

Temporal Analysis of Northern Corn Leaf Blight (*Exserohilum turcicum* Pass. Leonard & Suggs) Epidemics

Análisis temporal de epidemias del tizón foliar común del maíz causado por *Exserohilum turcicum* (Pass.) Leonard & Suggs

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ABSTRACT

Field trials were conducted in six locations in central-northern Córdoba, Argentina, using four maize hybrids with varying resistance to northern corn leaf blight (NCLB), caused by *Exserohilum turcicum*. Naturally occurring NCLB epidemics were evaluated. We analyzed disease severity (S%), disease progress curve (DPC), area under the disease progress curve, final severity (FS%) and apparent infection rate (r). Disease progress curves were simultaneously analyzed by fitting nonlinear epidemiological models (Gompertz and Logistic). Ballesteros and Villa María were the localities with the highest FS in susceptible hybrids (45% and 37.5%, respectively). Levels of FS were below 5% in Jesús María, Río Segundo and Freyre, and under 1% in El Tío. The highest AUDPC values were also observed in Ballesteros and Villa María (2150.1 and 1335.7, respectively). In the other locations, AUDPC values remained under 320, with statistically significant differences in all cases ($p < 0.05$). The resistant hybrid exhibited the lowest apparent infection rate compared to the other genotypes. Epidemic progress displayed, to varying degrees, sigmoid-shaped curves characteristic polycyclic diseases. On average, the Gompertz model best fitted disease progress data across all evaluated genotypes with an R^2 of 0.909 and an adjusted coefficient (R^{2*}) of 0.849. The temporal analysis provided key epidemiological insights into the maize-NCLB pathosystem, supporting the development of effective management strategies.

Keywords

Zea mays • *Helminthosporium* • epidemiology • AUDPC • Córdoba

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RESUMEN

Se realizaron ensayos de campo en seis localidades de la región centro-norte de Córdoba, utilizando cuatro híbridos de maíz con diferentes niveles de resistencia al tizón foliar común del maíz (TFC), causado por *Exserohilum turcicum*. Se evaluaron epidemias de la enfermedad generadas de forma natural. Se analizó la severidad (S%), la curva de progreso de enfermedad (CPE), el área bajo la curva de progreso de la enfermedad (ABCPE), la severidad final (SF%) y tasa infección aparente (r). Las curvas de progreso de la enfermedad se analizaron simultáneamente según el ajuste a los modelos epidemiológicos no lineales Logístico y de Gompertz. Ballesteros y Villa María fueron las localidades con mayor SF en materiales susceptibles, siendo de 45% y 37,5% respectivamente. Los niveles de SF fueron inferiores al 5% en Jesús María, Río Segundo y Freyre, y menores al 1% en El Tío. Así mismo, las mayores ABCPE se registraron en Ballesteros y Villa María (2150,1 y 1335,7, respectivamente). En las demás localidades los valores de ABCPE fueron menores a 320, presentando en todos los casos diferencias estadísticamente significativas ($p < 0,05$). El híbrido resistente obtuvo la menor tasa de infección aparente en comparación con los otros genotipos. El progreso de las epidemias determinó, en mayor o menor magnitud, curvas de formato sigmoidal típicas de enfermedades policíclicas. En promedio, el modelo de Gompertz fue el que mejor se ajustó a los datos de progreso de la enfermedad en todos los genotipos evaluados, con un R^2 de 0,909 y un coeficiente ajustado (R^{2*}) de 0,849. El análisis temporal proporcionó información epidemiológica clave sobre el patosistema maíz - tizón foliar común, que ayuda a la implementación de técnicas efectivas para su manejo y control.

Palabras clave

Zea mays • *Helminthosporium* • epidemiología • ABCPE • Córdoba

INTRODUCTION

Corn (*Zea mays* L.) is a strategic crop in Argentina. According to the final report elaborated by the Bolsa de Cereales de Buenos Aires (2019) for 2020-21, more than 6.6 million hectares were sown, producing 57 million tons of grains. Average national production was 8280 kg. ha⁻¹, contributing over 14.8 billion USD to the country's gross domestic product.

