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Soil health and *Verticillium* disease of potato Part I: The role of site properties and management history

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Introduction

Verticillium wilt is a common limiting factor of potato production in the Northwest. It has become the predominant pathogen of potatoes because its microsclerotia can survive in soil for over a decade. Verticillium is difficult to eradicate from soils using rotation management techniques due to its ability to use numerous weeds as alternative hosts. Breeding potatoes for resistance to Verticillium is challenging, and there are currently no truly resistant clones. Conventional disease control has focused on reducing the populations of microsclerotia in soil using broad-spectrum fumigants. But, the high costs and potential negative health and environmental consequences associated with the use of fumigants are strong incentives to find non-chemical control methods for managing this soil-borne disease.

Soil-borne pathogens such as Verticillium are frequently observed to affect crops in a patchy, discontinuous manner, reflecting variable concentrations of inoculum and/or variations in the ability of the soil to suppress the pathogen. As a first step towards the development of non-chemical control methods for soil-borne diseases it is thus advisable to determine such site and soil properties that either favor or suppress the pathogen and can then potentially be exploited in support of defensive strategies.

The rationale underlying our research was that, if we can isolate and understand the factors that contribute to disease suppression, we may eventually be able to outsmart the pathogen instead of trying to fight it in what appears to be an uphill battle. We also hope that when we understand the fundamentals of disease suppressiveness, we can work to duplicate and implement those factors at any site. This would lead to a technology of controlling the potato production system with less or no fumigation, potentially reducing costs for the growers and the environmental impact of the crop system.

To this end, we formulated the following goals for our investigation:

1. Identify existing soil conditions and management practices with the potential to render potato fields disease suppressive, and
2. Derive recommendations for the development of an integrated management approach to restore diseased soils to a state of disease suppressiveness.

To achieve this goal, we adopted a participatory research strategy, where information was obtained directly from growers and from NRCS databases. This was done to achieve a maximum of practical, real-world applicability of results. Growers across the Northwest potato growing region were asked to identify 20 fields with either a current outbreak and/or a history of Verticillium disease and 20 contrasting field sites with little or no history of disease. The latter were considered “potentially disease suppressive.” To homogenize our data set, we imposed the following requirements for a field to be included in the study:

- must have been planted to potato at least twice during the past 5 years;
- planted to potato in the year 2017;
- grower is able to provide a 5-year management history for their sites.

This allowed us to compile a total of 40 sites across the Northwest, of which 20 fell in the diseased category and 20 were considered “healthy” with respect to Verticillium disease. We intended to represent the potato industries of WA, OR, and ID, proportional to their economic importance, but found it very difficult to identify fields in Idaho that had been cropped to potato twice over the years 2013-2017. For this reason, our representation of the Northwest potato industry is somewhat skewed towards the extended Columbia Basin. In the end, our study comprised 31 fields in the extended Columbia Basin, 5 in the Klamath Basin and 4 in the Snake River plain, Idaho.

Once sites were selected, we initiated a survey of the management history for each. This activity had the objective to find out if certain management practices contribute more to disease suppressiveness than others. Growers were requested to provide, for the period from 2012 to 2017, information regarding: potato varieties; crop rotation; fertilizer applications; cover crops; pesticide, fungicide and fumigant applications; yields; yield reduction from disease; irrigation cycles; organic matter amendments (manure, compost, other biosolids, etc.). We found growers extremely supportive in helping us to compile the vast catalog of data, however, it was not always possible to obtain the desired information for all 40 fields. For instance, four fields had proprietary potato varieties in 2017 that were not disclosed to us. This issue of limited uncertainty pertained to almost all parameters collected during our survey.

Soil type and susceptibility to disease

Verticillium is a soil-borne pathogen, suggesting that the type of soil that the pathogen finds itself in may have an influence on its ability to survive and proliferate. We found that our 40 fields represented four of the twelve soil orders known to U.S. Soil Taxonomy (Figure 1).

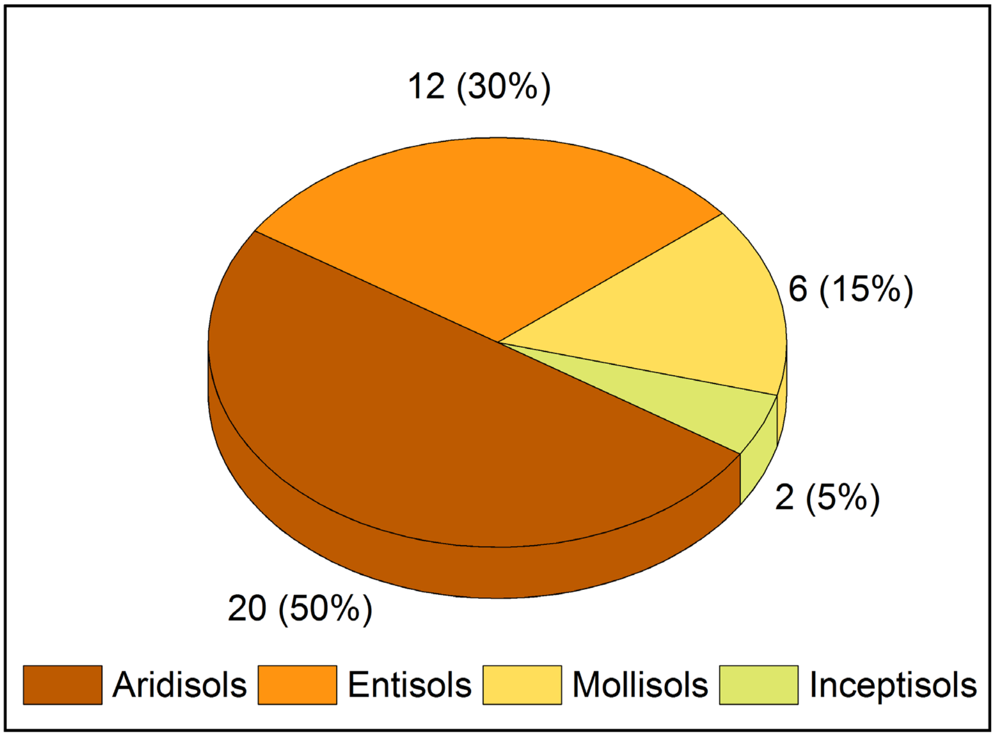

Figure 1: Soil orders represented among the 40 fields of this study.

