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Field and Management Factors Can Reduce Potato Early Blight Severity: an Observational Study on Farms Combined with Field Trials in Southern Sweden

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Abstract

Alternaria solani is causing early blight and thereby yield reduction in the potato production. The pathogen is today mainly controlled by fungicide applications. The severity of early blight can vary largely among fields. The aim of this study was to gain understanding of what field and management parameters are the most important for early blight severity to create more farm-specific fungicide treatment recommendations. Over three seasons, 2019–2021, 52 field plots were observed at farms in southern Sweden. In each field a 24 m × 24 m plot was left untreated against early blight. However, late blight fungicides were applied. The disease severity was scored twice in the untreated plot and information about various soil/plant parameters and farmer's management was collected from each field. In addition to the observational study, field trials were performed in 2021 and 2022, evaluating the effect of potassium fertiliser levels on severeness of infection. We found that the soil composition was of significant importance for the severity of infection, in particular the sand, clay, and potassium content. The early blight severity was directly positively correlating with a high sand content. Low levels of leaf potassium increased the severity of early blight infection, and this observation was confirmed in field trials where different levels of potassium fertiliser were applied. Further no reduction in disease severity was observed with a four-year crop rotation. With knowledge about field and management factors that influence disease, field-specific recommendations can be developed supporting an integrated pest management strategy for early blight to reduce and optimise the fungicide usage.

Keywords *Alternaria solani* · IPM · Participatory research · Potassium · Sand content · Soil

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Introduction

The soil-borne fungus *Alternaria solani* is causing early blight disease in potatoes. In Sweden the pathogen is mainly infecting the foliage causing earlier defoliation leading to a lower yield (Andersson and Wiik 2008; Edin et al. 2019). The main method to decrease the yield loss from early blight today is fungicide usage with multiple sprays per season (Horsfield et al. 2010). The development of integrated pest management, IPM, is aiming to optimise holistic methods in disease control strategies with minimised use of chemical pesticides to tackle plant diseases (Barrera 2020). IPM is not a strict principle that applies to all situations uniformly, but rather a philosophy of guidance to use the most suitable and sustainable tool appropriate for the situation (Dara 2019). IPM could be considered for early blight in potatoes as well (Jindo et al. 2021). However, IPM is not being used to a great extent for early blight management in Sweden today, meaning fungicides are probably overused. The EU green deal (Guyomard et al. 2020) is aiming to reduce the use of pesticides by 50%, and to achieve that for potato early blight, studies of factors linked to IPM including the importance of soil, plant and management factors for early blight disease development are of great importance. Late blight treatment is the main reason for the high amounts of pesticides being used in potato production (Haverkort et al. 2008), but also early blight is currently demanding many treatments to be controlled. There are multiple prognosis systems for potato early blight being developed; most of them are only based on weather conditions and plant age (Meno et al. 2022a, b), but it would be beneficial if field soil specific parameters would also be taken into consideration in these models to create more accurate simulations.

Mineral nutrients are important for plant resistance to pathogens even if there are contradicting reports on the effect of nutrients on plant disease (Dordas 2008) that need to be further elucidated. The effect may depend on the type of pathogen, since obligate pathogens may increase disease severity at high nitrogen levels, while disease caused by facultative pathogens usually decrease at high N levels (Dordas 2008). Since nutrients are important for both plants and microorganisms, many interactions between plant and soil factors may occur and the effect of a specific nutrient can vary in different environments (Dordas 2008; Huber et al. 2012; Tripathi et al. 2022). Low nitrogen levels are reported to increase severity of early blight disease in potato (Jindo et al. 2021; Abuley et al. 2019). However, the effect of other nutrients on potato early blight does not seem to be well investigated.

Starch potatoes in Sweden are usually late-maturing and harvested later in the season with a longer growth period than table potatoes and are therefore more prone to early blight infection. Starch potato farmers in southern Sweden started to notice an increase in early blight infection around the season of 2017. This was probably due to an increased incidence of fungicide resistance to boscalid, at that time the most used fungicide available, and azoxystrobin (Mostafanezhad et al. 2021; Odilbekov et al. 2019). This gave rise to awareness of early blight in Sweden and was partly the reason for the initiation of this study.

This investigation was designed as an observational study of commercial farms representing the starch potato production area in Sweden in 2019–2021. The hypothesis of this study, based on the large variations in disease observed by farmers and advisors, was that the severity of infection depends on specific field, soil, plant, and crop management factors. The reason for the large field variation in early blight severity in Sweden is mostly unknown, and we aimed to unravel factors that are most important for the disease development.

To experimentally confirm an observation in the farmer study, field trials were performed in 2021 and 2022. Ladders of three different levels of potassium fertilisation were applied for both fungicide-treated and untreated plots to study the effect on early blight disease.

The main question for the study was are there any soil, plant or crop management parameters that we can observe or control in order to customise and calibrate the disease control management towards more field-specific IPM strategies?

Materials and Methods

Observational Study

Over three seasons, 2019, 2020 and 2021, a total of 52 unique fields were included in this observational study (Fig. 1). The fields were situated in southern Sweden where starch potato is grown for “Sveriges Stärkelseproducenter Förening” (SSF) (Fig. 1). The fields were chosen to represent the different conditions in the area (e.g., crop rotation, soil type, farmer- and advisor perceived infection pressure) of potato starch primary production. It was also of importance to select farms where the

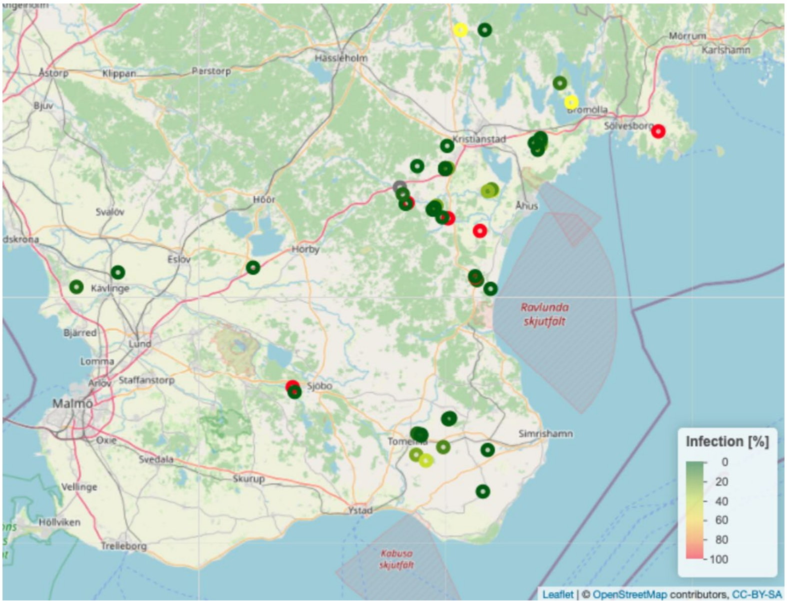

Fig. 1 Map presenting the geographical location in southern Sweden of all untreated farm plots for all three years (2019–2021) with a colour scale indicating the severeness of early blight infection (%)

farmers were interested in participating in the study and ready to collaborate, since it required them to sacrifice time to manage an untreated plot and fill out a survey. Table 1 gives an overview on the data that were collected from each field: soil analysis, leaf analysis and the specific management strategies at each farm.