Among several diseases affecting corn, northern corn leaf blight (NCLB) is highly prevalent, with increasing incidence and severity in Argentina (8). NCLB is caused by the fungus *Exserohilum turcicum* (Pass.) K. J. Leonard & Suggs [synonym: *Helminthosporium turcicum* Pass.], anamorph of *Setosphaeria turcica* (Luttr.) K. J. Leonard & Suggs. This disease can cause severe yield losses under particular host-pathogen-environment interactions. Yield reductions typically range between 15 and 50% (7, 10, 28) but may even reach 98% (18).

In general, effective management strategies are based on epidemiological studies. Temporal analysis of disease progress is critical for many epidemiological investigations (23). Understanding temporal dynamics of NCLB is essential to describe disease progression, develop sampling plans, design controlled experiments, and assess yield losses. To date, Argentina has scarce information on NCLB development in different corn hybrids, and thus, we hypothesize that temporal epidemiological information can contribute to more effective management decisions.

Temporal analysis allows constructing disease progress curves (DPCs) representing the epidemic process (19) and pathogen, host, and environment interactions (31). Curve shapes and their components, initial disease level (y_0), apparent infection rate (r), final disease level (y_f), and area under the progress disease curve (AUDPC), allow epidemic characterization and management (3).

DPCs can be studied using mathematical models that quantitatively describe epidemic biological dynamics, considering parameter estimates, like Logistic, Gompertz, and monomolecular models (23).

NCLB severity and temporal progress significantly vary among maize hybrids with different resistance. These differences can be characterized using nonlinear epidemiological models, under the agro-climatic conditions of the central-northern region of Córdoba.

NCLB epidemiology provides the basis for developing management strategies within an agroecosystem. This study conducted a temporal analysis of NCLB epidemics by comparing hybrids with different disease responses across multiple localities.

MATERIALS AND METHODS

Experimental Sites, Hybrids and Experimental Design

During the 2015/2016 growing season, six field experiments were conducted across six locations of central-northern Córdoba, Argentina (latitudes -32.519004 to -29.432741 and longitudes -62.185749 to -64.069798) (table 1). Four corn hybrids were evaluated at each site in a randomized complete block design with four replicates. Plots consisted of eight rows, 4 m wide and 10 m long, spaced 0.52 m. The four hybrids were KWS 4321 (susceptible, S), KWS 1516 (moderately susceptible, MS), KWS 1529 (moderately resistant, MR), and KWS Exp20 (resistant, R). All seeds were provided by KWS Argentina corn seed company.

Sowing was performed between December 2015 and February 2016, following soybean season. Crop rotation scheme was corn-soybean-corn under non-tillage conditions; thus, corn debris from the two preceding seasons remained in the fields. Seeding rates varied by location according to yield potential, with an average of 72.000 seeds. ha⁻¹. Each experiment followed standard commercial agronomic practices, including fertilization with 240 kg. ha⁻¹ urea at sowing and 4 L. ha⁻¹ of liquid nitrogen at the V4 stage. Insecticides were not required, and no fungicides were applied to allow natural development of foliar diseases.

Table 1. Site, sowing date, and georeferencing of trials conducted in central-northern Córdoba, Argentina, during the 2015-16 maize season.

Tabla 1. Lugar, fecha de siembra y georreferenciación de los ensayos establecidos en la región centro-norte de Córdoba durante la campaña agrícola 2015-16 para maíz.

Trial (n°)	Site	Sowing date	Latitude	Longitude
1	Ballesteros	02/02/2016	-32.538153	-62.963570
2	Villa María	14/12/2015	-32.478755	-63.236600
3	Jesús María	17/12/2015	-30.790571	-64.069798
4	Río Segundo	23/12/2015	-31.614026	-63.937066
5	Freyre	15/12/2015	-31.153642	-62.185749
6	El Tío	10/01/2016	-31.366282	-62.825914

Field Evaluations

Experimental plots were established in intensively cultivated areas. NCLB epidemics developed naturally. Initial inoculum originated from the experimental sites (infected seeds and saprophytically infected corn residues) and airborne spores from neighboring fields, generating primary and secondary infection cycles.