The majority (50%) of potato fields were mapped as aridisols, 30% were on entisols, with mollisols contributing another 15%. Two fields were on inceptisols. Soil orders were unevenly distributed among growing regions. All four soils from Idaho were Entisols, while the soils in the Klamath region were Mollisols and Inceptisols. Aridisols, Entisols and three of the Mollisols were situated in the Columbia Basin.

The major differences between these soil orders can be given as:

Aridisols: Aridity (scarcity of water) is the major characteristic of these soils. They often show an accumulation of calcium carbonate, gypsum or soluble salts, which can raise the pH well above neutral.

Entisols: In these soils there is a lack of evidence for all but the earliest stages of soil formation, either because they are so young or because their parent materials have not reacted to soil forming factors.

Mollisols: Mollisols have humus-rich surface horizons largely derived from the dense root systems of prairie grasses. Cation exchange capacity is high, as is overall fertility.

Inceptisols: In Inceptisols, the beginning of soil profile development is evident, but the well-defined profile characteristics of soils thought to be more mature have not yet developed.

When we grouped our 40 sites according to soil order and disease status (Figure 2), we noted that the majority of diseased fields were found in the Aridisol order.

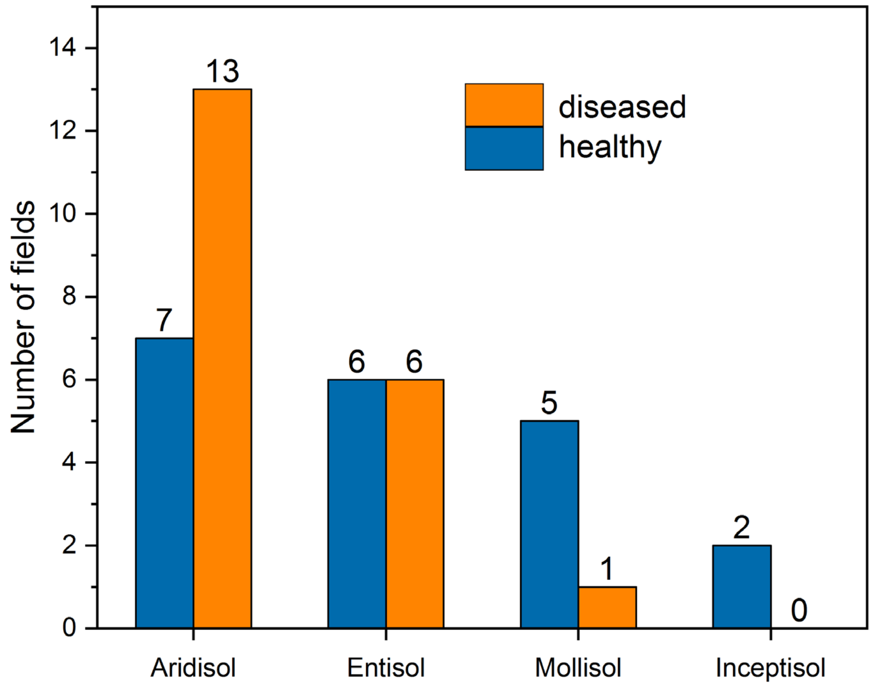

Figure 2: Disease status of potato fields as a function of soil order.

Being a member of the Entisol order did not seem relevant for disease status, while most of the potato crops grown on Mollisols were found to be healthy (5 out of 6). There were only two soils in the Inceptisol order, hence we do not think it means much that these turned out to be in the "healthy" category. We interpret these findings to indicate that Aridisols may either have fewer natural defenses against Verticillium than Mollisols or that Aridisols have one or more properties that are particularly conducive to the disease. However, it is obviously possible to grow a healthy potato crop on an Aridisol, while farming a Mollisol does not mean complete protection against the pathogen.

The implication of this finding is that by knowing the soil type, a grower can obtain an initial risk assessment. There are online tools that allow easy determination of soil type when field location is known, such as the Web Soil Survey of the NRCS (https://websoilsurvey.nrcs.usda.gov) and the SoilWeb tool of the University of California at Davis: (https://casoilresource.lawr.ucdavis.edu/gmap/). In the latter tool, growers can look up their fields on maps and by clicking on the respective map symbol, find the name of the soil series at which their ground is mapped. Figure 3 shows the soil series encountered in our study together with the disease status of the fields in the respective soil series. Note that almost all fields in the Sagehill and Shano series were affected by Verticillium wilt.

Figure 4 shows that these "high risk" soils make up a substantial part of the potato growing region of the Northwest and are of relevance for growers in Washington, Oregon, and Idaho.