Field Plots

The 24 m × 24 m (24 m is the width of a standard tractor sprayer) plot untreated against early blight was located inside the field to avoid edge effects. All other

Table 1 Overview of descriptive statistics for measured parameters in farmer field plots from the observational study 2019–2021

Parameter	Max	Min	Mean	CV [%]
Soil analyses				
pH	8.1	4.8	6.6	13
P-AL (mg P/100 g soil)	59	5.5	21	56
K-AL (mg K/100 g soil)	33	2.6	10	61
Mg–AL (mg Mg/100 g soil)	27	4.2	10	50
K/Mg	4.0	0.1	1.2	63
Ca-AL (mg Ca/100 g soil)	1900	54	330	130
Humus content (%)	11	0.9	3.4	52
Clay content (%)	25	2	8.3	54
Sand content (%)	96	41	74	17
Leaf analyses				
Calcium [%]	5.0	1.3	2.6	28
Magnesium [%]	1.9	0.5	0.8	31
Manganese [ppm]	630	27	330	58
Boron [ppm]	170	27	45	4.1
Copper [ppm]	20	2.9	8.1	54
Molybdenum [ppm]	4.5	0.1	1.0	81
Iron [ppm]	560	87	190	50
Zinc [ppm]	33	8.4	16	27
Sulphur [%]	0.8	0.3	0.5	22
Phosphorus [%]	0.4	0.2	0.3	18
Potassium [%]	3.9	0.9	2.3	34
Nitrogen [%]	6.1	3.4	4.4	13
Management				
Planting date	15-May	4-Apr	27-Apr	
50% emergence date	9-Jun	25-Apr	25-May	
Irrigation total (mm)	380	0	81	95
Seed tuber	N/A			
Cultivar	N/A			
Crop rotation year ($n-1$) = years without potato	10	3	5.6	44

management of the fields was left untouched and followed the general management strategy by each farmer.

Soil Analysis

To get an indication of the soil type and fertility (Table 1), soil samples were taken at the beginning of September by using a soil drill at a depth of 5–25 cm inside of the furrow where the tubers grow. Around twenty subsamples from the soil drill were taken from different spots in the field plots in a “W” pattern with an estimated total volume of one litre and then pooled and mixed in a plastic bag. The soil in the sealed plastic bag was stored at room temperature, in darkness until analysis the next day. The soil was delivered to Eurofins in Vä, Kristianstad Sweden, and analysed in their laboratory (Eurofins 2021). The soil parameters analysed were pH, P-Al, K-Al, Mg-Al, Ca-Al, humus content, clay content and sand content (Table 1). Accreditation and methods for soil analysis can be found in the Supplementary materials Table 1.

Leaf Analysis

Leaf samples representing plant nutrient content of the field plots (Table 1) were collected in the middle of August. The collection technique followed the instructions from Yara Megalab™ for whole potato leaf analysis (Yara 2022). The fourth fully developed leaf was picked. In total, twenty leaves from each untreated plot were picked. The leaf samples were put in paper envelopes and mailed the same day as the collection to Yara Analytical Services in Pocklington, UK, that carried out the analyses. The leaf analysis parameters analysed were Ca, Mg, Mn, B, Cu, Mb, Fe, Zn, S, P, K and N (Table 1).

Disease Assessment

The levels of disease and defoliation were evaluated twice during the season, in the middle of August and at the beginning of September. The early blight severity was visually scored according to Duarte et al. (2013). The scoring numbers (0–100) are defined as the percentage of the green foliage covered by dark early blight spots. The level of defoliation was scored as a percentage of the green biomass that had turned brown or fallen off from the plant. Both the disease levels in the untreated plot and in the surrounding field were evaluated, and so was the level of defoliation. This was performed to see if the fungicide management strategy used by the farmer had any effect on the disease. The surrounding fields were fungicide treated at most farms and never showed high levels of infection. For the “Results” section in this paper, the disease severity data (percent infection) from the untreated plots from the second scoring, at the beginning of September, was used. The infection in mid-August had not yet reached a point where larger differences could be seen among the fields (Supplementary materials Table 2).

Farm Management Form

After each field season, the farmers were asked to fill out a form containing information about their management. The following information was collected for each field: planting date, date at which 50% of crop emergence occurred, cultivar, seed tuber certification and/or treatment, irrigation type and amount, the number of potato free years and details about their historical crop rotation the last five years, soil management, fertilising schedule and amounts, yield and finally their own reflections of their disease levels.

Weather Data

Values of average daily temperature and precipitation were obtained from Lantmet, SMHI, 2019–2022, and are presented in the "Season" section. The weather station in Nymö-Fjälkinge was used for the comparison since it was operating during all seasons involved and represented the area of the observational study well.

Potassium Field Trials

Preliminary data from the first two seasons of the farmer study showed that low potassium levels in leaves correlated with high early blight infection. Therefore, to confirm these results, potassium field trials were performed in 2021 and 2022. The trials were located at two separate sites per season, 2021: Nymö (N 56.024848, W 14.335998) and Gärds Köpinge (55.947479, 14.182357), 2022: Åsums boställe (55.958602,14.151002) and Lyngby gård (55.886097, 14.143463). The sites were chosen based on their low levels of potassium available in the soil to be able to create deficiencies at low potassium application rates. The trial was designed with four completely randomised blocks. Each plot consisted of 18 m^2 of plants, except for the trial at Åsums boställe, where the plots had a size of 15.75 m^2 due to lack of space. Each plot contained five rows where the three middle rows were evaluated for disease progression, defoliation, leaf potassium concentration and tuber- and starch yield. Three different levels of potassium fertilisation were applied in both untreated and fungicide-treated plots (Table 3). Fungicides were applied following a full dose recommendation with four treatments and two-week interval with start in mid-July. The fungicide products Narita (0.4 L/ha, active component: difenoconazole 250 g/L) and Propulse (0.45 L/ha, active components: fluopyram 125 g/L, prothioconazole 125 g/L) were alternated. Standard late blight (Revus/RanmanTop alternated every week starting in mid-June) and insecticide treatments were conducted. A tractor sprayer (Lechler IDKT Purple 0,25) with a flat fan nozzle with medium droplet size was used with 300 L water/ha at 3 bar. The starch cultivar Kuras was used in all field trials and seed tubers were obtained from Lyckeby SSF. The trials were, except for potassium, fertilised and managed following standard recommendations by the Swedish Rural Economy and Agricultural Societies in the starch potato growing area in southern Sweden. The planting row distance was 75 cm with 38 cm in between the plants for all trials. All infection that occurred in the trials was natural.

Potassium Fertilisation

The experimental fields were fertilised before planting with a later (end of June) additional N fertilisation and weekly Mn treatments. For 2021, 137 kg/ha N, 63 kg/ha P and 50 kg/ha Mg and for 2022 200 kg/ha N, 63 kg/ha P and 50 kg/ha Mg were added in total, in the form of Axan Ns 27–4, MAP NP 12–23 and Kiserit. The potassium fertiliser (potassium sulphate) was applied by hand individually for each plot to be able to adjust the levels. In the first year, 2021, a potassium ladder was designed according to the soil analysis results with three steps (Table 3). The middle level, K2, was following the recommended fertilisation for the field, and the low level, K1, contained 100 kg K/ha less than K2, and the high level, K3, contained 100 kg K/ha more. Since the potassium leaf analysis for 2021 did not show the depletion that was aimed for (see “Results”), the ladders were changed for the 2022 season. For 2022, the ladder was designed so that the low level, K1, had no potassium fertilisation at all and the highest level, K3, was following the recommended level and the middle step, K2, was in between zero and the recommended value (Table 3).

