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Field Monitoring of Potato Late Blight (*Phytophthora infestans*) Using Visual Assessments and Epidemiological Indicators under the Climatic Conditions of Northern Romania

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ABSTRACT

Late blight, caused by *Phytophthora infestans*, is one of the most destructive diseases of potato, severely affecting yield and quality worldwide. This study aimed to evaluate the effects of climatic conditions, potato genotype, and fungicide treatment schemes on disease development under field conditions in ARDS of Suceava, Romania, during two consecutive growing seasons (2022-2023). A multifactorial field experiment was conducted using four potato genotypes (Temerar, Red Lady, Riviera, and Darilena) and five fungicide treatment schemes. Disease assessments were performed at seven growth stages, and frequency of attack, intensity of attack, attack degree, and area under the disease progress curve (AUDPC) were calculated. Multivariate and univariate analyses of variance were applied to determine the effects of experimental factors. Multivariate analysis revealed significant effects of year, treatment, and genotype on disease indicators ($p<0.01$). Univariate analysis showed that year had a strong influence on disease incidence, while treatment and genotype significantly affected disease severity parameters. Post-hoc tests indicated that Red Lady exhibited the highest tolerance, whereas Riviera was the most susceptible genotype. Preventive fungicide treatments resulted in the lowest disease severity, whereas the untreated control recorded the highest values. The results demonstrate that climatic variability represents the main driver of late blight epidemics, while cultivar selection and optimized fungicide programs play a crucial role in reducing disease severity. The integration of tolerant genotypes with well-timed fungicide applications provides an effective strategy for sustainable late blight management under temperate climatic conditions.

Keywords: potato, *Phytophthora infestans*, genotype, fungicide treatments.

INTRODUCTION

Late blight, caused by *Phytophthora infestans* (Mont.) de Bary, is one of the most damaging diseases affecting potato (*Solanum tuberosum* L.) crops worldwide. Despite continuous advances in disease management and breeding for resistance, late blight remains a major constraint to sustainable potato production, particularly in regions characterized by cool and humid climatic conditions. The pathogen is highly aggressive and capable of rapid epidemic development, leading to severe defoliation and tuber infection when environmental conditions are favorable (Fry, 2008).

The epidemiology of *P. infestans* is strongly influenced by climatic factors, including air temperature, relative humidity, rainfall, and leaf wetness duration. Numerous studies have shown that prolonged periods of high humidity combined with moderate temperatures favor sporulation, infection, and disease spread, resulting in severe epidemic outbreaks (Campbell and Madden, 1990; Forbes et al., 2014). Consequently, the intensity and progression of late blight epidemics vary considerably between growing seasons and locations, emphasizing the need for continuous field monitoring.

Field monitoring of potato late blight is traditionally based on visual assessments of disease symptoms. Visual scoring methods allow for the estimation of disease incidence and severity and remain a practical, cost-effective, and widely accepted approach in epidemiological studies (Campbell and

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Madden, 1990). Based on repeated visual observations, several quantitative indicators can be calculated to describe disease development, including frequency of attack, intensity of attack, degree of attack, and the area under the disease progress curve (AUDPC). These parameters provide valuable information on disease dynamics over time and enable comparisons between seasons, cultivars, and environmental conditions.

Among these indicators, AUDPC is frequently used as an integrative measure of disease intensity, as it summarizes disease severity throughout the assessment period (Campbell and Madden, 1990). Forbes et al. (2014) highlighted that AUDPC values are particularly useful for evaluating epidemic pressure and cultivar susceptibility under field conditions. Frequency and intensity of attack further contribute to a detailed characterization of disease distribution within the crop canopy and complement the interpretation of disease progress.

In recent years, the integration of meteorological data into late blight monitoring has gained increasing importance. Weather stations installed near experimental fields provide continuous measurements of key climatic variables that directly influence pathogen development. Magarey et al. (2022) demonstrated that combining visual disease assessments with meteorological data improves the understanding of epidemic behavior and supports the interpretation of disease progress indicators. Relationships between disease severity and weather variables such as temperature, relative humidity, and precipitation have been reported in different agro-climatic regions (Dey et al., 2022).