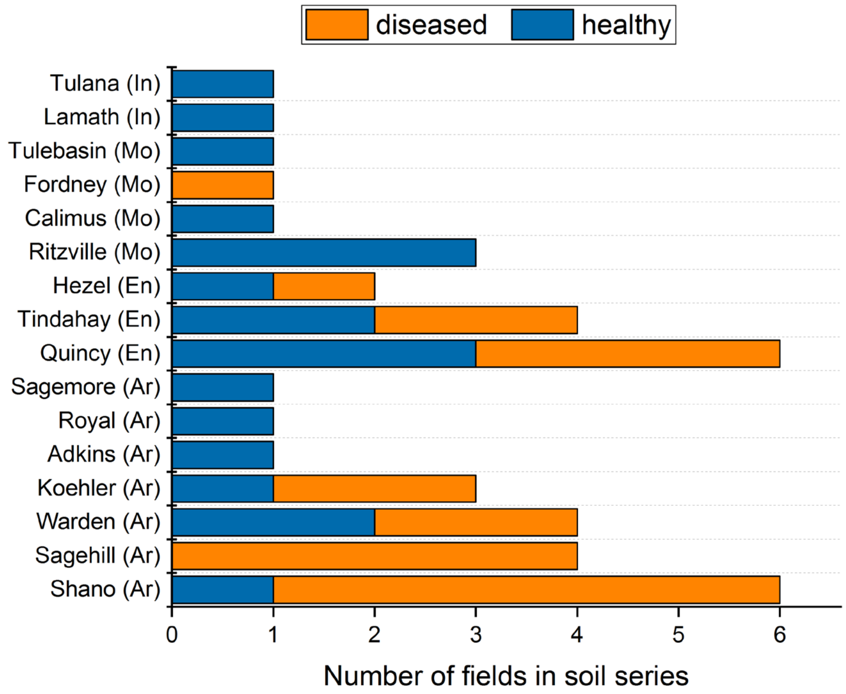

Figure 3: Potato fields were distributed among 16 soil series. (In = inceptisol; Mo = mollisol; En = entisol; Ar = aridisol).

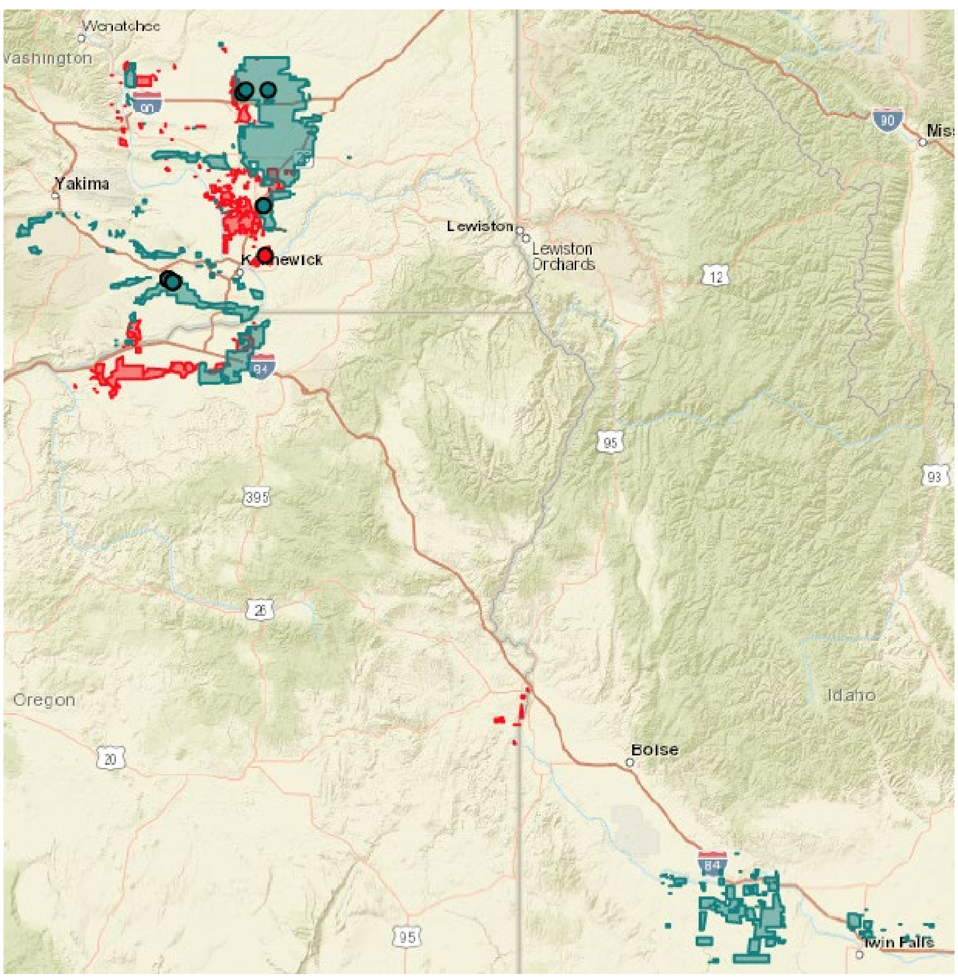

Figure 4: Extent of the Shano (green, 653,117 acres) and Sagehill (red, 151,476 acres) soil series across the potato growing region of the Northwest. Source: Web Soil Survey of the NRCS (https://websoilsurvey.nrcs.usda.gov).