Disease severity was assessed at 30, 45, 60, 85, 100 and 120 days after sowing (DAS) in each locality. Six plants per block were randomly selected, totaling 24 plants per hybrid at each time point. Leaf blight severity was estimated as the ratio of affected to healthy leaf area, expressed as a percentage, using the diagrammatic scale by Fullerton (1982). Evaluations were performed on the four uppermost unfolded leaves during vegetative stages and on the ear leaf (el), plus leaves immediately above (el+1) and below (el-1) ear leaves, during reproductive stages.

Final severity (FS, %) was determined at 100 DAS, corresponding to the dough grain stage (R4) (29). Severity assessments over time were used to calculate AUDPC for each hybrid using the following equation:

$$AUDPC = \sum_{i=1}^{n-1} \left[\left(\frac{Y_i + Y_{i+1}}{2} \right) ((ti + 1) - ti) \right]$$

where:

Y_i and Y_{i+1} = disease severity values recorded in two consecutive assessments

$[(ti + 1) - ti]$ = time interval between assessments

n = number of evaluations (23).

FS and AUDPC were subjected to ANOVA and Tukey test ($p=0.05$), with InfoStat statistical package (11).

DPCs were constructed by plotting accumulated disease severity (dependent variable) against time (independent variable). Disease progress rate curves (dy/dt) were also plotted for each hybrid at each location.

Disease severity data were fitted with nonlinear Logistic and Gompertz models (20) for each hybrid x location x replicate combination:

$$y = (1 + Be^{-rLt})^{-1} \quad (i)$$

for the Logistic model, and

$$y = \exp(-Be^{-rGt}) \quad (ii)$$

for the Gompertz model

where $B = (1 - y_0) / y_0$ in Equation *i* and $-\ln(y_0)$ in Equation *ii*

y = disease severity (as a proportion)

rL and rG = rate parameters for the Logistic and Gompertz models, respectively

t = time

y_0 = disease severity at epidemic start (at V4, $t = 0$). Model fit was evaluated using the coefficient of determination (R^2) of transformed disease proportion vs. time, and the adjusted coefficient of determination (R^{2*}) of predicted vs. observed values (nonlinearized, untransformed) (20).

RESULTS AND DISCUSSION

The temporal analysis of NCLB epidemics revealed differences in DPCs, AUDPC, FS, and r among the four evaluated hybrids across six localities during the 2015-16 growing season (table 2, page 130 and table 3, page 131; figure 1, page 132 and figure 2, page 133).

All hybrids exhibited similar disease progress trends across the six localities. However, FS and AUDPC showed statistically significant differences among localities ($p<0.05$). The highest FS values in susceptible (S) hybrids were recorded in Ballesteros and Villa María (45 and 37.5 %, respectively) (figure 3, page 134). In contrast, FS values in Jesús María, Río Segundo and Freyre were under 5%, while in El Tío, under 1 %. Although disease pressure was low in the latter locations, differences in FS remained statistically significant ($p<0.05$). Similarly, the highest AUDPC values were observed in Ballesteros and Villa María (2150.1 and 1335.7, respectively), whereas in the remaining localities, AUDPC values were below 320, with statistically significant differences ($p<0.05$) (table 2, page 130). Notably, the February sowing date in Ballesteros was experimentally included to expose the hybrids to different environmental conditions.

Both FS and AUDPC effectively differentiated hybrid reactions across localities. FS is a practical and easy-to-measure parameter, whereas AUDPC requires greater sampling effort but discriminates between hybrids with similar disease behavior (table 2, page 130). The FS assessed on el, el+1 and el-1 at R4 stage has been frequently reported as strongly associated with yield losses, differentiating hybrids with responses to NCLB (12, 25, 26).

Table 2. Final severity (FS) and area under the disease progress curve (AUDPC) in maize hybrids with different reactions to northern corn leaf blight (*Exserohilum turcicum*) in central-northern Córdoba, Argentina, during 2015-16.