Potassium Leaf Analysis

The leaf analysis was performed on September 6th in 2021 and on August 25th for 2022, following the same method as for the leaf analysis in the observational study, the “Leaf Analysis” section. It was planned for a later analysis in 2022 as well but due to early defoliation caused by potassium deficiency the later analysis was not possible. Ten leaves from each block were picked. Blocks 1 and 2 and 3 and 4 were pooled, respectively, to 20 leaves each giving two replicates for each treatment in 2021. In 2022, twenty leaves were collected from each of blocks 1, 2 and 3 giving three replicates. Results are presented in Table 3.

Disease Assessment

The level of early blight disease and defoliation was visually scored weekly as in the “Disease Assessment” section. The disease scoring data was used to calculate the relative area under disease progress curve, rAUDPC (Shaner & Finney 1977). The defoliation data was used to calculate the area under the defoliation curve, rAUC, in a similar way. The visual scoring was carried out weekly during the season, but since the disease in the different fields progressed very differently both in the two years and at the different sites, the exact dates for the calculations differed over the seasons and fields. For the 2021 trials, the calculations were done from 9th of August to 13th of September for both rAUDPC and rAUC at both sites. For 2022 at the Lyngby gård trial site rAUDPC was calculated from 18th of July to 22nd of August and rAUC from 8th of August to 5th of September. For the second trial site in 2022, Åsums boställe, both rAUDPC and rAUC were calculated from 9th of August to 12th of September. Thus, Lyngby gård had to be evaluated during a different period than the other sites, due to a very early onset of infection and an earlier defoliation. Disease assessment data is presented in Tables 4 and 5.

Yield and Starch Measurements

The yield from each plot was measured at harvest and the starch content of the tubers was calculated following the standard method set by the International Starch Institute Denmark (1986). The yield and starch data are presented in Tables 4 and 5.

Statistical Analysis

For data analysis and creation of most graphs, the language R was used with R studio as an interface (Version 1.1.456© 2009–2018 RStudio, Inc.). Some graphs were made with MS Excel. To investigate how the rate of infection (as a percentage) was influenced by the measured soil, leaf and farm management parameters in the observational study of the farms, first Spearman correlations were performed between infection rate and all parameters for (i) soil measures, (ii) leaf measures and (iii) farm management parameters. All field plots were considered as independent samples. Second, to test whether selected parameters that correlated with infection rate in the initial tests also had an effect when year of study was taken into account or occasionally the combined effect of two parameters was taken into account, analyses of variances (Anovas) were performed. These models included the fixed factors selected parameter(s), year and their interactions. Type II sums of squares were used and normality of residuals were tested with the Shapiro–Wilk normality test. Correlation plots were created using the corrplot (Wei and Simko 2021) package, cor.mtest. The ggplot2 (Wickham 2016) package was used for the plots. The leaflet package (© 2014–2016 RStudio, Inc.) was used to create the map.

To test whether potassium fertilisation level affected the dependent variables: infection rate (rAUDPC), defoliation rate (rAUC), yield, starch content and starch yield in the field trials, a series of analyses of variances (Anovas) were performed for each of the dependent variables. rAUDPC and rAUC were log-transformed. Data from each of the two years were analysed in separate models because of the difference in design between the years. The models included the fixed factor treatment (potassium treatment K1–3 for each of fungicide-treated and control plots), block nested within field site and the interaction between treatment and field site. Type II sums of squares were used. Post hoc tests were performed to test treatment differences using estimated marginal means with Tukey’s method. Normality of residuals was tested with the Shapiro–Wilk normality test. The packages used for statistical analyses were car (Fox and Weisberg 2019), emmeans (Lenth 2022) and stats (R core team 2022).

Results

Observational Study

An overview of the investigated parameters in the observational study is presented in Table 1. Several measured parameters showed very high variation among the investigated farmer's fields indicated by large differences between min and max values and high CV values. For example, the soil parameters K-AL, K/Mg, Ca-AL, and the leaf parameter copper all had a CV higher than 60%. However, several other parameters showed much lower variation. The soil parameters pH and sand content together with the leaf parameters boron, phosphorous and nitrogen content all had CV values lower than 20%.

Soil and Leaf Analyses

Soil Analysis

From the initial correlation analysis, the soil type, i.e., sand and clay content, showed a strong correlation (Spearman) with each other and with the early blight infection ($p < 0.001$, Fig. 2a). Testing the effect of sand content when taking year into account confirmed that a high sand content seemed to imply a higher risk of early blight infection (Anova; sand content: $F = 22.9$, $\mathrm{Df} = 1$, $p < 0.0001$; year: $F = 6.29$, $\mathrm{Df} = 2$, $p = 0.0039$; interaction: $F = 2.88$, $\mathrm{Df} = 2$, $p = 0.067$, Fig. 3). Sand content was divided into low (< 80%) and high (> 80%) based on general agronomic practice in the local area. Infection rates above 20% were only found on soils with a sand content above 75% (Fig. 3). However, in some cases soils with high sand content also had low

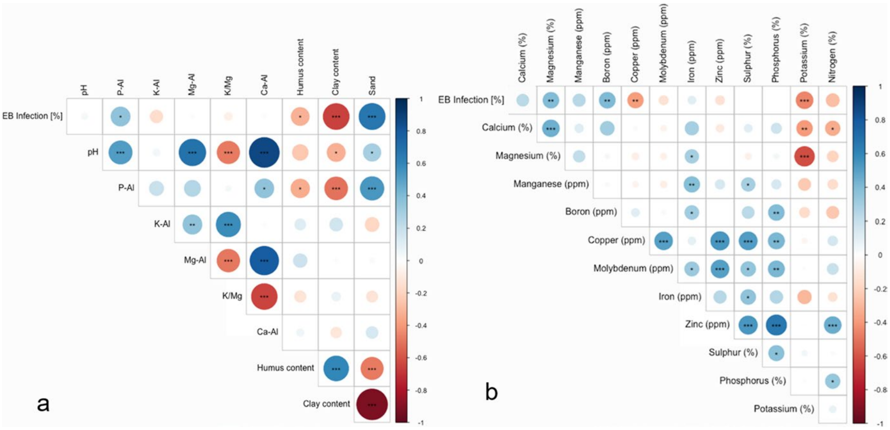

Fig. 2 Correlation plots (Spearman) for the soil (**a**) and the leaf (**b**) parameter analyses together with the scored early blight infection (in percentage) in the untreated plots. The correlations are described with a colour scale (where red is a negative correlation, and blue is positive) and with a circle (bigger circle shows a higher correlation). Also asterisks are indicating the significance in the correlations