Weather-based information has also contributed to the development of decision support systems aimed at improving late blight management. Systems integrating climatic data with field observations have been shown to enhance disease forecasting and optimize fungicide application timing (Meno et al., 2024). However, despite the development of advanced modeling approaches, traditional field monitoring based on visual assessments and epidemiological indicators remains fundamental for validating disease models and for characterizing disease dynamics under specific climatic conditions.

Northern Romania is characterized by climatic conditions that are generally favorable for the development of potato late blight, particularly during growing seasons with frequent rainfall and high relative humidity. Under these conditions, late blight outbreaks can occur rapidly and cause significant yield losses if not properly monitored and managed. Previous studies conducted under Romanian conditions have indicated considerable variability in disease severity between years, largely driven by weather patterns and local environmental factors (Hermeziu, 2021). Nevertheless, comprehensive field studies combining visual disease assessments with detailed meteorological data remain limited for this region.

A better understanding of late blight dynamics under northern Romania climatic conditions is essential for improving disease monitoring and supporting sustainable management strategies. Quantitative epidemiological indicators such as frequency of attack, intensity of attack, degree of attack, and AUDPC provide robust tools for describing disease development and assessing epidemic intensity. When analyzed in relation to meteorological data, these indicators allow for a more accurate interpretation of the factors driving disease progression.

Therefore, the objective of the present study was to conduct field monitoring of potato late blight caused by *Phytophthora infestans* under the climatic conditions of northern Romania, using visual assessments combined with epidemiological indicators. Disease development was quantified through frequency of attack, intensity of attack, degree of attack, and the area under the disease progress curve, and related to meteorological data recorded during the growing season.

MATERIAL AND METHODS

Experimental site and climatic conditions

The study was carried out at the Agricultural Research and Development

Station (ARDS) Suceava, Romania, over two consecutive growing seasons (2022-2023).

During the experimental period (April-September), which corresponds to the main growing season of potato in the study area, notable differences in climatic conditions were recorded between the two years (Table 1). The average air temperature was higher in 2023 (20.53°C) than in 2022 (16.71°C) and exceeded the multiannual average (14.91°C). Total rainfall during the growing season was lower than the multiannual average in both years, particularly in 2023 (263.9 mm), resulting in water deficit conditions. These contrasting climatic conditions contributed to the significant year effect observed in disease development.

Table 1. Monthly mean air temperature and total rainfall during the growing season in Suceava (2022-2023)

Year	Month						**Average**
	April	May	June	July	August	September	
	Air temperature (°C)						
2022	8.9	14.1	20.4	21.5	21.4	14	20.53
2023	7.6	15.1	18.9	21.9	22.7	18.4	14.91
MAA	8.0	13.7	16.9	18.4	18.3	14.2	**Total**
	Amount of rainfall (mm)						
2022	56.8	44.3	53.0	45	71.2	54	263.9
2023	46.5	31	61.4	44	54.6	26.4	413.4
MAA	48.2	80.2	93.6	88.6	62.8	40	**Average**

Experimental design and treatments

The experiment was conducted under field conditions over a two-year period (2022-2023) using a multifactorial design.

Each experimental variant was established in three replicates, arranged in two rows, with a row spacing 70 cm and a row length of 8 m. The distance between tubers within rows was 25 cm.

The studied factors were potato genotype (factor A), with four levels: A1 - Temerar, A2 - Red Lady, A3 - Riviera, and A4 - Darilena, and treatment scheme (factor B), with five levels (B0-B4).

Five fungicide treatment schemes were evaluated:

- **B0** - untreated control.
- **B1 - Preventive systemic treatment (6 applications):** applied at 10-day intervals between BBCH growth stages 35-39. Active substances were alternated and included: fluopicolide + propamocarb hydrochloride (Infinito, 62.5 + 625 g L^{-1}) at 1.4 L ha^{-1}, mandipropamid + difenoconazole (Carial Star 250 + 250 g L^{-1}) at 0.6 L ha^{-1}, oxathiapiprolin + benthiavalicarb (Zorvec Endavia) at 0.4 L ha^{-1} (applied in 2022-2023) and oxathiapiprolin + amisulbrom (Zorvec Entecta) at 0.25 L ha^{-1} (applied in 2024).
- **B2 - Curative systemic treatment (6 applications):** applied weekly starting at the first appearance of disease symptoms (BBCH 50-55). The same fungicides as in B1 were used, but applications began after symptom onset.
- **B3 - Systemic + contact treatment (6 applications):** applied at 10-day intervals between BBCH growth stages 40-49: mandipropamid + difenoconazole (Carial Star 250 + 250 g L^{-1}) at 0.6 L ha^{-1}, copper hydroxide (Champ 77 WG, 50%) at 2 kg ha^{-1}, fluopicolide + propamocarb hydrochloride (Infinito, 62.5 + 625 g L^{-1}) at 1.4 L ha^{-1}, fluazinam (Nando 500 g L) at 0.4 L ha^{-1}, followed by repetition of the treatment sequence until six applications were completed.
- **B4 - Contact treatment (6 applications):** alternating applications of Champ 77 WG at 2 kg ha^{-1} and Nando at 0.4 L ha^{-1} applied at 10-day intervals until six applications were completed.

Assessment of late blight attack

Late blight (*Phytophthora infestans*) attack was assessed through repeated visual observations performed at seven distinct growth stages: leaf development; main stem elongation/beginning of row coverage;

advanced vegetative development/initiation of tuberization; early tuber formation; tuber growth/inflorescence development; full flowering with tuber mass accumulation; and end of flowering/continued tuber growth. These stages correspond to the main phases of disease development during the growing season and follow classical plant disease assessment approaches (James, 1971; Campbell and Madden, 1990).

At each assessment date, 20 plants per experimental plot were evaluated (N = 20).

Frequency of attacks (F%)

The frequency of attack was expressed as the percentage of plants showing visible late blight symptoms relative to the total number of evaluated plants, according to standard epidemiological procedures (Zadoks and Schein, 1979; Campbell and Madden, 1990):

$$F(\%) = \frac{\text{Number of infected plants}}{\text{Total number of assessed plants}} \times 100$$

Intensity of attack (I%)

The intensity of attack was determined by visual assessment using a rating scale from 0 to 5 (0=0%; 1=1-10%; 2=11-25%; 3=26-50%; 4=51-75%; 5=76-100%), corresponding to increasing proportions of leaf area affected on infected plants.

Visual severity scales are widely used in plant disease epidemiology and represent a reliable method for estimating disease intensity under field conditions (James, 1971; Bock et al., 2010).

Degree of attack (GA%)

The degree of attack was used as an indicator of disease severity at crop level and was calculated by combining frequency and intensity of attack, as described in classical epidemiological studies (Zadoks and Schein, 1979; Campbell and Madden, 1990). This parameter reflects the overall impact of late blight on the potato canopy.

Disease progress over time (AUDPC and rAUDPC)

Disease progress over time was quantified using the area under the disease progress curve (AUDPC), calculated based on degree of attack values, according to the method proposed by Shaner and Finney (1977) and further detailed by Campbell and Madden (1990).

AUDPC provides an integrative measure of disease severity over the assessment period and is widely used for comparing disease development among experimental treatments (Jeger and Viljanen-Rollinson, 2001).

Because absolute AUDPC values are influenced by the duration of the observation period and seasonal disease pressure, relative AUDPC (rAUDPC) values were also calculated and expressed as percentages, following the approach described by Simko and Piepho (2012), to facilitate comparisons among genotypes, treatment schemes, and environmental conditions.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics.

A multivariate analysis of variance (MANOVA) was first applied to assess the overall effects of year, genotype, and treatment scheme on the set of disease variables. Subsequently, a three-way analysis of variance (ANOVA) was used to evaluate the effects of these factors and their interactions on individual parameters, including disease indicators (e.g., AUDPC). Mean comparisons were performed using Tukey’s Honestly Significant Difference (HSD) test at $p<0.05$. Hierarchical cluster analysis was conducted using Ward’s method and Euclidean distance to evaluate the potato genotypes based on disease severity indicators.

RESULTS AND DISCUSSION

The present study evaluated the effects of year, genotype, and fungicide treatment schemes on the development and progression of late blight in potato under field conditions.