Tabla 2. Severidad final (FS) y área bajo la curva de progreso de la enfermedad (ABCPE) en híbridos de maíz con diferente respuesta al tizón foliar común del maíz (*Exserohilum turcicum*) en la región centro-norte de Córdoba, Argentina, durante la campaña agrícola 2015-16.

Site	Reaction	FS (%)		AUDPC	
Ballesteros	R	2.0	a*	147.4	a*
	MR	15.0	ab	640.1	b
	MS	18.0	b	911.1	b
	S	45.0	c	2150.1	c
Villa María	R	3.3	a	165.3	a
	MR	3.0	a	161.0	a
	MS	4.7	a	244.3	a
	S	37.5	b	1335.7	b
Jesús María	R	0.0	a	8.0	a
	MR	3.0	b	161.9	b
	MS	3.0	b	206.0	b
	S	5.0	b	270.3	b
Río Segundo	R	1.0	a	29.5	a
	MR	1.5	a	68.3	b
	MS	2.0	a	83.0	bc
	S	4.0	b	142.1	c
Freyre	R	1.0	a	90.0	a
	MR	1.0	a	92.8	a
	MS	1.5	a	151.6	a
	S	3.5	b	319.4	b
El Tío	R	0.0	a	7.5	a
	MR	0.0	a	3.6	a
	MS	0.0	a	7.5	a
	S	0.1	b	13.1	b

Reaction: R = resistant,
MR = moderately
resistant, MS = moderately
susceptible,
S = Susceptible;
FS (%) = final severity;
AUDPC = area under
the disease progress
curve; * Different letters
indicate statistically
significant differences,
Tukey test ($\alpha = 0.05$).

Reacción: R = resistente,
MR = moderadamente
resistente, MS =
moderadamente
susceptible,
S = Susceptible; FS (%) =
Severidad final; ABCPE
= área bajo la curva
de progreso de
la enfermedad; *
Letras diferentes
indican diferencias
estadísticamente
significativas, test de
Tukey ($\alpha = 0,05$).

Table 3. Nonlinear regression for Logistic and Gompertz models fitted to disease severity data of northern corn leaf blight (*Exserohilum turcicum*) in the 2015/16 season, in Ballesteros, Villa María and Jesús María, central-northern Córdoba, Argentina, for four maize hybrids with different reaction to NCLB.

Tabla 3. Regresión no lineal para modelos Logísticos y Gompertz ajustados a los datos de la severidad del tizón foliar común del maíz (*Exserohilum turcicum*) en la campaña agrícola 2015/16, en las localidades de Ballesteros, Villa María y Jesús María, de la región centro-norte de Córdoba, Argentina para cuatro híbridos de maíz con diferente reacción a la enfermedad.

Site	Hybrid reaction	Models	R ²	R ^{*2}	y ₀	r
Ballesteros	R	Logistic	0.745	0.352	-9.205	0.060
		Gompertz	0.812	0.506	-2.200	0.009
	MR	Logistic	0.893	0.795	-9.545	0.082
		Gompertz	0.985	0.943	-2.340	0.017
	MS	Logistic	0.900	0.697	-7.972	0.067
		Gompertz	0.942	0.863	-2.165	0.016
	S	Logistic	0.890	0.867	-7.736	0.078
		Gompertz	0.957	0.971	-2.210	0.023
Villa María	R	Logistic	0.865	0.711	-8.648	0.053
		Gompertz	0.874	0.814	-2.194	0.009
	MR	Logistic	0.859	0.647	-8.625	0.052
		Gompertz	0.867	0.765	-2.187	0.009
	MS	Logistic	0.894	0.764	-8.371	0.055
		Gompertz	0.944	0.891	-2.165	0.010
	S	Logistic	0.979	0.842	-9.738	0.084
		Gompertz	0.894	0.939	-2.607	0.022
Jesús María	R	Logistic	-	-	-	-
		Gompertz	-	-	-	-
	MR	Logistic	0.821	0.861	-7.819	0.043
		Gompertz	0.914	0.936	-2.064	0.008
	MS	Logistic	0.779	0.654	-7.623	0.043
		Gompertz	0.879	0.775	-2.026	0.008
	S	Logistic	0.822	0.839	-7.685	0.048
		Gompertz	0.926	0.936	-0.009	0.009