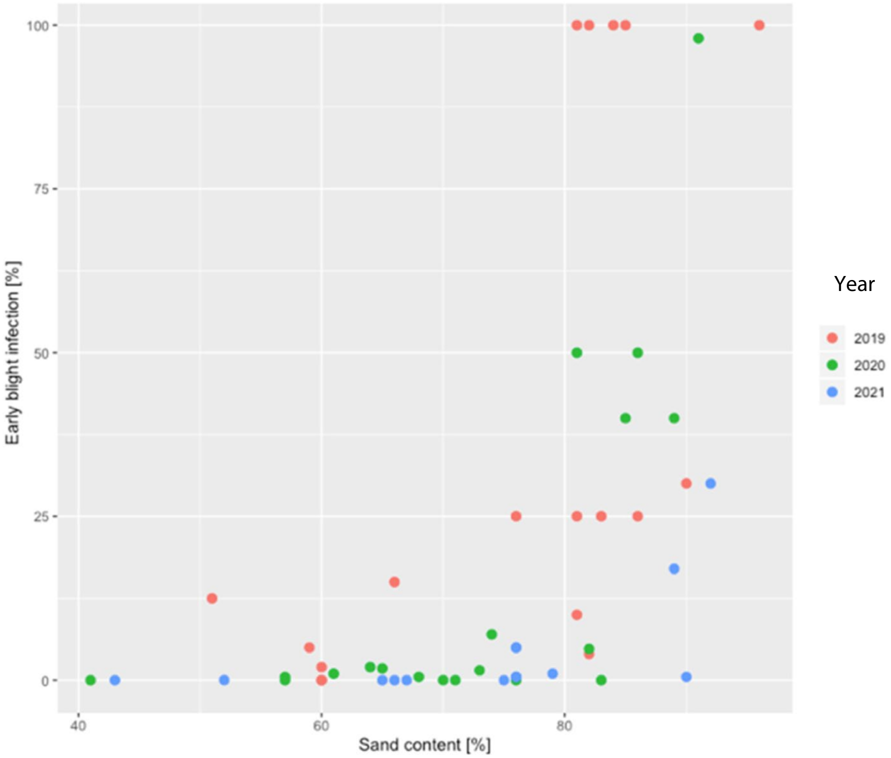

Fig. 3 Infection of early blight in relation to sand content together with season showed in colour

infection rate due to other factors like year (Fig. 3). Tukey's post hoc test confirmed that the average infection rates were lower in 2021 compared to 2019 ($p=0.0077$, Fig. 3).

A significant positive correlation between P-AL and infection rate was found in the initial analysis (Fig. 2a) and in the Anova also including the effect of year (Anova; P-AL: $F=10.7$, Df = 1, $p=0.0020$; year: $F=3.72$, Df = 2, $p=0.032$; interaction: $F=2.14$, Df = 2, $p=0.13$). However, high P-AL values were mainly found in soils with high sand content (Figs. 2a and 4, Table 2).

Leaf Analysis

Overall, the initial leaf analysis indicated a highly significant negative correlation between leaf potassium content and the severity of early blight infection (Fig. 2b, Table 2). However, that seemed to be mainly the case in sandy soils where a negative correlation was observed all three years (Fig. 5). Testing the combined effects of potassium content of sand content as a categorical factor either above or below 80% across years showed a significant interaction between leaf potassium content, sand content category and year (Table 2). There is also a three-way

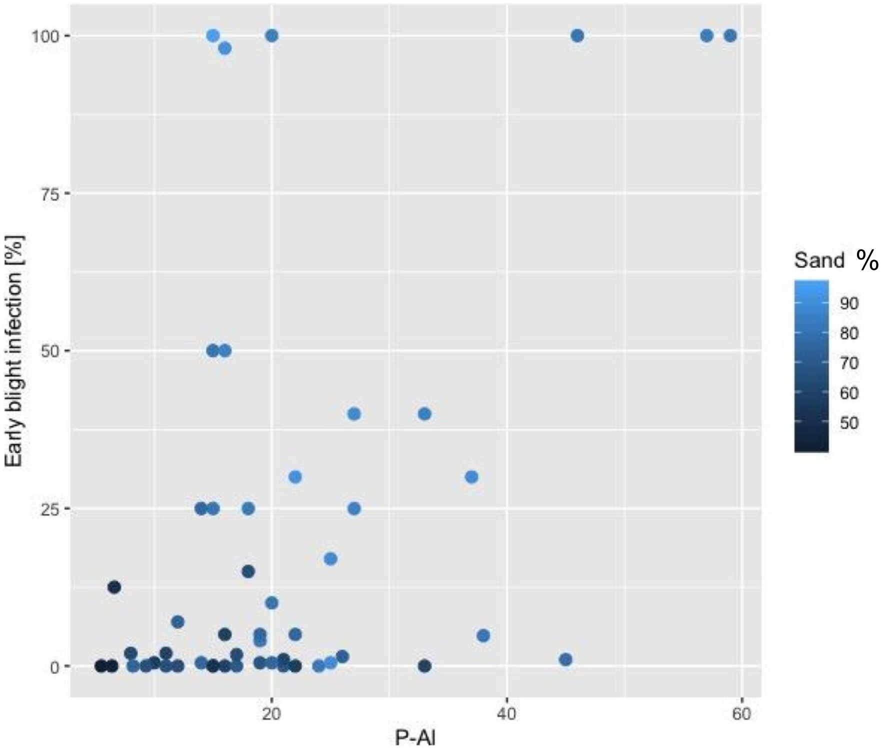

Fig. 4 Relationship between early blight infection rate and soil phosphorus level, P-AL, with sand content (%) shown in colour scale

interaction to be found (Table 2), showing that in years with higher infection pressure the effect of potassium content on infection matters on heavier soils as well. There is a marginally non-significant correlation to be found between leaf potassium content and soil sand content (Df = 1, $F = 3.99$, $p = 0.0529$), and this correlation would much likely be stronger if the fields were not soil type precisely fertilised directly to not cause depletion in potato.

There was a significant negative correlation between the leaf copper content and infection rate in the initial analysis (Figs. 2b and 6). However, when taking year into account the effect of copper was marginally non-significant (Anova: leaf Cu content effect on infection: $F = 3.8$, Df = 1, $p = 0.056$; year: $F = 5.8$, Df = 2, $p = 0.0059$; interaction: $F = 0.22$, Df = 2, $p = 0.80$). Copper content was also related to the soil sand content (Fig. 6), where lighter soils tended to be lower in Cu (Anova: leaf Cu content effect on sand content: $F = 39.5$, Df = 1, $p < 0.0001$). Leaf phosphorus and nitrogen content showed no significant correlation with the infection rate and is therefore not analysed in separate models involving year. Positive correlations between the leaf analysis and infection rate were found for boron and magnesium (Fig. 2b), suggesting that these micronutrients may also have some

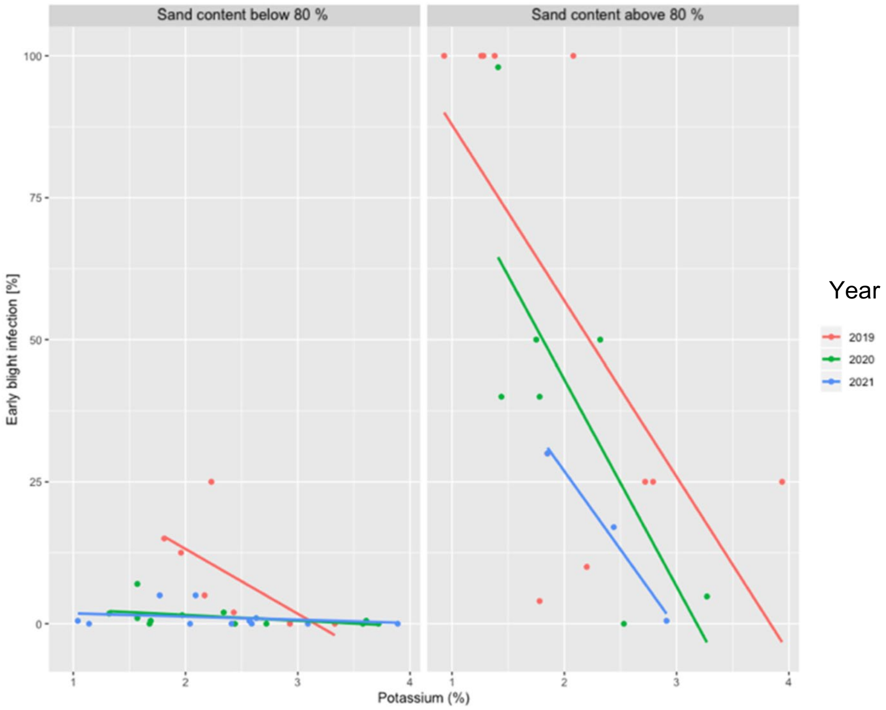

Fig. 5 The relationship between early blight infection rate and leaf potassium content in soils with sand content above and below 80%

