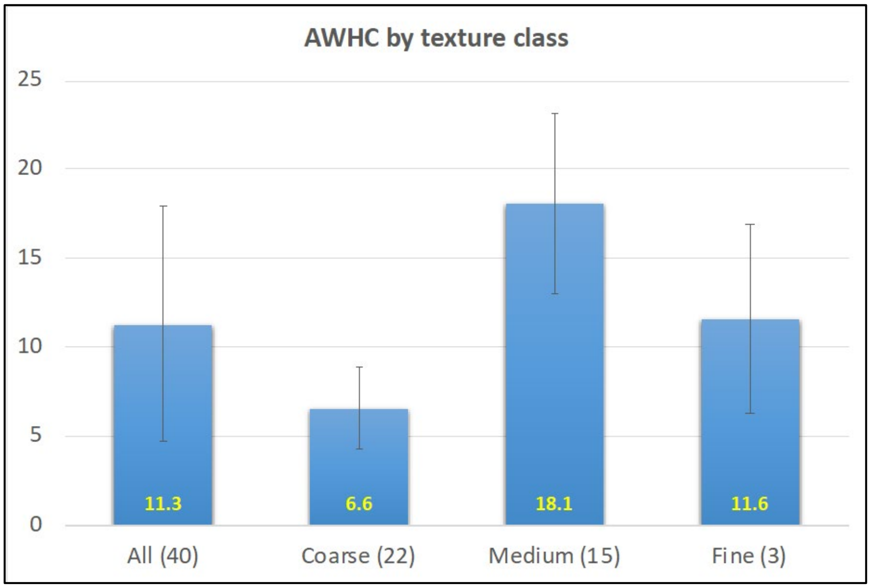


Figure 3: Average AWHC (% of total soil volume) based on consideration of all 40 soils (All) and for the three texture categories [coarse, medium and fine] as defined in Figure 1. Error bars are ±one standard deviation.

Figure 3 shows that the average available water holding capacity among our 40 soils was at 11.3 % of total soil volume. If we were to rank coarse textured soils (mean AWHC = 6.6% volume) based on the average value for all 40 soils (11.3 %), they would all receive low scores. If we did the same for the medium textured soils (mean AWHC = 18.1%), they would all receive very high scores. Essentially, the subdivision into texture classes prevents us from judging coarse soils "unfairly", as well as overestimating the performance of medium textured soils. In order to stand out among medium textured soils, an individual soil would have to be in the 20% range for AWHC, while a value as low as 10% would make coarse soil a strong performer.

These considerations lead us to a critical insight: **Soil health assessments rank individual indicator values and overall health scores within a predetermined pool of data**. This means that to assign meaning to a health assessment, one must predetermine and know the data pool against which comparisons are being made. In a sense, the first action in a soil health analysis is to choose the field of competitors - if the competition changes, the placement of a given soil among its competitors will change as well.

Procedure

To demonstrate the process of assigning meaning (such as "very high" or "low") to an indicator value, we present as an example the scoring process for the health indicator "Available Water Holding Capacity". The first step in the process is to "bin" our full data set into three texture classes: coarse, medium, and fine as shown in Figures 1b and 3. That process leaves us with a total of 22 data points for the coarse textured soils, for which we can calculate an average or mean value. The data can be plotted to get a visual idea of the data range and eventual gaps in the data distribution (Figure 4.1).

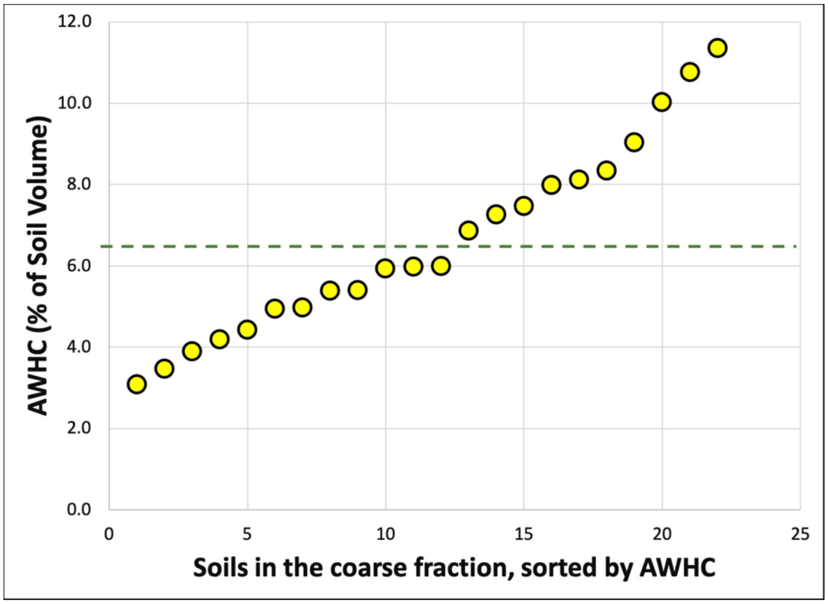


Figure 4.1: The range for AWHC values for the 22 soils with coarse texture. Each dot represents the AWHC value of one potato soil. The dashed horizontal line is the average AWHC of all 22 soils (= 6.6 %).