Significant variations in climatic conditions were recorded between the two experimental years, particularly with respect to air temperature and rainfall distribution. These differences created contrasting environments for disease development and significantly influenced pathogen activity and host response.

Multivariate and univariate statistical analyses revealed that year represented the main source of variation for most disease indicators, highlighting the strong impact of environmental factors on epidemic development. In addition, genotype and treatment effects were observed for several severity-related parameters, indicating differences in host susceptibility and treatment efficiency.

The following sections present and discuss the main effects and interactions of the studied factors on disease incidence, severity, and temporal progress, with particular emphasis on intensity of attack, attack degree, and AUDPC values.

The obtained results are discussed in relation to previous findings and current knowledge on potato-late blight interactions under temperate climatic conditions.

Effects of experimental factors on late blight development

The multivariate effects of year, treatment, and genotype on disease attack indicators are presented in Table 2.

Table 2. Mean phenotypic data values

Source	Pillai's Trace	F	Hypothesis df	Error df	p-value	Partial η²
Year	0.778	24.564	4	28	<0.001	0.678
Treatment	0.901	2.253	16	124	0.007	0.225
Genotype	0.775	2.612	12	90	0.005	0.258

Significance was assessed using Pillai's Trace statistic.

Multivariate analysis of variance (MANOVA) revealed that year had a highly significant effect on disease indicators (Pillai's Trace=0.778, F=24.564, p<0.001; Partial η²=0.678), indicating that environmental conditions represented a major source of variation in epidemic development. Similar findings have been reported by Campbell and Madden (1990) and Fry (2008), who emphasized the decisive role of climatic factors in late blight outbreaks.

Significant multivariate effects were also observed for treatment (Pillai's Trace=0.901, p=0.007; Partial η²=0.225) and genotype (Pillai's Trace=0.775, p=0.005; Partial η²=0.258), demonstrating that both fungicide application schemes and genetic background contributed to disease control. However, the lower effect sizes compared to year indicate that environmental variability partially influenced the expression of treatment and genotype effects.

Univariate effects on disease indicators

The univariate ANOVA highlighted distinct contributions of the studied factors depending on the disease parameter (Table 3).

Table 3. Univariate ANOVA results for the effects of year, treatment, and genotype on late blight attack indicators

Variable	Source	df	F	p-value	Partial η²
No. of damaged plants (%)	Year	1	71.970	<0.001	0.671
	Treatment	4	2.778	0.057	0.369
	Genotype	3	2.744	0.072	0.302
	Treatment x Genotype	12	1.065	0.437	0.402
	Treatment x Year	4	1.776	0.163	0.208
	Year x Genotype	3	0.991	0.411	0.096
Frequency of attack (%)	Year	1	71.970	<0.001	0.641
	Treatment	4	2.778	0.037	0.306
	Genotype	3	2.744	0.051	0.347
	Treatment x Genotype	12	1.065	0.163	0.407
	Treatment x Year	4	1.767	0.168	0.208
	Year x Genotype	3	0.979	0.414	0.097

Variable	Source	df	F	p-value	Partial η²
Intensity of attack (%)	Year	1	0.411	0.529	0.021
	Treatment	4	8.025	0.001	0.628
	Genotype	3	19.775	<0.001	0.657
	Treatment x Genotype	12	1.271	0.310	0.445
	Treatment x Year	4	0.178	0.948	0.026
	Year x Genotype	3	0.389	0.762	0.040
Atack degree (%)	Year	1	11.574	0.003	0.379
	Treatment	4	11.972	<0.001	0.616
	Genotype	3	22.964	<0.001	0.584
	Treatment x Genotype	12	1.403	0.247	0.470
	Treatment x Year	4	0.165	0.954	0.024
	Year x Genotype	3	0.380	0.768	0.039
AUDPC GA	Year	1	12.754	0.002	0.402
	Treatment	4	8.528	<0.001	0.642
	Genotype	3	.468	0.708	0.069
	Treatment x Genotype	12	12.786	<0.001	0.690
	Treatment x Year	4	0.097	0.983	0.014
	Year x Genotype	3	0.067	0.977	0.007