Potato varieties and susceptibility to disease

Over the course of 5 years, more than 20 different potato varieties were planted in the 40 study fields (Figure 5), with russet varieties making up the majority. Most popular were Russet Burbank (21) followed by Umatilla Russet (11), Ranger Russet (8), and Russet Norkotah (8)

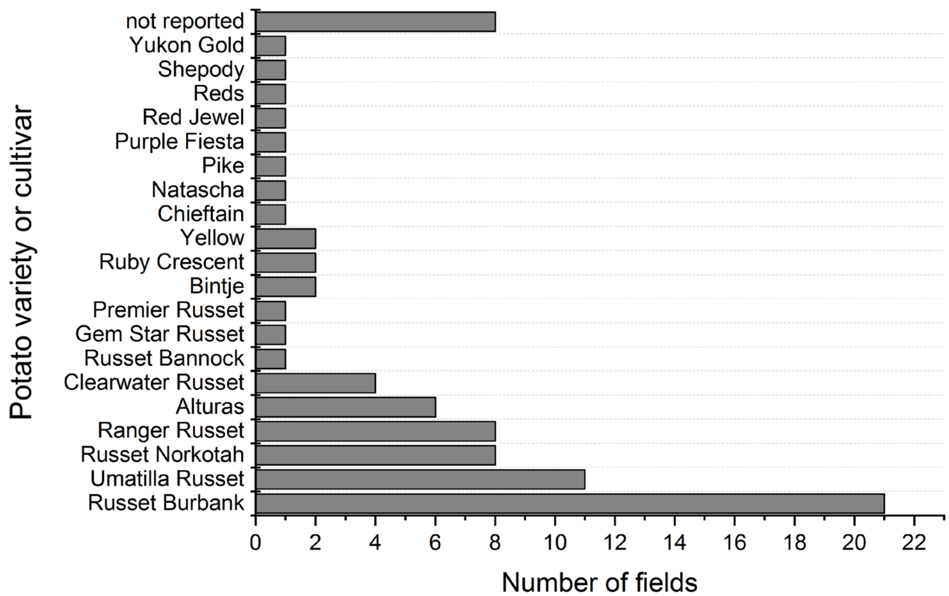

Figure 5: Potato varieties in the fields of this study, years 2013 - 2017

Disease status in the year 2017 did not show any obvious relation with potato variety (Figure 5). This is noteworthy, as different varieties are expected to exhibit variation in susceptibility to Verticillium disease (Table 1).

Table 1: Susceptibility of potato varieties to *Verticillium dahliae,* source: **Sagar Sathuvalli**, potato breeder, Hermiston Agricultural Research and Extension Center.

Potato variety	Susceptibility to verticillium disease
Red Jewel	not known but probably susceptible
Purple Fiesta (Purple Pelisse)	susceptible
Natascha	unknown
Yellow	unknown
Ruby Crescent	unknown
Gem Star Russet	moderately resistant
Clearwater Russet	moderately resistant
Alturas	moderately resistant
Ranger Russet	moderately resistant
Russet Norkotah	highly susceptible
Umatilla Russet	susceptible
Russet Burbank	susceptible

Among the more frequently used varieties, the likelihood of being diseased was 50% for Russet Norkotah and Umatilla Russet, while Russet Burbank had slightly more healthy fields (6 out of 10) and fields with Ranger Russet showed the disease in 4 out of 6 fields (Figure 6). We take this observation to indicate that under favorable circumstances, a susceptible variety such as Russet Burbank or Umatilla Russet can produce a healthy crop, while moderate or even high resistance to Verticillium does not guarantee the absence of the disease if the crop is under pressure through other management or environment related factors.

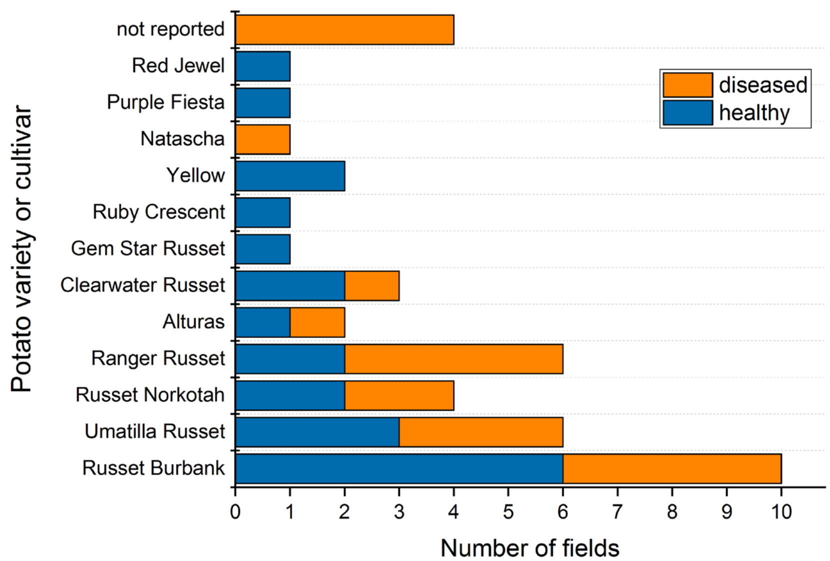

Figure 6: Incidence of Verticillium disease in the year 2017 as a function of potato variety.

Rotation

During the five years covered by this study (2013, 2014, 2015, 2016, and 2017), all fields had been planted to potato at least twice. One field had been planted three times (2013, 2015, and 2017), and interestingly, that field produced a healthy crop in 2017. The most frequent intermediate crops were corn and wheat, neither of these were related with disease status of the fields in 2017. Most fields (25 out of 40) had the previous potato crop planted in 2014 (Figure 7), indicating the predominance of a three-year rotation cycle in the growing region. As Figure 7 illustrates, the time elapsed since the previous potato crop had no influence on the incidence of the disease within our data pool of 40 fields. These data suggest that the time elapsed between potato crops was not a factor in disease suppression in our data set.