As we do this, we note that the steps between data points are pretty regular, with only a minor jump in the last three data points. Data that look like this are considered to be distributed "normally". This observation can also be illustrated by plotting the data in groups. In Figure 4.2 we plot the number of data points in increments of AWHC, each spanning a range of 2 % (The choice of increment is arbitrary and would change if we had 500 data points instead of 22).

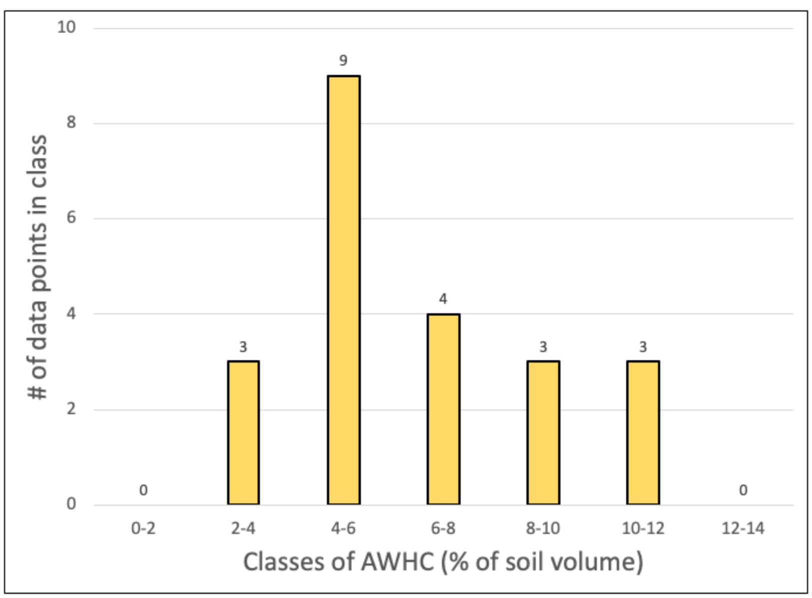


Figure 4.2. AWHC data sorted into intervals of 2 %, showing a single peak of data points in the 4-6% region.

This representation shows that 9 of our soils are found in the 4-6% region, while other segments have only 3 or 4 data points. This is a fact that we want to account for when we want to normalize the information to a neutral scale, where the "best" soils are close to 100% and the "worst" soils are near 0%. To do so, we first take the data shown in figure 4.2 and plot them in a cumulative fashion, keeping the same 2% increments of AWHC (Figure 4.3).

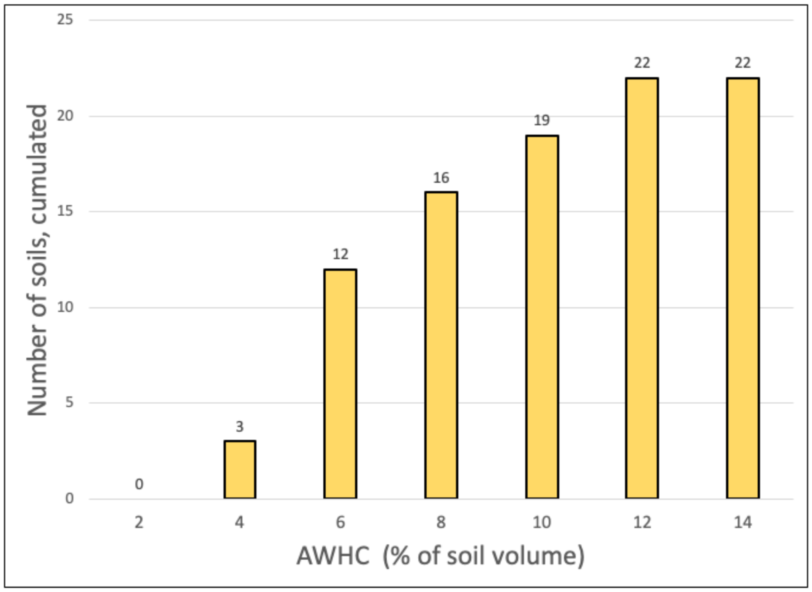


Figure 4.3 Cumulated AWHC data. Bars are constructed by subsequent addition of class values taken from Figure 4.2. Read: 12 (out of 22) soils have AWHC of less than 6%.

After this step, we are prepared to convert the individual counts per increment into percentages, with 100% = the total number of data points (= 22). The result of this transformation is given in Figure 4.4.