Reaction: R = Resistant.
MR = moderately resistant. MS = moderately susceptible. S = susceptible.
R² = coefficient of determination;
R^{*2} = adjusted coefficient of determination between non-transformed observed and predicted values; y₀ = initial inoculum; r = apparent infection rate

Reacción: R = resistente. MR = moderadamente resistente. MS = moderadamente susceptible. S = susceptible.
R² = coeficiente de determinación;
R^{*2} = coeficiente de determinación entre los valores predichos y observados no transformados; y₀ = inóculo inicial; r = tasa de infección aparente.

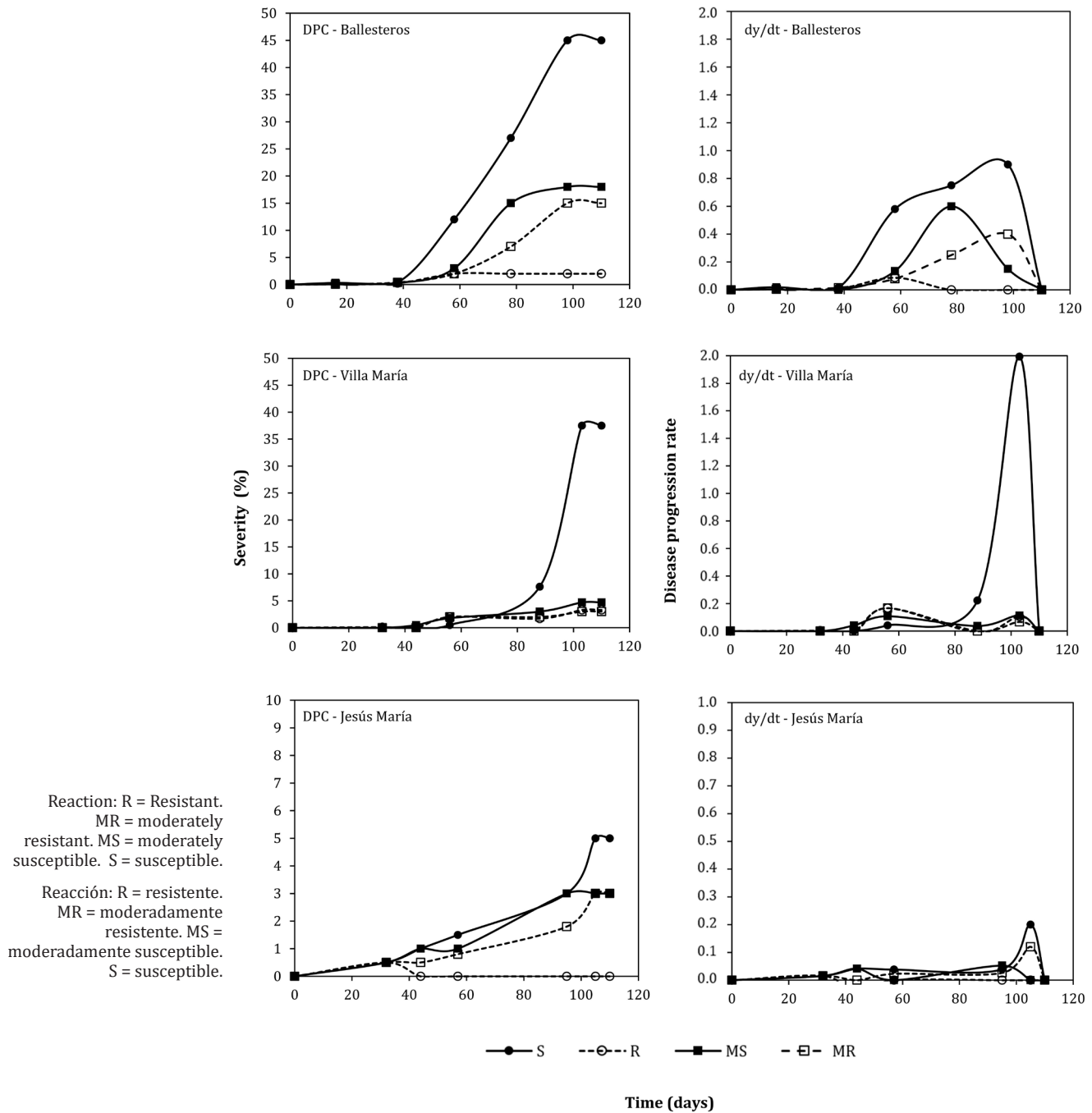


Figure 1. Disease progress curves (DPCs) and disease progress rate curves (dy/dt) of northern corn leaf blight (NCLB) (*Exserohilum turcicum*) in Ballesteros, Villa María, and Jesús María, central-northern Córdoba, Argentina, during the 2015-16 season, for four maize hybrids with different reactions to NCLB.

Figura 1. Curvas de progreso de la enfermedad (DPC) y curvas de la tasa de progreso de la enfermedad en el tiempo (dy / dt) del tizón foliar común del maíz (*Exserohilum turcicum*) en las localidades de Ballesteros, Villa María y Jesús María, pertenecientes a la región centro-norte de Córdoba, Argentina, durante la campaña agrícola 2015-16, para cuatro híbridos de diferente reacción a la enfermedad.