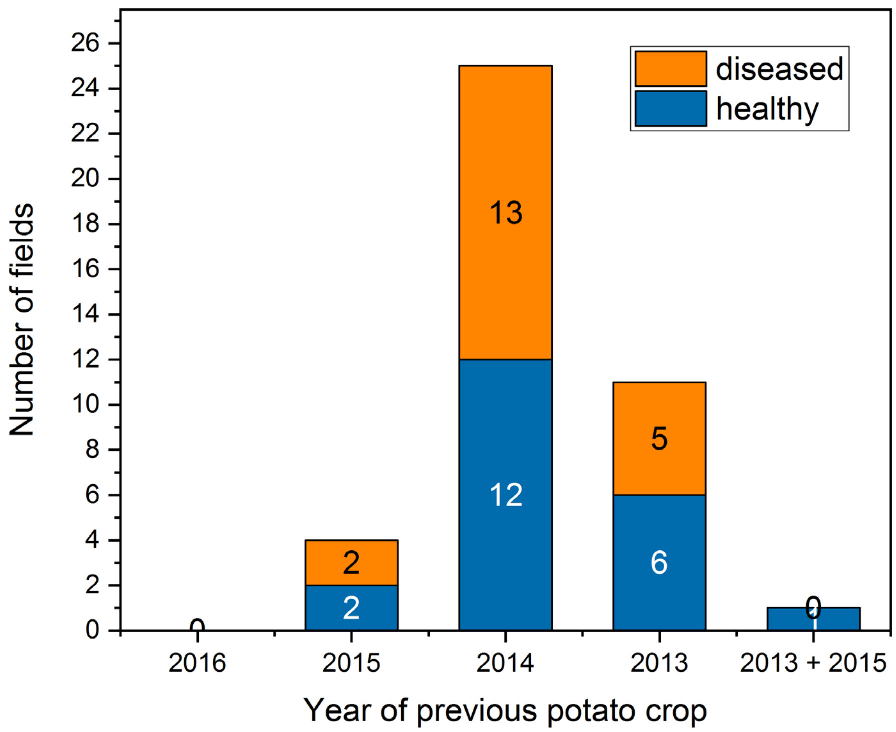

Figure 7: Year when the previous potato crop was planted (all fields had a potato crop in 2017). One field had potato crops in 3 out of five years.

Irrigation

The Northwest potato growing region has a semiarid climate, necessitating irrigation of potato crops. All 40 fields in our study had been irrigated, however, complete irrigation data was only available for 12 of the diseased and 15 of the healthy fields. While this restriction limits the inference that can be drawn, we still noticed a potentially important trend. During the year 2017, when all fields were cropped to potato, the diseased fields received a slightly larger amount of irrigation water compared with the healthy fields (34 inches in the diseased and 31 inches in the healthy fields; Figure 8). Although this is not a statistically significant difference, it hints at the possibility that greater soil moisture may promote the pathogen. A much more pronounced difference between diseased and healthy fields becomes visible when we summarized the amount of irrigation over the whole 5-year observation period (Figure 9). Averaging over 5 years, i.e., explicitly considering the amount of water applied to the non-potato intermediate crops, we now see the diseased fields receiving almost 10 inches of water more than the healthy fields (31.7 in the diseased vs 22 inches in the healthy, median values). In relative proportions, that means the diseased fields were treated to about 30-40% more irrigation water than the healthy fields. We hypothesize that greater soil moisture in the years between potato crops may be an overlooked factor in the epidemiology of *Verticillium dahliae*. This observation is particularly noteworthy as it lends itself to relatively easy correction through an adaptation of management strategies.

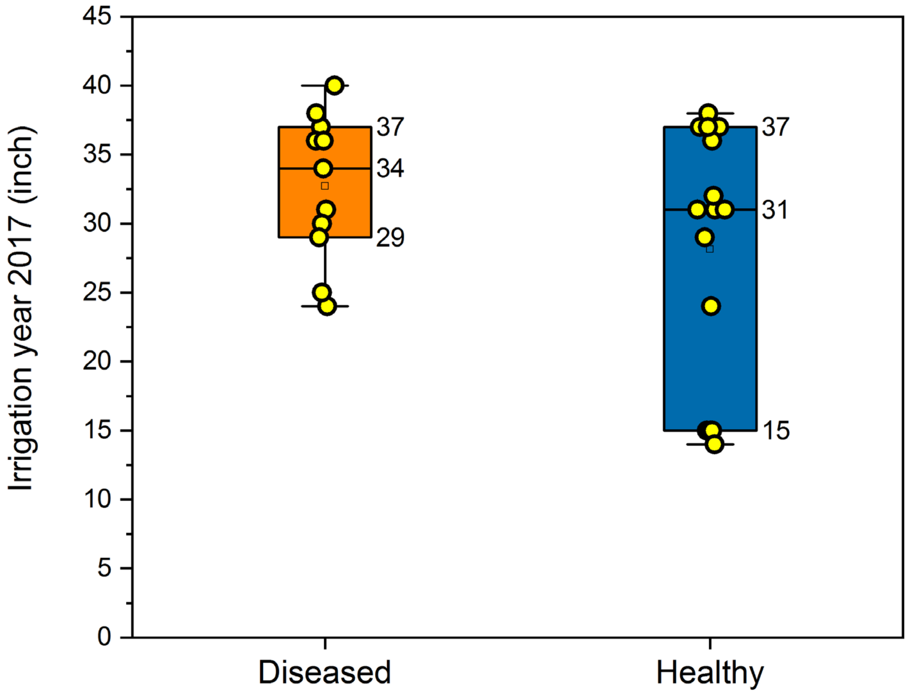

Figure 8: Irrigation water applied to potato fields during the year 2017. Yellow dots represent individual fields. Median, 25/75 percentiles and mean values (square symbol inside box).