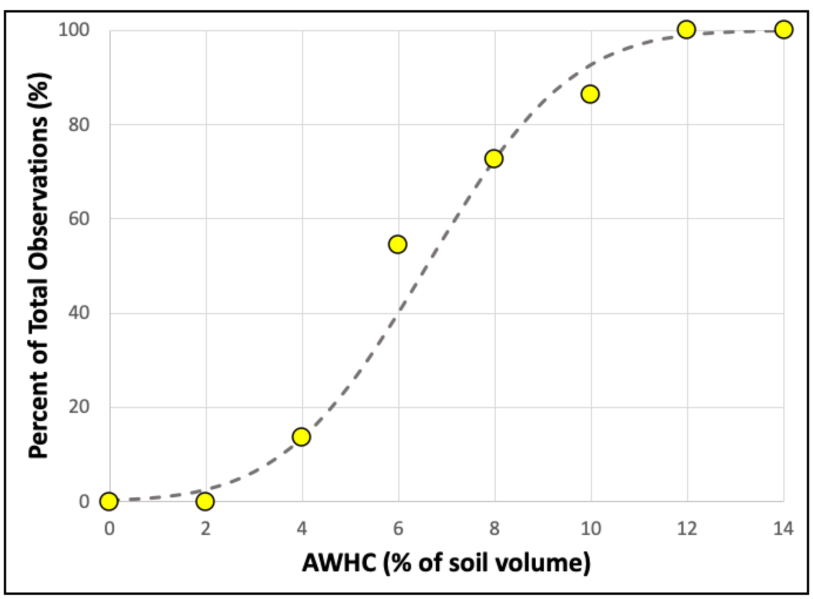


Figure 4.4 Cumulated AWHC data (from Figure 4.3) expressed as percentage of total observations. Note that the data points follow the same pattern as the bars in the previous

figure. The dashed line is the mathematical function (Cumulative Normal Distribution Function) that describes the 'general behavior' of this specific data set.

By assigning attributes to different segments of the function that describes our data set, we are now able to determine if a certain value scores high or low. For instance, an AWHC value of 10% would be considered to have a score of 92, which falls in the region of "very high" scores (Figure 4.5)

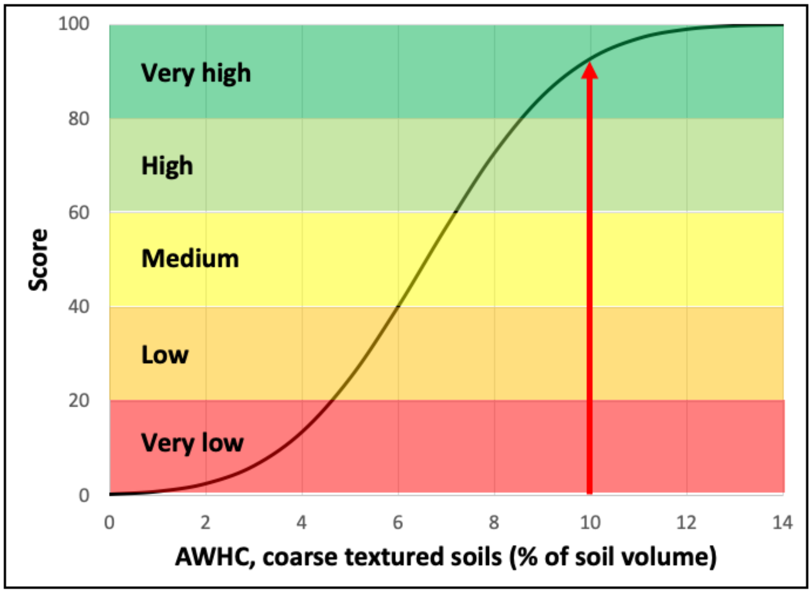


Figure 4.5. Cumulative normal distribution for scoring AWHC in the coarse textured soils from our study. Red arrow illustrates how a AWHC value of 10 % would lead to a score in the "**Very high**" region.

It cannot be overemphasized that **the scoring process is entirely dependent on the data pool** chosen. As we remember from Figure 3, mean AWHC values were much different between coarse and medium textured soils from our study. Necessarily, this leads to very different scoring functions, as illustrated by a comparison between Figures 4.5 and Figure 5.