Table 2 Anovas for early blight infection rate in potato fields 2019–2021 as an effect of selected soil and leaf parameters and their interactions with year and each other

Source of variation	Df	*F* value	*p* value
Leaf potassium and sand content above 80%			
Potassium (%)	1	18.2	0.00012
Year	2	6.84	0.0028
Sand > 80%	1	59.1	2.5*e* – 09
Potassium × year	2	0.164	0.85
Potassium × sand > 80%	1	1.02	0.32
Year × sand > 80%	2	0.483	0.62
Potassium × year × sand > 80%	2	7.05	0.0024
Soil P-Al and sand content			
P-Al	1	0.183	0.67
Year	2	11.9	9.1e – 05
Sand	1	36.7	4.3e – 07
P-Al × year	2	0.877	0.42
P-Al × sand	1	6.71	0.013
Year × sand	2	1.39	0.26
P-Al × year × sand	2	0.0585	0.94

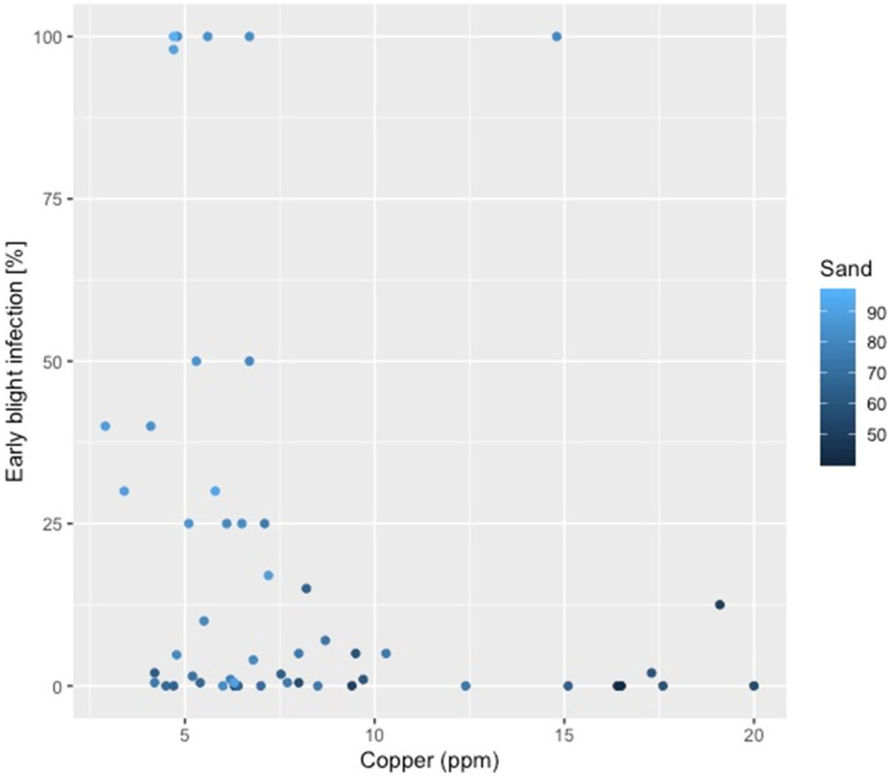

Fig. 6 Relation between copper content in leaves and early blight infection rate, sand content in different colour

importance. However, the effect on infection may also be indirect as magnesium content in the leaf had a strong negative correlation with potassium (Fig. 2b).

Management

Cultivar Resistance The form the farmers filled in gave information on what starch potato cultivar that was used in the plots, but since most farmers were growing the same cultivar, Kuras (67%), and the distribution of other cultivars were not even (Dartiest 10%, Saprodi 8%, Avenue 6%, Maxim 4%, Stratos 2%, Maxim 2%, N/A 2%), this study did not give enough input data on cultivar resistance to disease in order to draw any conclusions.

Season For early blight, as for many other plant diseases, the seasonal disease pressure may largely vary. The average infection rate was lower in 2021 than in 2019 and 2020 (Figs. 3 and 5). The daily average temperature and the precipitation for the years of the observational study and the field trials are seen in Fig. 7. Weather data

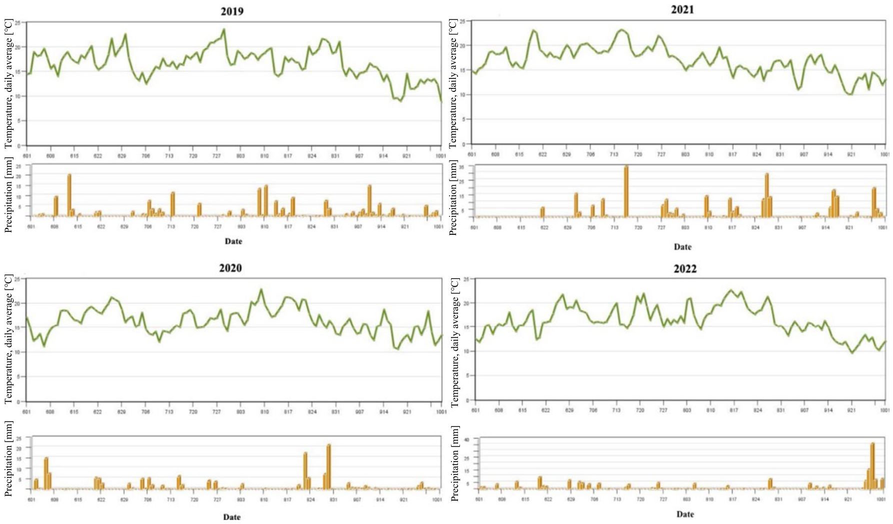

Fig. 7 Weather data for 2019–2022 with daily temperature average and precipitation obtained from Lantmet (2023) from the weather station in Nymö-Fjälkinge

from the years of the observational study 2019–2021 and for the potassium field trials 2021–2022 is presented.

Crop Rotation Visual inspection of the effect of crop rotation on infection rate in relation to the two most significant parameters influencing infection (sand content and leaf potassium content) suggested that longer crop rotations (> 8 years) never gave rise to very high early blight infection rates (Fig. 8a, b). The other factors, soil composition and potassium, seemed to be of bigger importance though. There is a lack of data points from farms with a crop rotation of 6–8 years, which makes it difficult to test the effect of crop rotation statistically. However, the results suggest that there is a weak significant correlation between short crop rotation and high infection rate (Anova: crop rotation effect on infection: $F = 6.30$, $Df = 1$, $p = 0.0158$).

Planting Date and Emergence Date There was no significant correlation between the planting date or emergence date and severity of early blight infection.

Furrowing Since *A. solani* is a soil pathogen and mostly spreads directly from the soil to the lower foliage on the potato plant, management strategies such as late furrowing could potentially help spread the spores to the foliage. However, there was no correlation between late furrowing and early blight infection.