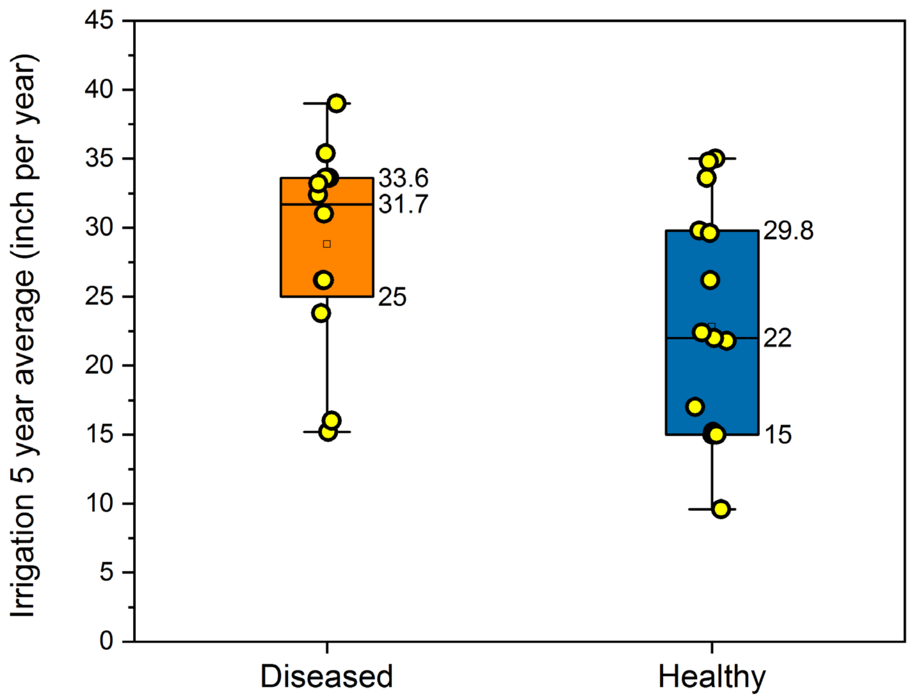

Figure 9: Irrigation water applied to potato fields during the whole 5-year period. Annual average, yellow dots represent individual fields. Median, 25/75 percentiles and mean values (square symbol inside box).

Fumigation frequency and disease

Fumigation is a relatively harsh treatment aimed at the elimination of fungal sclerotia. Thirty five out of 40 soils have received this treatment, 16 were fumigated once over the 5-year observation period while 19 fields were fumigated twice. Five soils did not receive a fumigation treatment. Our data suggest that fumigation did not provide complete protection against the disease (Figure 10).

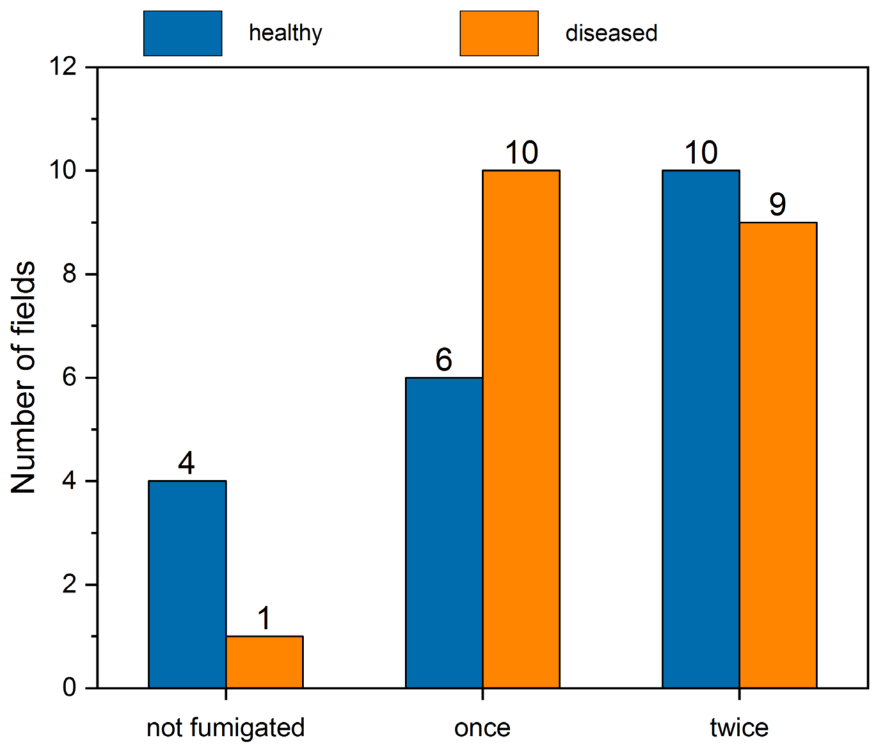

Figure 10: Frequency of fumigation events over the 5 year observation period

This assessment is augmented by an examination of the period elapsed since the last fumigation event (Figure 11). Seventeen of our fields had been fumigated in the same year (2017) when the potato crop was planted, out of these fields almost half (8 out of 17) ended up being diseased. Seven fields were fumigated the year prior to planting the potato crop, but out of these, only 2 = 30 % ended up being diseased. This could mean that it may be worth the consideration to give the beneficial soil microorganisms some time to recover after the amount of sclerotia has been reduced by fumigation.