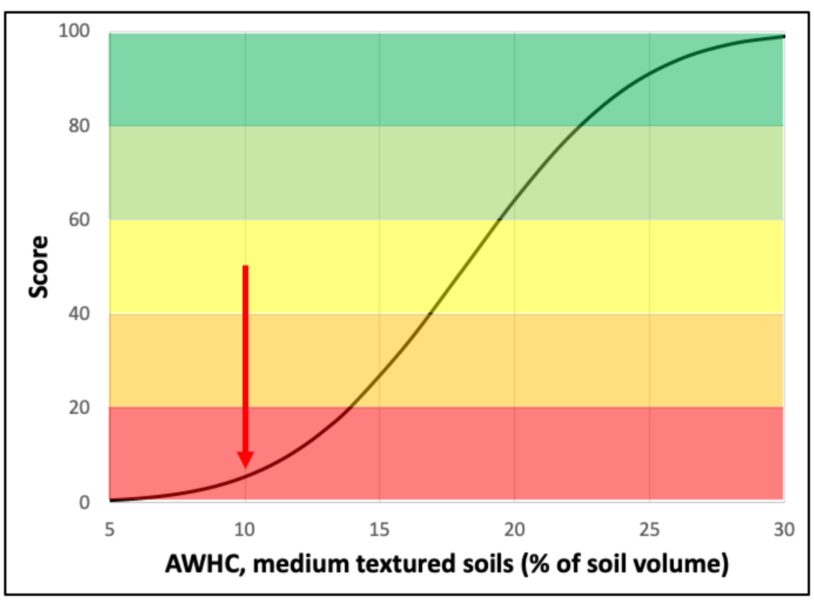


Figure 5 Cumulative normal distribution for scoring AWHC in the **medium** textured soils from our study. In this case, a value of 10% for available water holding capacity (red arrow) represents a **very low** score

An AWHC value of 10% yields a score of "very high" when the number comes from a coarse textured soil (Figure 4.5), and a score of "very poor" when the score comes from a medium textured soil (Figure 5, compare position of red arrows). This is a crucial insight: The question whether an indicator is scored as healthy or not depends entirely on the data pool to which the respective value belongs. An isolated value or observation cannot be scored unless it is connected to an appropriate data pool!

After this lengthy but necessary clarification of the scoring process, we can now turn our attention to the results of the soil health assessments among our potato soils and answer the question whether plant health was linked to soil health. As required by the rules of the CASH soil health assessment and as demonstrated for AWHC on the previous pages, we initially split our 40 soils into coarse, medium, and fine texture groups (Figure 6).

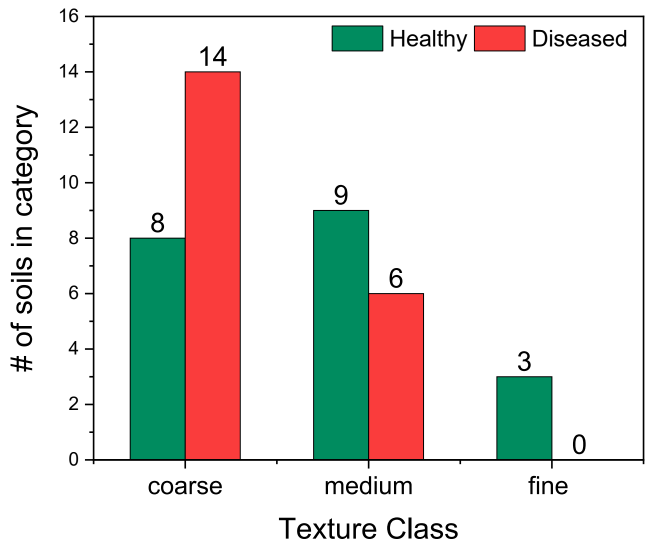
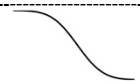
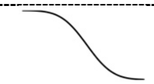
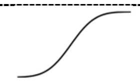
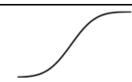
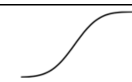
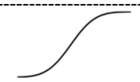
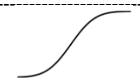
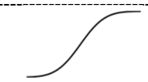
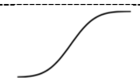
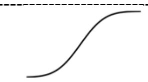
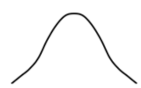
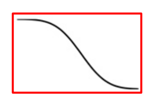
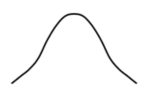
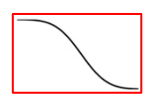
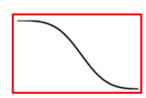
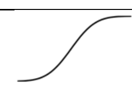
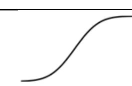
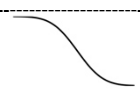
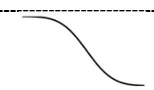


Figure 6: Distribution of healthy and diseased soils among coarse, medium, and fine textured categories in our pool of 40 potato fields from the Pacific Northwest. Note that only 36% (8 out of 22) of coarse textured soil were healthy, while 60% (9 out of 15) medium textured soils produced a healthy crop

Doing so revealed that we had only 3 soils in the fine texture class (all from the Klamath region), which makes the statistical data treatment needed to develop scoring functions problematic for plain lack of data.

For all three texture groups, we then proceeded to develop scoring functions for all 12 CASH indicators. In our demonstration of the scoring process, we assigned health classes (very low to very high) based on the understanding that a greater AWHC is generally better for plant growth, or "more is better". However, this cannot be assumed to be the case for all indicators. If we see high values for surface hardness, which we know is detrimental for plant growth, this prompts us to invert the scoring function (Table 3) and use the principle "less is better". The third type of scoring function is the optimum curve, which applies to pH and extractable phosphorus. In these cases, plants do poorly when the pH is outside of a certain optimum range and there is a risk of unacceptable environmental effects when phosphorus accumulates. However, we saw in the data from our study that fields with high pH, elevated P, and elevated K were more likely to grow a diseased crop. For this reason, and with the special topic of susceptibility to Verticillium disease in mind, we decided to deviate from the CASH protocol by assigning "less is better" functions to the chemical indicators pH, P, and K. The types of scoring functions used are compiled for all indicator values in Table 3.