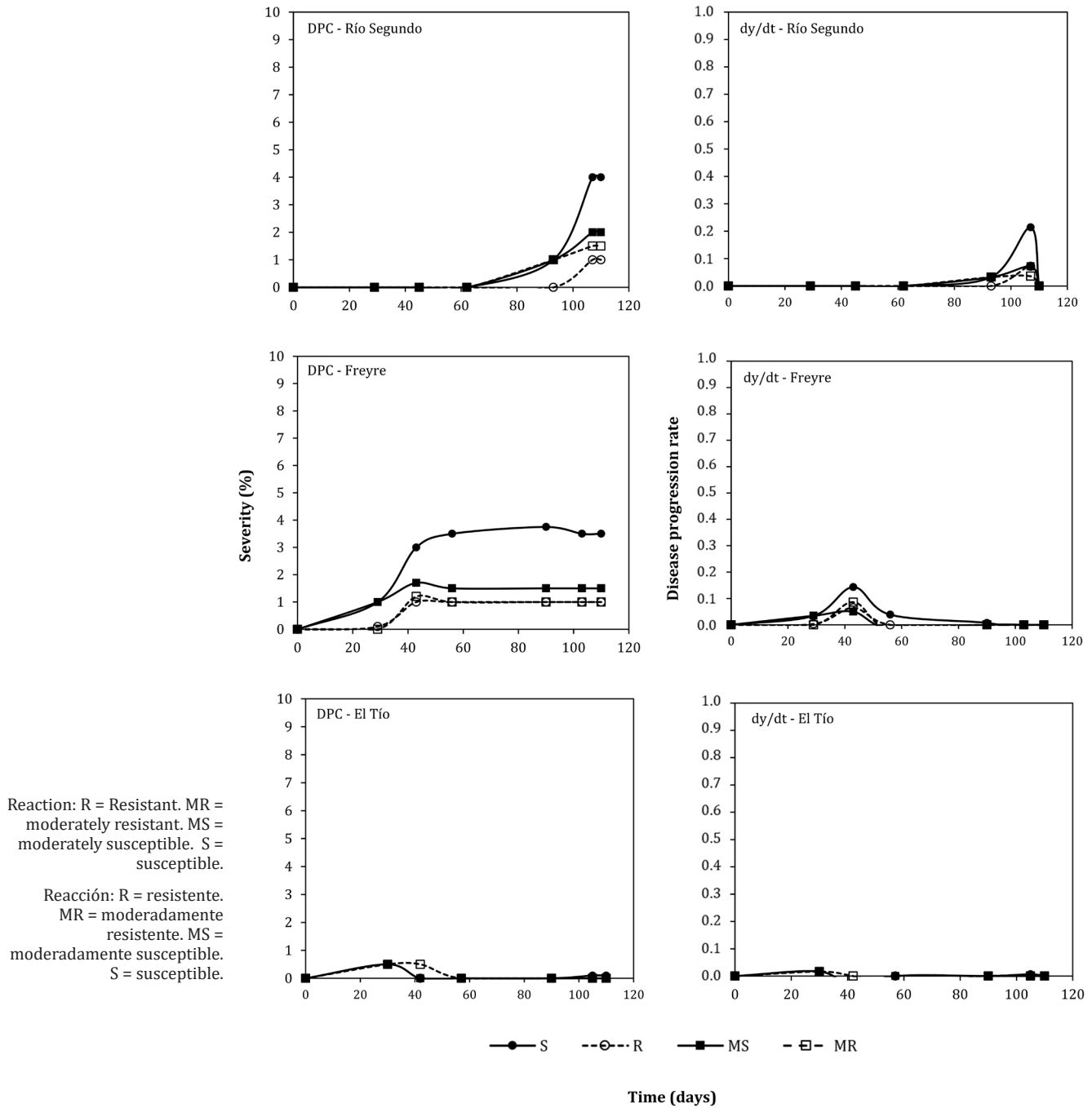


Figure 2. Disease progress curves (DPCs) and disease progress rate curves (dy/dt) of northern corn leaf blight (NCLB) (*Exserohilum turcicum*) in Río Segundo, Freyre and El Tío, central-northern Córdoba, Argentina, during the 2015-16 season, for four maize hybrids with different reactions to NCLB.

Figura 2. Curvas de progreso de la enfermedad (DPC) y curvas de la tasa de progreso de la enfermedad en el tiempo (dy / dt) del tizón foliar común del maíz (*Exserohilum turcicum*) en las localidades de Río Segundo, Freyre and El Tío, pertenecientes a la región centro-norte de Córdoba, Argentina, durante la campaña agrícola 2015-16, para cuatro híbridos de maíz de diferente reacción a la enfermedad.

The picture shows, from left to right, the leaf immediately below the ear leaf, the ear leaf, and the leaf immediately above the ear leaf, at R4 phenological stage in four maize hybrids with different reaction to NCLB: a) resistant, b) moderately resistant, c) moderately susceptible and d) susceptible.

La imagen muestra, de izquierda a derecha, la hoja inmediatamente inferior a la hoja de la espiga, la hoja de la espiga y la hoja inmediatamente superior a la hoja de la espiga, en la etapa fenológica R4, en cuatro híbridos de maíz con diferente reacción al TFC: a) resistente, b) moderadamente resistente, c) moderadamente susceptible y d) susceptible.



Figure 3. Final severity of northern corn leaf blight (NCLB), caused by *Exserohilum turcicum*, in Ballesteros, central-northern Córdoba, Argentina, during the 2015-16 season.

Figura 3. Severidad final del tizón foliar común del maíz (TFC), causado por *Exserohilum turcicum*, en Ballesteros, Córdoba, Argentina, durante la campaña 2015-16.