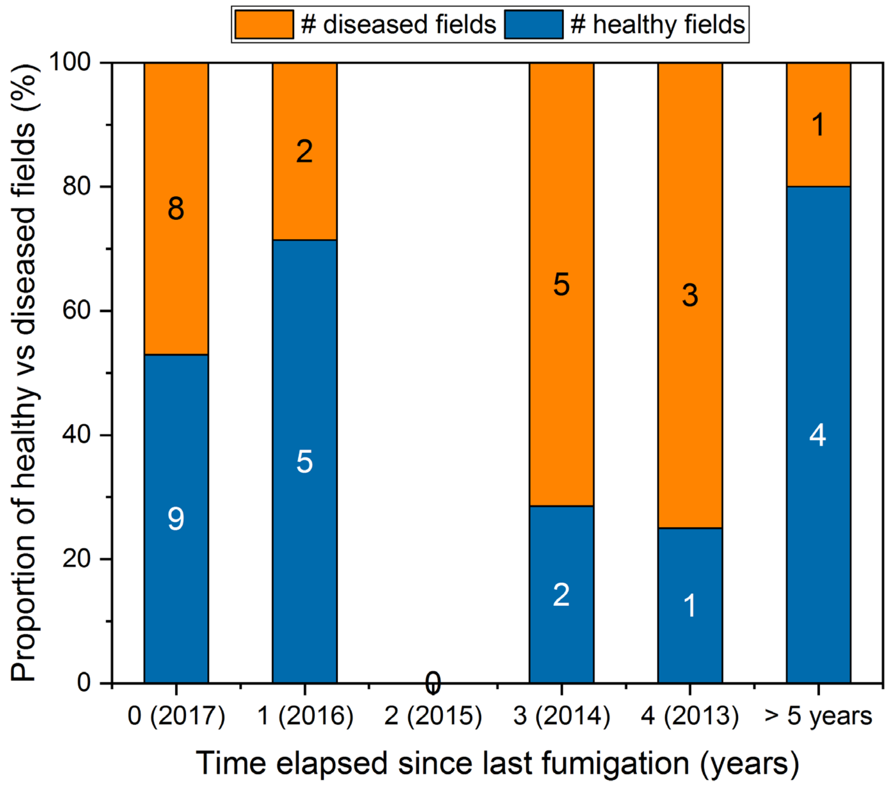

Figure 11: Time elapsed since last fumigation, in years with precise year of fumigation in brackets, and # of fields in the diseased vs healthy categories. Five soils did not receive a fumigation treatment during the 5-year observation period. Y-axis gives relative proportion of diseased vs healthy fields in %.

Our data also suggest that 3 and 4 years between fumigation and potato crop are too long an interval to ensure protection. We find that, although fumigation is probably the only means to directly reduce the amount of viable sclerotia in the soil, its efficiency as a protective measure is not as good as could be wished, particularly considering the high cost associated with the treatment. The fact that some soils produced healthy crops without any fumigation at all supports our hypotheses that it should be fundamentally possible to substitute appropriate management techniques for this costly management practice.

Applications of chemicals to protect the crop against pests and diseases

Unfortunately, Verticillium is not the only disease that may jeopardize crop yield and harvest quality. Crops must be protected against insects, weeds, fungi, bacteria, viruses, and nematodes. To this end, growers deploy a vast portfolio of agrochemicals in addition to the episodic fumigation process, which is targeting soil-borne pathogens such as Verticillium. When we budgeted all applications of agrochemicals over the course of our 5-year management history, we found that the median number of chemical applications was significantly higher in diseased fields (65.5 applications over 5 years; Figure 12) than in healthy fields (46 applications over 5 years).

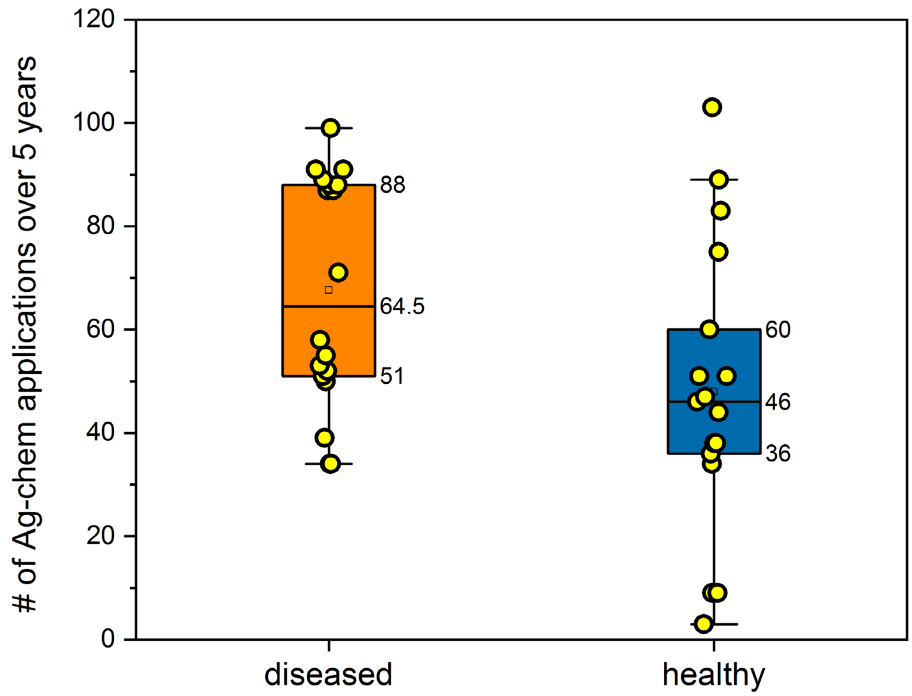

Figure 12: Total number of agrochemical applications over the 5-year period. Yellow dots represent individual fields.

At first sight, this result seems to suggest that "more diseased fields might need more medicine," but this view does not take into account the fact that the majority of the agrochemicals applied (compare Table 2) is aimed at pests and weeds and does not target the Verticillium disease.

We believe it might be worth considering an alternative possibility: the greater the stress from frequent chemical applications on the soil microbial community, the higher the likelihood that this community can no longer bring its antagonistic functionalities to bear when a soil-borne pathogen needs to be kept at bay. We also encourage growers to look at rotations with a fresh eye: a crop such as mint might increase the stress on the subsequent potato crop because it is a very good host for Verticillium.

Table 2: Cumulated applications of agrochemicals (5-year period) for a field with a diseased potato crop and a field with a healthy crop from the same operation.

The diseased field was under a Mint (2013) – Potato (2014) – Corn (2015) – Corn (2016) – Potato (2017) rotation and was fumigated in 2014.