Table 3: The types of scoring (more is better, less is better and optimum curve) recommended by CASH and the types of scoring used in our study. Deviations are emphasized by red frame. For all three curve types, the indicator value increases along the X-axis

Indicator	Curve type (CASH)	Curve used here
AWHC (*"more is better"*)		
Surface Hardness (*"less is better"*)		
Subsurface Hardness		
Aggregate Stability		
Organic Matter		
PoxC		
Soil Protein Index		
Soil Respiration		
pH ("*Optimum curve*")		
P		
K		
Micronutrients	average score value formed from Mg, Fe, Mn, and Zn scores	
Mg		
Fe		
Mn		
Zn		

Health scores and Verticillium disease

Tables 4 through 7 present comparative health assessments for fields that had crops with limited Verticillium disease ("healthy") and fields that saw more Verticillium symptoms ("diseased"). In each table data and scores are grouped in the sequence physical - biological - chemical indicator values. For each indicator, the average values (Mean) and the Standard Deviation (SD) from the mean are given. These two values determine the shapes of the curves used in the scoring process. For each of the texture classes, total health scores were calculated as the average of the twelve individual health indicator scores.

Data are presented for the individual texture classes as well as for all 40 soils taken together. In the latter comparison, the scores were also based on the respective texture classes as required by the CASH scoring procedure. A color code (compare caption of Table 4) was used to facilitate the quick recognition of trends and differences among scores.

Did the health assessment distinguish between healthy and diseased soils?

The health assessment placed diseased and healthy soils in the same medium soil health class (as indicated by the yellow color in the total health score boxes), regardless of texture class. For fine textured soils (Table 6), the data base is so limited (3 soils, all healthy) that no interpretation can be attempted. In the coarse texture group (Table 4), total health scores were basically identical between healthy and diseased soils. There were gradual differences in total health scores for the medium textured soils (Table 5) and when all health scores were evaluated together (Table 7).

When individual indicator scores are examined, we find that in the coarse texture group (Table 4), only the indicator PoxC (or biologically active carbon) scored in the "low" region, while the healthy soils had three indicator values in the low region (Subsurface Hardness, Organic Matter, and Respiration). However, the healthy soils had one indicator that (just barely) made it into the green, which was pH.

In the group of the medium textured soils (Table 5), the picture is more in line with our expectations. Here, the diseased soils had 5 indicators in the low region while the healthy soils had 4 indicators in the high region, with a fifth indicator just barely missing the threshold to qualify as high (PoxC with a score of 59).

The overall comparison of all health scores, which can be seen as an attempt to compare soils across texture classes (Table 7), showed almost all indicators in the medium range, with the healthy soils winning the total health score competition by a meager 5 points.

Given the very clear, statistically significant differences between individual parameter values that were observed in the comparison between all healthy and all diseased soils (compare Table 1), we have to concede that the process of laboriously scoring all the data according to textural groups did not add much to our understanding of the factors that may be involved in rendering potato soils suppressive to Verticillium wilt. It can be speculated that in coarse textured soils, the management history of a given site (such as amount of irrigation water applied and history of fumigation, compare Potato Progress Vol 19 Number 9) may play a greater role for disease suppressiveness than in medium textured soils, but investigations of significantly larger data sets would be needed to either refute or accept that assumption.

Table 4: Average indicator values and health scores for **coarse** textured soils. Units are the same as in Table 1 throughout Tables 4 to 8.

Score	Interpretation
80-100	Very high
60-79	High
40-59	Medium
20-39	Low
0-19	Very Low

	Data				Scores	
	Healthy (8 soils)		Diseased (14 soils)		Healthy	Diseased
	Mean	*SD*	***Mean***	*SD*	***Mean***	***Mean***
AWHC	**6.0**	2.4	**6.9**	2.4	**44**	**50**
Surface Hardness	**173**	73	**165**	74	**48**	**54**
Subs. Hardness	**400**	0	**371**	65	**36**	**49**
Wet Agg Stab	**14.6**	4.5	**14.3**	7.5	**45**	**48**
OM	**1.48**	0.46	**1.57**	0.53	**31**	**48**
PoxC	**255**	126	**171**	103	**51**	**36**
ACE Protein	**0.94**	0.3	**0.87**	0.29	**53**	**47**
Respiration day 1	**9.87**	3.15	**10.75**	2.89	**34**	**49**
pH	**7.16**	0.58	**7.51**	0.52	**60**	**42**
P	**134**	71	**117**	55	**49**	**54**
K	**275**	188	**301**	173	**57**	**50**
Micronutrients	Mean value from Mg,Fe,Mn and Zn scores				**48**	**47**
Mg	**263**	66	**253**	81	52	38
Fe	**157**	76	**113**	64	40	59
Mn	**66**	14	**61**	17	46	51
Zn	**11.7**	7.8	**8.4**	2.7	55	38
Total Score					**46**	**48**