The resistant (R) hybrid showed the lowest FS and AUDPC values across all localities, remaining symptomless in El Tío and Jesús María (table 2, page 130). Similarly, apparent infection rates (r), estimated by the b parameter, ranged from 0.008 to 0.084 (table 3, page 131) in Ballesteros, Villa María, and Jesús María. The R hybrid had the lowest r among all genotypes, emphasising the importance of genetic resistance in reducing disease prevalence in maize production systems. These findings align with numerous reports emphasising the use of resistant cultivars as the most cost-effective and sustainable approach for disease management (6, 27, 30).

Although nonlinear models provided a reliable description of the temporal dynamics of NCLB across different hybrids and locations, certain methodological limitations should be acknowledged. First, the negative y_0 values (initial inoculum) observed in both models should not be interpreted as actual inoculum levels but as model-derived parameters resulting from mathematical fitting, lacking direct biological meaning. Additionally, given extremely low or null infection levels, we could not fit a model for the R hybrid in Jesús María, confirming the high resistance level of this hybrid at this location.

Generally, the Gompertz model provided better fits, consistent with its suitability for polycyclic diseases. However, some exceptions were noted. The S hybrid in Villa María exhibited higher R^2 with the Logistic model, likely due to environmental factors or differences in epidemic progression. This warrants further investigation.