Seed Tuber The farmers gave information about seed tuber treatment and certification level of tubers planted in the fields. None of these seed tuber parameters seemed to correlate with the early blight infection rate.

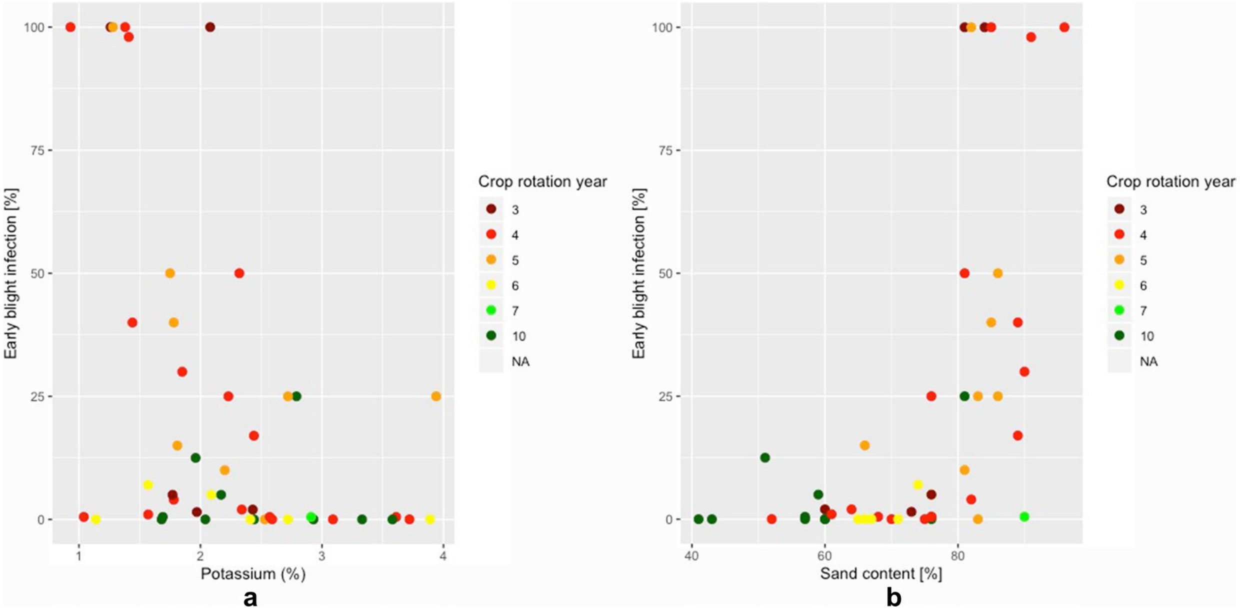

Fig. 8 **a**, **b** Crop rotation in colour and leaf potassium content/soil sand content versus infection

Table 3 Soil potassium (K-AL) analysis before planting and application of fertilisers. Level of K (potassium sulphate) fertiliser applied and resulting leaf potassium content (September 6th in 2021 and 25th of August 2022) in the four field trials 2021–2022

K-AL [mg K/100 g soil]	K level	Applied K fertiliser K [kg K/ha]	Resulting K content in leaf [%]
2021 Nymö			
18	1	20	2.75 ± 0.36
	2	120	2.62 ± 0.05
	3	220	2.39 ± 0.68
2021 Gärds Köpinge			
14	1	100	2.01 ± 0.01
	2	200	2.75 ± 0.10
	3	300	2.93 ± 0.21
2022 Lyngby Gård			
5,7	1	0	0.86 ± 0.13
	2	133	1.22 ± 0.13
	3	265	1.66 ± 0.37
2022 Åsums boställe			
11	1	0	0.74 ± 0.16
	2	133	1.26 ± 0.17
	3	265	2.11 ± 0.23

Irrigation There was no significant correlation between total volume of irrigation and early blight infection rate. However, farms that lacked any irrigation system had lower early blight infection. These farms also had heavier soils (lower sand content) that were less prone to early blight infection (see the “Soil Analysis” section). The type of irrigation used by the farmers was mostly water canon (85%) and therefore no conclusion on the effect of irrigation type can be drawn.

Yield The tuber yield data that was collected in the survey was not complete. Not all farmers filled it out, and for those who did, it was based on estimates and guesses. Therefore, the yield data was excluded from the results.

Potassium Field Trials

In the potassium field trials the effect from different levels of potassium fertilisation (Table 2) on the rate of early blight infection was evaluated. Higher level of potassium fertilisation resulted in lower rate of early blight infection (Table 3, Fig. 9). However, in 2021, the significant effect of treatment ($\mathrm{Df} = 5$, $F = 47.2$, $p < 0.0001$) was only due to a difference between fungicide treated and untreated but no significant effect of potassium fertiliser (Table 3). The lower levels of fertiliser did not lead to potassium deficiency, and the leaf potassium concentrations were all above 2% (Table 2) this year. Fungicides reduced the infection rate significantly (Table 3). In 2022, when the ladder used started at zero K added for K1, large differences in leaf K concentrations were obtained and there was

Table 4 Infection rate (rAUDPC), defoliation rate (rAUC) and yield data, compared between untreated and fungicide-treated plots with three different levels of potassium fertilisation (K1–3, where 1 is the lowest) at two field trial sites in 2021

K level	Treatment	rAUDCP*		rAUC*		Yield [ton/ha]		Starch content [%]		Starch yield [ton/ha]	
Nymö 2021											
1	Untreated	4.56E − 02	a	1.98E − 01	ab	72.6	a	18.7	a	13.5	a
2		5.35E − 02	a	2.48E − 01	a	58.6	a	18.3	a	10.7	a
3		3.62E − 02	a	1.84E − 01	ab	74.7	a	19.1	a	14.3	a
1	Treated	5.39E − 03	b	1.59E − 01	ab	63.8	a	18.6	a	11.9	a
2		2.61E − 03	b	1.30E − 01	b	64.6	a	18.9	a	12.3	a
3		2.81E − 03	b	1.48E − 01	ab	70.2	a	19.1	a	13.4	a
Gärds Köpinge 2021											
1	Untreated	2.09E − 01	a	4.85E − 01	a	69.4	a	19.6	a	13.6	a
2		1.29E − 01	a	3.54E − 01	a	73.3	a	18.9	a	13.9	a
3		1.66E − 01	a	4.19E − 01	a	71.1	a	19.3	a	13.7	a
1	Treated	1.66E − 02	b	1.26E − 01	b	81.9	a	19.9	a	16.3	a
2		1.62E − 02	b	1.28E − 01	b	77.1	a	19.2	a	14.8	a
3		1.83E − 02	b	1.42E − 01	b	76.7	a	19.1	a	14.7	a

*rAUDPC and rAUC were evaluated 9th of August–13th of September at both sites. Different letters indicate significant difference according to Tukey test

Table 5 Infection rate (rAUDPC), defoliation rate (rAUC) and yield data, compared between untreated and fungicide-treated plots with three different levels of potassium fertilisation (K1–3, where 1 is the lowest) at two field trial sites in 2022

