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Aptitude of Brazilian oat cultivars for reduced fungicide use while maintaining satisfactory productivity

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ABSTRACT. The aggressiveness of fungal diseases in oats compromises grain yield. Although fungicides are effective for control, there is a need for productivity with food and environmental safety. Thus, we seek cultivars responsive to more sustainable management. The objective of this study was to identify oat cultivars that are more responsive to reduced fungicide use and a longer application-to-harvest interval with satisfactory yields, and to identify relevant variables in the simulation of grain yield by multiple linear regression. The study was carried out in 2019 and 2020 in Augusto Pestana, RS, a prominent region for oat cultivation in Brazil. The experimental design was randomized blocks, with three replications in a 22 x 4 factorial scheme, for 22 oat cultivars, recommended and no longer suitable for cultivation and four conditions of sequential use of fungicide (no application; one application 60 days after emergence; two applications, 60 and 75 days after emergence; and three applications, 60, 75 and 90 days after emergence). The fungicide used was FOLICUR® CE, at a dosage of 0.75 liters ha^{-1}. The variables analyzed were necrotic leaf area and grain yield. The Stepwise technique was used to identify potential variables for the multiple linear regression model. The cultivars FAEM 4 Carlasul, URS Altiva, URS Charrua and URS Guará show superiority in grain yield in the absence of fungicide. In a single application, 60 days after emergence, FAEM 4 Carlasul and URS Charrua showed productivity above 3000 kg ha^{-1} with a long interval (around 60 days) from application to harvest. The variables minimum average temperature, necrotic leaf area and number of fungicide applications were found to be suitable for the composition of a multiple linear regression model to simulate grain yield.

Key words: *Avena sativa*; *Puccinia coronata*; *Drechslera avenae;* Necrotic leaf area; Air temperature; Rainfall; Multiple regression

INTRODUCTION

White oat (*Avena sativa*) is widely cultivated in southern Brazil and is an alternative species to wheat cultivation during the cold season (Silva et al., 2015; Coelho et al., 2019). It provides numerous benefits in crop succession and rotation, including pasture composition, haymaking, silage, and animal feed (Mantai et al., 2016; Coelho et al., 2019). In human food, oats have been highlighted as a functional food (containing antioxidants, lipids, high levels of proteins and fibers) contributing to the diet of people seeking a healthier life (Maximino et al., 2021).

The benefits of the multifunctionality of oats have contributed to an increase in the cultivation area, contributing to significant advances in the milk and meat production chains, in addition to the grain processing industries (Zhao et al., 2020). On the other hand, the increase in the cultivated area favors the appearance and development of fungal diseases, mainly leaf rust (*Puccinia coronata* Cda. f. sp. *avenae*) and Helminthosporium leaf spot (*Drechslera avenae*, promoting significant losses in grain yield (Dornelles et al., 2021). The high genetic uniformity in relation to resistance and large-scale cultivation provide a favorable condition for the emergence and evolution of fungal pathogens, contributing to the greater severity of fungal diseases (Leonard and Martinelli, 2015; Brunetto et al., 2017).

A favorable environment for the fungus is described as one of high air temperature and humidity, presence of the pathogen and susceptible host, recurrent elements in the elongation and grain filling phases, a characteristic condition in southern Brazil. This condition promotes infection and disease progression, reducing photosynthetically active leaf area, dramatically affecting productivity (Dietz et al., 2019; Pereira et al., 2020). Due to the damage caused by leaf rust and leaf spot in oats, and the lack of cultivars with effective genetic resistance, the use of fungicides has become the most common and most effective alternative for control (May et al., 2020), with recurrent application during the stage of plant elongation and grain filling.

The use of pesticides is a common and often necessary management in agriculture, but it has numerous negative consequences for the ecosystem and human health (Ndayambaje et al., 2019). Pesticides are easily spread in soil, water, air and food, a condition that favors the occurrence of poisoning of organisms present in the ecosystem (Pignati et al., 2017). Human exposure to pesticides, whether through contact and/or ingestion, results in skin and eye irritation, headache, nausea, dizziness, diarrhea, vomiting, asthma, diabetes and cancer (Elahi et al., 2019).