The field with the healthy crop was under a Alfalfa (2013) – Potato (2014) – Onion (2015) – Corn (2016) – Potato (2017) rotation and was also fumigated in 2014.

Compounds that were applied to both fields are in bold face

Brand Name	Diseased	Healthy field
A 5-0-7 solution	2	1
ABBA Ultra	3	3
Actara	1	
Admire Pro	2	
Alder Bark		1
Asana XL	13	10
Avaunt	1	
Beleaf 50 SG	2	2
Bravo Wstk	1	
BROX 2EC	1	
Cabrio Plus	1	1
Capture LFR	1	
Chateau WDG	1	1
Cruiser Maxx		1
Dimethoate 4E (FMC)	2	2
Dimethoate 4EC (Drexel)	1	
Echo 720	1	
Eptam 7E		1
Fulfill		1
Gly Star Plus		1
Goal 2XL	1	
Gramoxone Inteon	1	1
Harmony Extra SG	1	
Headline SC	1	
Initiate 720	3	3
Makaze	2	
Maxim 4FS		1
MCPA Amine 4 (Albaugh)	1	
Moncut 70-DF	1	
Movento 240SC	1	
Omega 500F	2	2
Onager		1
Outlook	3	
Penncozeb 75DF	2	2
Prowl H2O	1	1
Quadris	1	1
Select 2 EC	1	
TriCor DF	1	1
Ultra Flourish	1	1
Vertisan		1
Volunteer	1	
Vydate L	2	6
Total	**60**	**46**

Miscellaneous management information

Many additional management parameters were collected but did not yield significant differences between diseased and healthy fields, typically because variability between fields was so high (the number in brackets gives the variability of the parameter value in % of that value). A selection of these parameters is presented in Table 3 to demonstrate some trends that do not qualify as statistically significant but may be worth following up.

Table 3: Management history and disease level. Numbers in brackets give the variability in % (Coefficient of variation). Significance was tested using Student's t-test and the "Probability for a significant difference" is the inverse of the p-value expressed in %. For all variables reported, "total" refers to the sum of the past five years.

Parameter	diseased	healthy	Probability of significant difference
	(number)		%
Years field was in an alfalfa, barley or wheat rotation	1.7 (50.9)	2.0 (28.5)	**90**
Years field was in a beans or peas rotation	0.35 (140.0)	0.15 (244.2)	**85**
Total number of tillage events	112.9 (29.2)	108.0 (21.3)	50
	(lbs/acre)		
Total N fertilizer applied	291.6 (75.4)	249.9 (66.4)	**82**
Total K fertilizer applied	426.5 (63.4)	367.4 (194.6)	35
Total P fertilizer applied	169.9 (92.3)	172.4 (82.0)	7
	(gal/acre)		
Total amount of active ingredient of fumigant applied	32.7 (32.1)	30.0 (32.4)	55
	(US tons/acre)		
Potato crop yield	34.3 (77.8)	37.3 (80.8)	26

For instance, it seems that keeping fields in a rotation with either alfalfa, barley or wheat may contribute to suppressiveness against Verticillium (Table 3, we found a 90% probability for this trend, to be considered statistically significant, that probability would have to be above 95%), while introducing beans or peas into the rotation may have the opposite effect. We also note that diseased fields received more N and K over the 5-year period, while P applications were nearly identical. Average crop yields were not significantly different but given the fact that we had more than 20 potato varieties with different yield potentials, our yield data have little more than anecdotal value. A comparison of the amount of fumigants applied shows no significant difference between healthy and diseased fields.

Conclusions

Despite the fact that our study involved only 40 potato fields and must therefore be considered of limited size, we succeeded in identifying a number of soil conditions and management practices with the potential to render potato fields either susceptible or suppressive towards verticillium disease.

a) Our data suggest that soils in the order of aridisol have particularly weak defenses against the disease. Growers farming ground in the Shano and Sagehill soil series should be aware that potato crops in these soils are at high risk for contracting the disease.

b) Mollisols seem to be better in suppressing the disease than the other three soil orders (aridisols, entisols, inceptisols).

c) The potato variety showed little correlation with Verticillium disease status. This result was unexpected since there are distinct differences in the susceptibility to disease among potato varieties.

d) Within the 5-year time frame of our study, it did not matter for disease suppressiveness how much time had elapsed since the last potato crop. With sclerotia being able to survive in the soil upwards of 10 years, this result was probably to be expected.

e) Soil moisture above a certain threshold seems to be a major factor in disease susceptibility. However, it was not the amount of water during potato years but the overall amount of water supplied to the field that was correlated with disease incidence. This means that irrigation practices between potato years may be of greater importance for disease susceptibility than the irrigation regime chosen while the crop grows!

f) Ideally, fumigation would eradicate all sclerotia and guarantee a crop free of Verticillium. This was not observed in our study. In fact, repeated fumigation (within the 5-year observation period) was necessary to have at least a 50/50 chance for a disease-free field. An observation that merits follow-up research (investigating a larger number of fields) relates to timing: we saw a trend for fumigation in the year before the potato crop being more efficient than fumigation in the same year. It may well be that by fumigating the year before (which basically equates to fall fumigation), the beneficial microorganisms in the soil have more time to grow back and regain their ability to put pressure on the pathogen.

g) The fact that diseased fields tend to have a history of significantly more frequent applications of agrochemicals seems to suggest that what is intended to be preventive care to control weeds, pests, and diseases may actually manifest itself as a serious stress factor for soil microorganisms.

h) There are other trends all suggesting that relatively small adjustments to existing management practices may have the potential to go a long way towards strengthening soil health and, by default the ability of soils to suppress *Verticillium*. Towards this goal, we propose that the trends and correlations seen in this study be subjected to more focused studies.

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