K level	Treatment	rAUDCP*		rAUC*		Yield [ton/ha]		Starch content [%]		Starch yield [ton/ha]	
Lyngby gård 2022											
1	Untreated	7.50E−02	a	0.765	a	43.5	a	19.6	a	8.5	a
2		2.87E−02	ab	0.655	a	51.1	bc	19.6	a	10.0	bc
3		1.31E−02	bc	0.633	a	52.9	c	19.7	a	10.4	c
1	Treated	1.50E−02	bc	0.731	a	45.6	ab	19.6	a	9.0	ab
2		7.66E−03	c	0.599	a	55.1	c	19.3	a	10.6	c
3		5.81E−03	c	0.593	a	55.3	c	19.8	a	11.0	c
Åsums boställe 2022											
1	Untreated	8.39E−02	a	6.17E−01	a	59.1	a	22.3	a	13.2	a
2		4.00E−02	a	4.13E−01	bc	68.4	b	22.4	a	15.3	b
3		3.38E−02	ab	3.62E−01	c	70.0	b	22.2	a	15.5	b
1	Treated	1.20E−02	b	5.19E−01	ab	61.1	a	22.6	a	13.8	a
2		2.76E−03	c	3.25E−01	c	70.1	b	23.1	a	16.2	b
3		6.15E−04	d	2.34E−01	d	73.0	b	22.6	a	16.5	b

*At Åsums boställe rAUDPC and rAUC were evaluated 9th of August–12th of September; at Lyngby gård due to early defoliation, rAUDPC was evaluated 18th of July–22nd of August and rAUC 8th of August–5th of September. Different letters indicate significant difference according to Tukey test

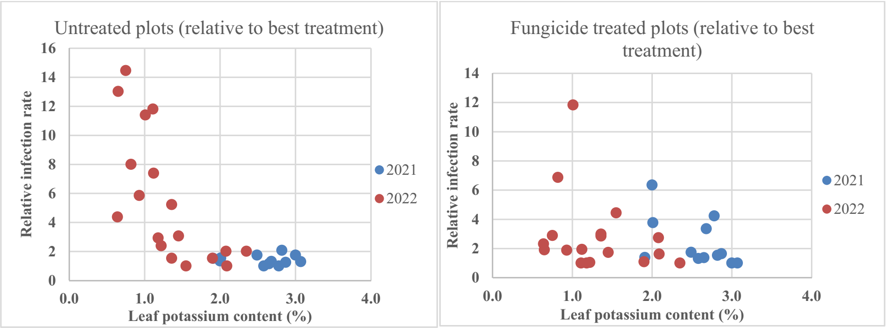

Fig. 9 Graph showing the relationship between the leaf potassium content (%) and the relative infection rate of early blight in the field trials 2021 and 2022 for untreated and fungicide-treated field plots

a significant effect of fertiliser level on the early blight infection rate (Table 3, Df = 5, $F = 53.6$, $p < 0.0001$). There was also a significant effect of potassium on the starch yield. There is a known connection between the tuber starch content and amount of potassium fertiliser where a higher potassium fertilisation tends to give a lower starch content. This effect was not significant for our trials when all treatments were pooled for both sites, but since the effect on tuber yield was positive with a higher K fertilisation, the overall starch yield was affected by the potassium fertilisation levels (Tables 4 and 5). In Fig. 9 the levels of leaf potassium are compared with the 'relative infection rate' instead, where the relative infection is calculated by dividing the rAUDPC value with the lowest rAUDPC value scored, within untreated or fungicide-treated plots, at each specific site and year. These figures show that there was a seasonal difference but more importantly that there was a relationship between the leaf potassium content and early blight infection rate. The effect was most clear in the untreated plants.

Discussion

We found large variation in early blight infection rates among 51 investigated farmer's fields in southern Sweden over three years. We also found large variation in several soil and plant parameters analysed that could explain some of the variation in infection rate. Soil sand content and leaf potassium concentration were clearly negatively associated with higher early blight infection rates. The effect of potassium was confirmed in field trials where we found that low levels of potassium fertilisation, leading to deficiencies at the end of the season, resulted in significantly higher infection. Also, other parameters, e.g. leaf copper content and soil phosphorous levels and crop rotation, may be associated with infection rate but need further studies to be confirmed.

Soil Composition

Our results indicate that the sand and clay content of the soil is important for the risk of severe early blight infection. To explain that we suggest two different hypotheses that may be linked with each other. The first is that plants in a lighter soil will more easily experience drought stress and nutrient depletion because the soil cannot hold as much water and nutrients will easily leak out leading to deficiencies. Secondly, heavier soils have different soil microbiome composition, a composition that could offer more competition with *A. solani* from other microorganisms. Thereby, the survival of *A. solani* could be affected and result in decreasing soil inoculum concentration or reduce the sporulation rate of the pathogen. Future studies to test these hypotheses would be of importance.

Another soil factor that requires some explanation is the P-AL content. This parameter shows how much phosphorus is available in the soil for the plant to take up, and there was a positive correlation between P-AL and early blight infection. However, P-AL also correlated with the sand content so that heavier soils appeared to have less P-AL (Table 2). By consulting agronomic experts we hypothesise that farms with lighter soils in a historical perspective have had a need of animals at the farm to achieve and maintain fertile soils with positive economic results. These farms have most likely used more manure in their fertilisation strategy leading to higher P-AL. The P-AL values on some of the farms with light soils were extremely high, and those values would not be preferred by the farmer but is most probably a result of having lots of manure at the farm to use (Liu et al. 2012). Thus, it cannot be concluded from this study if the soil available phosphorus has anything to do with the severeness of infection, or if the P-AL parameter is just linked to higher use of manure on sandy soils.

Leaf Nutrient Components

The supply of nutrients affects the plants' resistance to pests and pathogens (Huber et al. 2012) and therefore leaf nutrient parameters were studied. The leaf analysis was conducted in the middle of August for all three seasons included in this study. The sampling date is later than what is usually done to correct deficiencies in potato production, but since this was an observational study, we did not want to fertilise to support the plants, and it was decided that a later sampling would give more information about deficiencies related to early blight. There is most probably a correlation between nitrogen content and early blight infection (Dordas 2008), but we did not find any significant effect in our study. This might be explained by the intense nitrogen fertilisation strategy that is practised in most farms. Most plots had a good nitrogen value, and no deficiencies were observed (Table 1). However, in many fields the potassium levels were lower than what would be recommended, which might explain why a deficiency-related infection could be seen. Further, the negative correlation between leaf potassium and infection was mainly found on sandy soil, which is not surprising since sandy soils often are inherently low in K (Zörb et al. 2014). Amtmann et al. (2008) state that K application is beneficial for plant defence against most fungal diseases. This has been explained by the effect K has on primary metabolism by helping to synthesise high molecular weight compounds that is reducing the concentrations of low molecular weight compounds that are feeding the pathogens (Römheld & Kirkby 2010). According to Huber et al. (2012), potassium addition is only effective in disease control if there is a deficiency in the plant and is related to the metabolic functions of K and several other biochemical and physiological processes (Amtmann et al. 2008; Dordas 2008). This agrees with the results in our potassium field trials where increased infection rates were only found at low potassium levels in the leaves, i.e. below 2%. Higher potassium levels than 2% did not lower the infection rate. However, in a review by Jindo et al. (2021), potassium was not considered as important for early blight infection in potato, but it does not seem to be well investigated and further research is needed for clarification. Blachinski et al. (1996) reported no effect from potassium foliar treatment in lowering early blight infection rate; however the K depletion was not as high in their fields as it was in our study. On the other hand, they mention that the developmental stage of the potato plant is related to the potassium leaf content and could therefore influence the amount of early blight infection, since the disease is related to senescence. We could not find any relationship between the planting or emergence date and potassium leaf levels in our study. In some cases, it has been observed that potassium-deficient plants were less infested by insects and necrotrophic pathogens (Amtmann et al. 2008). This was explained by the fact that potassium deficiencies may induce the jasmonate signalling network (Armengaud et al. 2004) that classically is supposed to trigger defence responses to insects and necrotrophic pathogens, while salicylic acid signalling is important for defence against biotrophic pathogens. *A. solani* is a necrotrophic pathogen and according to this potato plants should be more resistant at lower potassium levels. However, that seem to be different in different plant species. Brouwer et al. (2020), reported that in potato instead an intact salicylic acid signalling is required for defence against *A. solani* and that has also earlier been reported in tomato (Sarkar et al. 2017). Thus, a possible increase in jasmonic acid levels at low potassium level does not contradict our results.