Year had a highly significant effect on the number of damaged plants and frequency of attack ($p<0.001$), with large effect sizes (Partial $\eta^2>0.64$), confirming the strong influence of environmental conditions on disease incidence. In contrast, year did not significantly affect the intensity of attack ($p=0.529$), suggesting that local symptom expression was less sensitive to interannual climatic variability. However, year significantly influenced attack degree ($p=0.003$) and AUDPC ($p=0.002$), indicating a stronger impact on overall epidemic development. Similar trends have been reported by Campbell and Madden (1990) and Fry (2008), Haverkort et al. (2009) who emphasized the dominant role of temperature and moisture regimes in determining late blight epidemics.

Treatment significantly affected intensity of attack, attack degree, and AUDPC ($p\leq0.001$), with high effect sizes (Partial $\eta^2>0.60$), confirming the effectiveness of fungicide application schemes in reducing disease severity. Although the effect of treatment on the number of damaged plants was not statistically significant ($p=0.057$), the relatively large effect size suggests potential biological relevance. These results confirm previous reports indicating that well-timed fungicide programs remain essential for late blight management (Cooke et al., 2011; Kirk et al., 2013).

Genotype significantly influenced intensity of attack and attack degree ($p<0.001$), with large effect sizes (Partial $\eta^2>0.58$), indicating differences in host susceptibility. No significant genotype effect was observed for AUDPC ($p=0.708$).

Importantly, a highly significant Treatment × Genotype interaction was detected for AUDPC ($p<0.001$; Partial $\eta^2=0.690$). This result indicates that the effect of genotype on epidemic development depended on the fungicide treatment applied. This interaction highlights the importance of integrating host resistance and chemical control in disease management strategies, as also suggested by Kapsa (2010) and Haverkort et al. (2009).

No significant interactions involving year were observed for most disease parameters, suggesting that the relative effects of genotype and treatment were generally consistent across years.

Effect of genotype on disease severity

Post-hoc analysis (Tukey’s HSD) revealed significant differences among genotypes for intensity of attack and attack degree.

Red Lady showed the lowest values for both parameters, indicating a higher level of tolerance to late blight. Riviera exhibited the highest disease severity, followed by Darilena, while Temerar showed intermediate responses.

The similar grouping patterns observed for both variables indicate that genotypic differences were mainly expressed through variation in symptom severity rather than disease incidence or overall epidemic development. These findings are consistent with previous studies (Bradshaw et al., 2006; Fry, 2008), which reported that partial resistance in potato is associated with reduced lesion expansion.

Effect of fungicide treatments

Significant differences among fungicide treatments were observed for intensity of attack and attack degree (Table 5).

Table 4. Mean values (± SD) and Tukey's HSD grouping for genotypes

Genotype	Intensity of attack	Group	Attack degree (%)	Group
Red Lady	28.05 ± 8.99	a	21.53 ± 10.01	A
Temerar	39.03 ± 7.66	ab	32.33 ± 8.12	Ab
Darilena	48.35 ± 11.11	bc	41.67 ± 12.6	Bc
Riviera	53.65 ± 12.81	c	47.48 ± 14.3	C

Means followed by different letters differ significantly at p<0.05 according to Tukey's HSD.

Table 5. Mean values (± SD) and Tukey's HSD grouping for treatments

Treatment scheme	Intensity of attack	Group	Attack degree (%)	Group
B1	35.13 ± 11.30	a	28.8 ± 12.30	a
B4	38.4 ± 15.80	ab	31.94 ± 15.30	ab
B3	39.42 ± 10.28	ab	31.16 ± 12.27	a
B2	42.6 ± 8.50	ab	35.20 ± 8.76	a
B0 (Control)	55.7 ± 13.40	a	51.60 ± 14.20	b

Means followed by different letters differ significantly at p<0.05 according to Tukey's HSD.

The untreated control recorded the highest disease severity, confirming the high susceptibility of the tested genotypes in the absence of chemical protection. Among treated variants, B1 showed the lowest disease levels, while B2, B3, and B4 displayed intermediate effectiveness.