Table 5: Average indicator values and health scores for **medium** textured soils

	Data				Scores	
	Healthy (9 soils)		Diseased (6 soils)		Healthy	Diseased
	Mean	*SD*	***Mean***	*SD*	***Mean***	***Mean***
AWHC	**18.9**	5.6	**16.9**	4.4	**53**	**44**
Surface Hardness	**168**	75	**172**	35	**51**	**48**
Subs. Hardness	**388**	37	**400**	0	**47**	**41**
Wet Agg Stab	**11.5**	4.5	**15.2**	7.8	**42**	**59**
OM	**1.67**	0.55	**1.63**	0.23	**46**	**47**
PoxC	**221**	106	**131**	122	**59**	**35**
ACE Protein	**0.89**	0.15	**0.67**	0.2	**64**	**29**
Respiration day 1	**9.3**	4.15	**10.06**	1.47	**43**	**55**
pH	**6.19**	0.64	**6.65**	0.57	**60**	**39**
P	**104**	22	**135**	15	**67**	**24**
K	**396**	97	**911**	348	**72**	**25**
Micronutrients	Mean value from Mg,Fe,Mn and Zn scores				**50**	**49**
Mg	**297**	123	**243**	53	**51**	**39**
Fe	**135**	18	**137**	34	**51**	**56**
Mn	**62**	15	**80**	16	**63**	**27**
Zn	**8.14**	4.2	**13.43**	3.17	**36**	**73**
Total Score					**55**	**41**

Table 6: Average indicator values and health scores for **fine** textured soils. There were no diseased soils in this texture class.

	Data				Scores	
	Healthy (3 soils)		Diseased (0 soils)		Healthy	Diseased
	Mean	*SD*	***Mean***	*SD*	***Mean***	***Mean***
AWHC	**11.6**	5.3			**51**	
Surface Hardness	*no data*				*no data*	
Subs. Hardness	*no data*				*no data*	
Wet Agg Stab	**39.6**	29.2			**51**	
OM	**8.82**	4.81			**52**	
PoxC	**570**	103			**52**	
ACE Protein	**1.17**	0.31			**49**	
Respiration day 1	**17.09**	8.39			**50**	
pH	**6.73**	1.35			**49**	
P	**70**	46			**52**	
K	**577**	294			**52**	
Micronutrients	Mean value from Mg,Fe,Mn and Zn scores				**51**	
Mg	**1141**	423			**52**	
Fe	**90**	28			**52**	
Mn	**41**	20			**50**	
Zn	**5.96**	1.91			**50**	
Total Score					**51**	

Table 7: Average indicator values and health scores for **all 40 soils**.
Here, scores are based on the respective texture classes as required by the CASH scoring procedure, and **not** on the mean values listed in the table.

	Data				Scores	
	Healthy (20 soils)		Diseased (20 soils)		Healthy	Diseased
	Mean	*SD*	***Mean***	*SD*	***Mean***	***Mean***
AWHC	**12.7**	7.5	**9.9**	5.6	**49**	**49**
Surface Hardness	**171**	72	**167**	64	**50**	**52**
Subs. Hardness	**394**	27	**380**	55	**42**	**46**
Wet Agg Stab	**17**	14.3	**14.6**	7.4	**45**	**51**
OM	**2.67**	3.11	**1.59**	0.45	**41**	**47**
PoxC	**287**	164	**159**	108	**55**	**36**
ACE Protein	**0.95**	0.25	**0.81**	0.28	**57**	**41**
Respiration day 1	**10.7**	5.1	**10.54**	2.53	**40**	**51**
pH	**6.66**	0.83	**7.25**	0.66	**59**	**41**
P	**111**	53	**122**	47	**57**	**45**
K	**375**	192	**484**	367	**63**	**43**
Micronutrients	*Mean value from Mg,Fe,Mn and Zn scores*				**50**	**47**
Mg	**410**	355	**250**	73	**52**	**39**
Fe	**137**	54	**120**	57	**47**	**58**
Mn	**60**	17	**67**	19	**54**	**44**
Zn	**9.25**	5.92	**9.91**	3.64	**46**	**49**
Total Score					**51**	**46**

At first sight, this analysis of health scores across our entire pool of 40 fields seems to return a somewhat inconclusive result. But a different picture emerges when health scores are evaluated on a farm operation basis. Table 8 shows a comparison of health scores for two fields from the same farm operation. Both soils were from the same texture group (coarse). The total health score assessed for the diseased field (38) is 15 points lower compared with the total score of the field (53) that did not show Verticillium disease. Examination of individual indicator values shows that the diseased field has 3 indicators in the **very low** category and 6 indicators in the **low** category, compared to one and three, respectively, in the healthy soil. This comparison enables the farm manager to recognize weaknesses and deficiencies in a given field. It also points the way towards corrective action, because the farm manager can now compare the management history of the "healthy" field to the history of the "diseased" field, and execute a kind of internal knowledge transfer that does not necessarily involve major deviations from established farm routines.