Potassium also influences potato starch content. Too high potassium fertilisation may reduce the dry matter starch content (Miča, 1988), and potassium can also affect the physiochemical properties of the starch (Zhang et al. 2018). But the effect on the decreasing starch content is cancelled out by a higher tuber yield, making the effect less relevant. It is also mentioned by Miča (1988) that this phenomenon might be explained by errors in the methods of how to measure starch content. If the starch content calculation is done on dry or fresh weight, the results differ, meaning that it might not be that the actual starch content in the tuber goes down, rather the water content of the tuber goes up as a result of higher K, giving false values on starch content when using fresh weight calculations. In this study no effect on starch yield from potassium was observed and the physiochemical properties of the starch were not evaluated. Since increased infection rate of early blight only seems to happen when there is a clear depletion of potassium, and no further correlations with infection and higher potassium fertilisation levels that are exceeding the depletion threshold, the conclusion would be that if the recommended potassium fertilisation guidelines are followed, nor infection or starch yield will be affected.

Micronutrients

Many of the nutrients are correlated with each other which can be explained by two factors. First, a richer soil will have more micronutrients in general to supply the crop (Montgomery et al. 2022). Secondly, a farmer that is careful with micronutrient fertilisation will make sure that there are enough of all micronutrient components available for the plants (these fertilisers are often sold as mixes with many micronutrient components). There were positive correlations between infection and boron and magnesium, and high magnesium content is correlating with low potassium. A possible explanation for this phenomenon is that Mg ions and K ions are competing in the uptake of the plant (Senbayram et al. 2015; Taiz and Zeiger 2002; Tränkner et al. 2018). High levels of Mg also compete with the uptake of Ca which also may increase the rate of disease (Huber & Jones 2013). Boron on the other hand is not taken up in its ionic form (Taiz and Zeiger 2002) and is the least understood plant micronutrient. Still, it is the most widespread micronutrient deficiency in the world (Dordas 2008) and we have no explanation for the correlation with infection rate. The negative correlation between copper and infection might be explained by the leaf copper content being related to the soil composition, i.e. sandy soils generally led to lower copper values. Copper also has a role in plant defence against pests as it is important for detoxification of oxygen radicals and hydrogen peroxide (Huber et al. 2012). According to the leaf analysis, a copper value below 7 ppm would indicate a deficiency (Yara 2022) and in most cases field plots with high infection had lower than 7 ppm copper (Fig. 6).

Seasonal Differences

The seasonal weather difference is the single most important factor when it comes to disease severity; however it is also one of the factors that we cannot control (Meno et al. 2022a, b). Work on decision support systems for early blight in Sweden is ongoing and as a part of an integrated pest management strategy these interpretations of weather data and the direct weather effect on disease are of great importance to include in the farm strategies when reliable models are available. Weather models were not evaluated in this study, but the differences in observed infection rates over the three seasons indicate that the seasonal weather parameters are of great influence. In 2020 the total precipitation was higher than in 2019 and 2021, but most of that rain came early in the season. In 2019 there was more rain in July than the other two years which might have facilitated sporulation. This may explain the general higher infection rate in 2019 and 2020 compared to 2021. However, to draw conclusions about weather data and its influence on infection of early blight, more specific studies must be carried out.

Management Strategies

Of all the management strategies that were evaluated in this study: seed tuber treatment, irrigation, cultivar, planting date, emergence date and crop rotation, there was only an indication that crop rotation affected the disease severity. Early blight is a soilborne pathogen; hence the survival rate in the soil is an important factor related directly to the amount of infection (Suganthi et al. 2020). In Fig. 8b it appears that farms with a longer crop rotation also seem to have heavier soils. This is most probably due to heavier soils being better at delivering economic advantageous yields for other crops, like cereals, in between the potato, and further the farmers are not pushed to have short time in between their potato years. Since the economic calculations are most crucial for the survival of a farm, it is hard to find farms with long potato rotation on lighter soils and vice versa. It can be assumed from the graphs (Fig. 8a, b) that a four-year (or shorter) crop rotation is not making a big difference on the severity of disease later in the season. Previous studies like Shtienberg and Fry (1990) and Abuley et al. (2018) have been studying shorter crop rotations and linkage with potato early blight, from zero to four years, concluding that the initial appearance of infection comes earlier with a very short (< 2 years) or no rotation of crops. Crop rotations below three years are not present in our study since it is not recommended for potato and further this statement could not be verified in this observational study. Moreover, the true onset of infection was not scored in our fields but only the later severity of disease. It would be of interest in future studies to find the point in crop rotation years where soilborne onset of infection and following disease severity seems to decrease, and this breaking point is most likely different for heavy and light soils and also how the onset of infection links with the disease severity.

Conclusion

By using an observational study on a large number of commercial farms and a follow-up field trial, the most important message is the significance of the soil composition for early blight infection. Sandy soils imply higher risk for severe infections. Therefore, when deciding on disease management strategies, for example fungicide treatment against early blight, the soil composition should be evaluated beforehand and taken into consideration when planning treatments. We have also seen an interesting association between potassium and early blight infection that needs to be further investigated in a more controlled environment. Potassium deficiencies will occur more easily on sandy soils and therefore extra care must be taken to optimise applications of fertilisers. If there is a lack of potassium available for the potato plant, the rate of early blight infection is increasing. This study highlights the extreme complexity of agricultural systems, but also the importance of conducting studies at farms as alternative plant protection methods and IPM would need to be adapted to the farm conditions. When studying what factors are directly relevant for a plant disease, there will be multiple parameters directly or indirectly correlating with each other and to separate them is a demanding task. As in this study, the soil parameters, e.g. sand content, will closely correlate with the plant nutrient uptake which further makes it complicated to decipher what factors from the leaf nutrient composition are related to the severity of disease and what could be explained by the soil composition.

Future Work

It would be of interest to incorporate soil structure in the development of decision support systems for diseases like early blight, since soil type has great influence on infection rate. Since we did not observe a drop in infection rate after four years, as other studies have suggested, but a slower decrease of infection over many years, it would also be valuable to further investigate if there is a minimum crop rotation time where the soil inoculum decreases enough to result in a slower development of disease. Studies on inoculum survival in different soil types would be important in this context. The role of potassium, especially on potassium-depleted soils, and soil phosphorus content for early blight development also needs further research. In an IPM perspective it is also important to consider differences in host plant resistance among available cultivars and for the future breed cultivars with improved resistance.

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Author Contribution All authors contributed to the study conception and design. Data collection and analysis were performed by LS. ÅL performed statistical analysis and EL helped with visual disease evaluation. The first draft of the manuscript was written by LS and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data Availability The data generated during this study are available from the corresponding author on reasonable request.

Declarations

Conflict of Interest The authors declare no competing interests.

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