These results indicate that treatment efficiency varied depending on the applied scheme and environmental conditions, rather than suggesting a strict hierarchy between treatment types. Similar observations were reported by Cooke et al. (2011) and Kirk et al. (2013).

The significant Treatment × Genotype interaction for AUDPC further demonstrates that treatment effectiveness depended on host genetic background, highlighting the importance of integrating resistant cultivars with optimized fungicide programs.

Cluster analysis of genotypes

Hierarchical cluster analysis (Ward's method) grouped the genotypes according to their disease severity patterns.

Darilena and Temerar formed a cluster with intermediate responses, while Riviera was associated with higher susceptibility. Red Lady formed a distinct group, characterized by the lowest disease severity.

This clustering pattern confirms the results obtained from ANOVA and post-hoc analysis, emphasizing the role of genetic background in determining disease severity under variable environmental conditions.

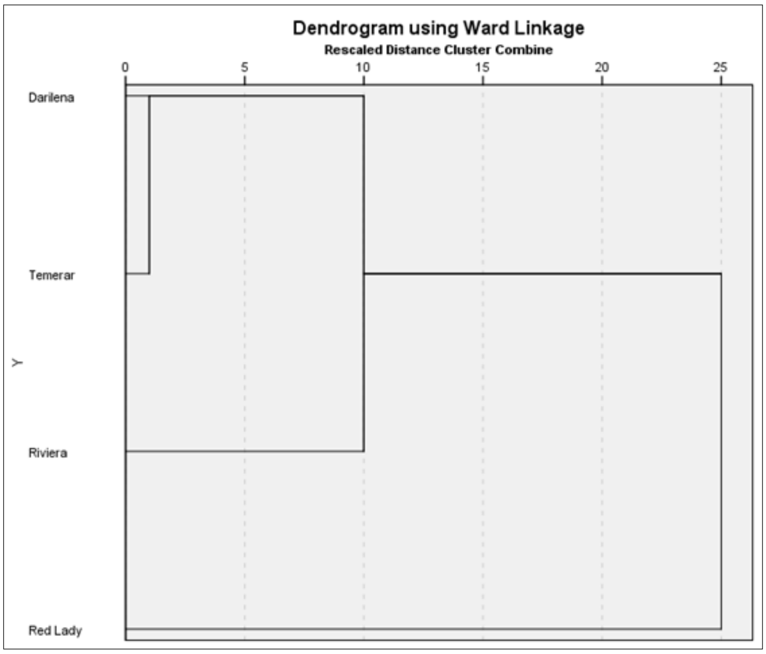

Figure 1. Dendrogram of potato genotypes based on disease severity indicators (Ward's method, 2022-2023)

The results demonstrate that environmental conditions represented the main driver of disease incidence, while disease severity and epidemic progression were strongly influenced by fungicide treatments and genotype, particularly through their interaction.

The significant Treatment × Genotype interaction for AUDPC highlights that effective late blight management requires the combined use of tolerant cultivars and appropriately timed fungicide applications, adapted to specific climatic conditions.

CONCLUSIONS

The present study highlights the complex interaction between environmental conditions, genetic background, and fungicide treatment schemes in determining late blight development in potato.

Year was identified as the main factor influencing disease incidence, confirming the strong impact of climatic variability on epidemic dynamics. Genotypes significantly affected disease severity parameters, demonstrating the importance of cultivar selection in reducing symptom expression. Fungicide treatments significantly reduced disease intensity and attack degree, particularly when properly timed.

Hierarchical cluster analysis confirmed the stable response of potato genotypes across contrasting climatic conditions, clearly distinguishing tolerant and susceptible groups. Red Lady exhibited consistent tolerance, whereas Riviera showed high susceptibility, while Temerar and Darilena displayed intermediate responses.

The significant Treatment × Genotype interaction for AUDPC indicates that treatment efficiency depends on host susceptibility, reinforcing the need for integrated disease management strategies.

These findings provide valuable information for optimizing late blight control under temperate climatic conditions and support the combined use of tolerant cultivars and well-timed fungicide programs to achieve sustainable disease management. Under similar environmental conditions, the cultivar Red Lady can be recommended as a suitable option for reducing disease severity, particularly when combined with appropriately managed fungicide treatments.

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