It is also interesting to note that both fields score relatively well in the chemistry section (pH, P, K and micronutrients), reflecting a traditional emphasis and the well-developed ability of growers to respond to nutrient deficiencies. However, comparisons of this kind suggest that it may be meritorious to monitor physical and biological soil properties more closely, since it is those areas where diseased fields differ most evidently from healthy fields.

Table 8: Indicator values and respective health scores for two soils from the same farm operation.

	Data		Scores	
	Healthy	Diseased	Healthy	Diseased
	Mean	*Mean*	*Mean*	*Mean*
AWHC	7.5	6.0	67	38
Surface Hardness	235	250	18	13
Subs. Hardness	400	400	36	36
Wet Agg Stab	23	9	92	19
OM	1.4	1.03	37	16
PoxC	227	163	58	37
ACE Protein	0.9	0.69	47	23
Respiration day 1	8.9	8.58	31	27
pH	6.7	7.70	90	26
P	92	104	70	63
K	170	130	75	81
Micronutrients	Average score		56	52
Mg	378	303	98	79
Fe	114	71	58	78
Mn	58	70	62	34
Zn	5.3	6.9	5	15
Total Score			53	38

Score	Interpretation
80-100	Very high
60-79	High
40-59	Medium
20-39	Low
0-19	Very Low

Trends of the same kind as reported in Table 8 were observed in 6 out of the 8 participating farm operations (Figure 7): for the majority of the participating farms, healthy fields scored significantly higher than fields afflicted by the disease. The reasons for this deviation will be discussed directly with the relevant farm managers.

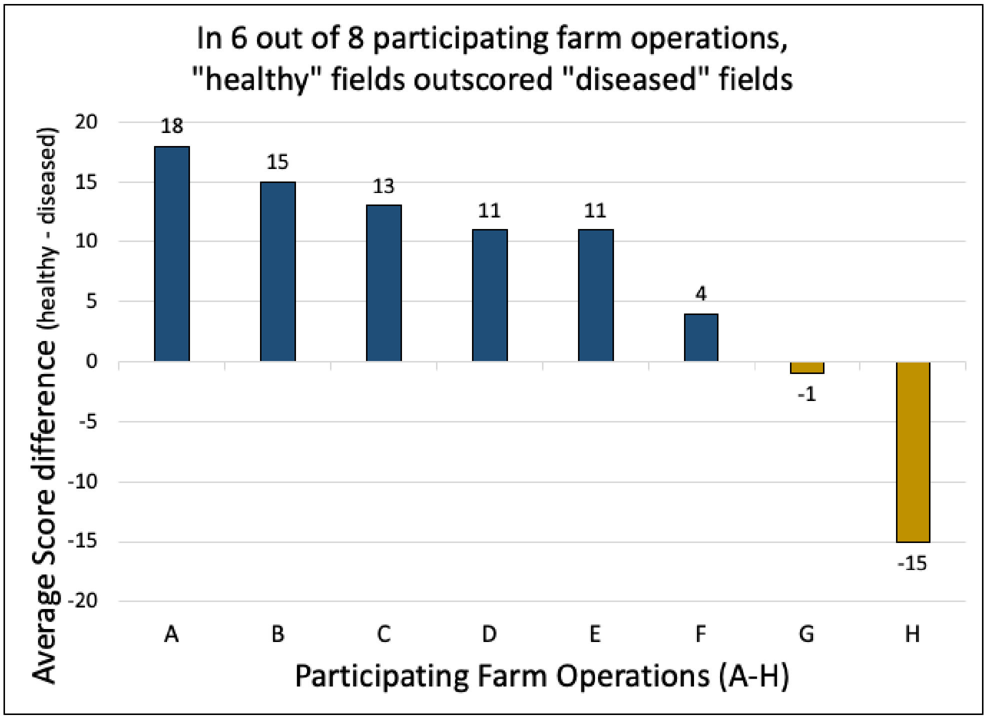


Figure 7: Point range by which total health scores in healthy fields exceeded the health scores of diseased fields, listed by farm operation (read: For operation A, the average health score of healthy fields was 18 points higher than the average health score of the diseased fields from the same farm). Each operation contributed at least one healthy and one diseased field to the investigation, but most contributed multiple fields in either category.

Conclusions

This investigation had **two major objectives**: a) recognize soil indicator values that may possibly be tied to soil suppressiveness towards Verticillium wilt and b) examine the suitability of the Comprehensive Assessment of Soil Health (CASH) for its ability to distinguish between disease-suppressive and disease-prone soils.