Substantial NCLB development in Ballesteros, Villa María, and Jesús María provided suitable conditions for fitting and comparing temporal epidemiological models. This was not feasible in Río Segundo, Freyre and El Tío; thus, results from these localities are not presented. Epidemics exhibited sigmoidal curves (figure 1, page 132 and figure 2, page 133), characteristic of polycyclic diseases with multiple infection cycles during the cycle (2, 13). The widely used Logistic and Gompertz models well describe such development (1, 2, 5, 21, 33). Both models had highly significant fits, with R^2 exceeding 80%. On average, the Gompertz model provided the best fit across all genotypes, with $R^2 = 0.909$ and $R^{2*} = 0.849$, outperforming the Logistic model in all cases* (table 3, page 131). These findings agree with Oddino *et al.* (2010), who reported significant fits with both models for NCLB epidemics in a susceptible corn genotype grown in Olaeta (southern Córdoba). The Gompertz model had R^2 over 80%, providing the best fit across DPCs obtained under various fungicide application timings.

Both Logistic and Gompertz curves are useful for modeling growth data. Despite certain limitations, they share similar features. Symmetry is a drawback of the Logistic model, whereas the asymmetrical Gompertz model has an earlier inflexion point, making it more suitable for representing rapid-growth biological phenomena (9).

The better fit of the Gompertz model to NCLB epidemics reflects that the maximum disease rate occurs earlier in this model than in the Logistic curve. Consequently, according to this model, management decisions should be implemented earlier. This observation aligns with Achicanoy López (2000) and March *et al.* (2012), who emphasize that epidemiological models should be employed to predict future disease levels and guide management action, avoiding crop damage. Understanding DPCs enables accurate predictions of disease progression and helps select optimal management strategies for specific pathosystems.

Several criteria may identify the best-fitting model. However, R^2 may not suit model evaluation (15, 17). Instead, the adjusted coefficient of determination (R^{2*}) derived from the regression between non-transformed observed and predicted values provides a more accurate representation of disease progress (5). We provide both coefficients, facilitating model comparison (table 3, page 131).

This study compared different maize genotypes across multiple locations. In polycyclic diseases such as NCLB, the initial inoculum has relatively little influence on FS, whereas the number of infection cycles is critical (2, 22). Management tools in polycyclic diseases, like quantitative resistance, environmental modification, and chemical control at sowing, are commonly employed to reduce apparent infection rates, limiting the number of infection cycles (32). Epidemiological models summarize the disease vs. time relationship into simple mathematical expressions, easing the analysis of disease progression and resistance levels (2). While these models simplify reality, they provide insights experimentally difficult or impossible to obtain.

However, considering no model has been specifically developed for plant pathology, biological interpretations concerning variables and parameters require caution. Proper analysis of these models helps elucidate field conditions and disease progression patterns, supporting effective prevention and control strategies (1).

Vanderplank (1963) emphasized that genetics and chemistry constitute excellent disease control tools, but epidemiology defines strategy. This link between epidemiology and disease management remains essential (16, 34). Temporal analysis provides quantitative insights for understanding epidemic drivers, pathosystem comparisons, prediction systems development, risk mapping, and strategy formulation (23). For the maize-NCLB pathosystem, temporal analysis provides fundamental epidemiological knowledge for mitigating disease impact in central-northern Córdoba.

CONCLUSIONS

The temporal analysis of northern corn leaf blight (NCLB) epidemics in central-northern Córdoba differentiated maize hybrids based on resistance levels and emphasized epidemiological importance of genetic background. The evaluated hybrids exhibited distinct disease progression dynamics, reflected in differences in disease progression curves, final severity, area under the disease progression curve, and apparent infection rates, validating their expected reactions to NCLB.

Among the nonlinear models tested, the Gompertz model consistently provided the best fit, suggesting an early exponential phase and gradual disease progression, typical of NCLB under field conditions. These findings help understand disease temporal dynamics and support the use of quantitative epidemiological tools to guide hybrid selection and optimize integrated disease management strategies against NCLB in maize production systems.

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