For Objective a), we are pleased to report that it was possible to isolate several indicator values that are significantly related to the incidence of Verticillium wilt, together with several others that warrant close attention. According to their statistical significance, these indicators can be grouped into three tiers (Table 9), those that were statistically significant (tier 1) and those that had probabilities of error of less than 10 % (tier 2) and 20 % (tier 3). The information presented in Table 9 represents the equivalent of a general insight that should be applicable to the entire potato industry in the Pacific Northwest.

Regarding the evaluation of the CASH soil health assessment procedure as a tool to identify disease suppressive soils (Objective b), we believe that the data pool in our study was too small to allow this approach to reveal its full potential, especially given the necessity that data must be binned into three texture classes. Nevertheless, this effort had merit when applied to individual farm operations. Here, the CASH assessment helps the grower to recognize weaknesses and deficiencies that would be missed in a classical soil analysis. Knowing which of their fields are in good shape, and which may need attention, offers the grower the opportunity to practice the equivalent of "in-house technology transfer" by extending procedures and practices associated with healthy fields to those that show deficiencies. Note that such practice would not incur additional cost for external consultation.

Table 9: Indicator values with the ability to identify soil properties and mechanisms conducive to soil suppressiveness towards Verticillium wilt in the Pacific Northwest. Compare Table 1 for numerical differences between healthy and diseased soils.

Tier	Indicator
One *Statistically significant at $p < 0.05$*	1. Decrease in respiration over 4 days 2. Permanganate oxidizable C (PoxC) 3. pH 4. Clay content
Two *$0.05 < p < 0.1$*	1. Mg 2. K/Mg ratio 3. ACE Protein index
Three *$0.1 < p < 0.2$*	1. N 2. Organic C and OM 3. Sand content 4. AWHC

When seen in combination with results from an analysis of the management history of diseased versus healthy fields (compare Potato Progress Vol. 19 No 9, October 2019), the data presented here emphasize one additional, major insight: Abundant and well-curated data are the foundation to the recognition of trends as much as to the development of solutions in modern land management. Probably the most effective tool for the efficient handling of stubborn disease such as Verticillium wilt is the availability of high-quality management and soil data. Such data must reach back in time to allow for the recognition of both beneficial and detrimental practices, and they must allow for the comparison of a field with multiple other fields, to enable horizontal (field-to-field) knowledge transfer. The CASH assessment procedure is particularly useful when repeated in regular intervals (at least once per full rotation cycle) due to its ability to document change over time. **Hence, we want to encourage the industry to work towards the development of comprehensive databases for soil indicator values and soil health assessments.**

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References

Andrews, S.S., D.L. Karlen and C.A. Cambardella. 2004. The soil management assessment framework: A quantitative soil quality evaluation method. Soil Sci. Soc. Am. J. 68:1945–1962. doi/pdf/10.2136/sssaj2004.1945.

Haney, R.L., E.B. Haney, D.R. Smith, R.D. Harmel and M.J. White. 2018. The soil health tool-theory and initial broad-scale application. Appl. Soil Ecol. 125:162–168. doi:10.1016/j.apsoil.2017.07.035.

Idowu, O.J., H.M. van Es, G.S. Abawi, D.W. Wolfe, J.I. Ball, B.K. Gugino, B.N. Moebius, R.R. Schindelbeck and A.V. Bilgili. 2008. Farmer-oriented assessment of soil quality using field, laboratory, and VNIR spectroscopy methods. Plant Soil 307:243-253. doi:10.1007/s11104-007-9521-0.

Karlen, D.L., Goeser, N.J., Veum, K.S. and Yost, M.A., 2017. On-farm soil health evaluations: Challenges and opportunities. J. Soil Water Conserv. 72:26A-31A. doi.org/10.2489/jswc.72.2.26A

Kleber, M and D.D. Myrold. 2019. Soil health and *Verticillium* disease of potato Part I: The role of site properties and management history. Potato Progress XIX Number 9, October 2019.

Moebius-Clune, B.N., D.J. Moebius-Clune, B.K. Gugino, O.J. Idowu, R.R. Schindelbeck, A.J. Ristow, H.M. van Es, J.E. Thies, H.A. Shayler, M.B. McBride, D.W. Wolfe and G.S. Abawi. 2016. Comprehensive Assessment of Soil Health – the Cornell Framework manual, edition 3.0 Cornell University. Available at http://soilhealth.cals.cornell.edu/training-manual/.

Wienhold, B.J., D.L. Karlen, S.S. Andrews and D.E. Stott. 2009. Protocol for soil management assessment framework (SMAF) soil indicator scoring curve development. Renew. Agric. Food Syst. 24:260–266. doi:10.1017/S1742170509990093.

Yost, M.A., K.S. Veum, N.R. Kitchen, J.E. Sawyer, J.J. Camberato, P.R. Carter, R.B. Ferguson et al. 2018. Evaluation of the Haney Soil Health Tool for corn nitrogen recommendations across eight Midwest states. J. Soil Water Conserv. 73:587-592. doi:10.2489/jswc.73.5.587.