The consumption of oats in food occurs largely through the "in natura" product, which is intended for the manufacture of bran, flour or flakes, generating insecurity about probable risks of agrochemical residues translocated to grains during control of fungal diseases (Silva et al., 2015; Pereira et al., 2018). In Brazil, the National Health Regulatory Agency (Anvisa) establishes maximum residue limits, however, studies have shown the presence of pesticide residues in cereal grains and that they often exceed the limits established by regulatory bodies (Matos et al., 2019). The study carried out by Scheer (2021) stands out, which found residues of the active principle of the fungicide Tebuconazole after controlling oat diseases with sequential applications, mainly during the grain filling period.

The identification of oat cultivars that are more resistant to diseases, together with management that promotes a reduction in the number of applications and/or a longer interval from application to harvest, can generate satisfactory productivity with food safety for the consumer (Silva et al., 2015; Dornelles et al., 2020). Thus, models that incorporate variables related to plant, fungus injury and meteorological conditions during cultivation that act on the environment-pathogen-host trinomial can generate information on predictability and behavior of cultivars under agrochemical management conditions. In this perspective, several studies have shown the use of multiple linear regression as a tool to generate predictability from different scenarios, involving biological and environmental variables (Majumdar et al., 2017; Alessi et al., 2021).

The objective of the study was to identify oat cultivars that are more responsive to reduced fungicide use and a longer application to harvest interval with satisfactory yields, and to identify potential variables for the simulation of grain yield by multiple linear regression.

MATERIAL AND METHODS

The experiment was carried out in the field, in the agricultural years of 2019 and 2020, in the municipality of Augusto Pestana, RS, Brazil (28° 26’ 30’’ latitude S and 54° 00’ 58’’ longitude W). The soil of the experimental area is classified as a typical dystroferric red latosol and the climate of the region, according to the Köeppen classification, of the Cfa type, with hot summer without a dry season. In the study, ten days before sowing, soil analysis was performed and identified, over the years, the following chemical characteristics of the site: pH = 6.2, P = 33.9 mg dm^{-3}, K =200 mg dm^{-3}, MO = 3.0%, Al= 0 $cmol_c$ dm^{-3}, Ca = 6.5 $cmol_c$ dm^{-3} e Mg = 2.5 $cmol_c$ dm^{-3}. The experimental design was a randomized block, with three replications in a 22 x 4 factorial, for white oat cultivars (Barbarasul, Brisasul, FAEM 006, FAEM 007, FAEM 4 Carlasul, FAEM 5 Chiarasul, IPR Aphrodite, UPFA Gaudéria, UPFA Ouro, UPFPS Farroupilha, URS 21, URS Altiva, URS Brava, URS Charrua, URS Corona, URS Estampa, URS Fapa Slava, URS Guará, URS Guria, URS Tarimba, URS Taura and URS Torena) and conditions of sequential fungicide applications (without application, one application at 60 days after emergence, two applications at 60 and 75 days after emergence and three applications at 60, 75 and 90 days after emergence), respectively. The fungicide used was the commercial product FOLICUR® CE, used at a dosage of 0.75 liters ha^{-1} (active ingredient:

tebuconazole). The application of the fungicide was carried out with a back sprayer with a 45 PSI pressure nozzle and a spray volume of 120 liters ha^{-1}. The conditions of use of the fungicide were proposed based on the indication of the product, which varies in intervals of 15 days and a maximum of three applications during the crop cycle. The last application of the fungicide at 90 days after emergence is highlighted to guarantee a considerable interval between the last application and the maturity of the grain (about 30 days), allowing a longer interval between the last application and harvest of the grains.

Sowing was carried out with a seeder-fertilizer for the composition of plots with 5 lines of 5 m in length and spacing between lines of 0.20 m, forming the experimental unit of 5 m^2. At sowing, 45 and 30 kg ha^{-1} of P_2O_5 and K_2O were applied, respectively, based on the P and K contents in the soil for expected grain yield of 3 t ha^{-1} and N in the base with 10 kg ha^{-1}, with the urea source, the remainder being applied in coverage at stage V_4 (fourth expanded leaf), with nitrogen made available in the form of urea (45%). The seeds were submitted to a germination and vigor test in the laboratory, in order to correct the desired density of 400 viable seeds m^{-2}. To control weeds, the herbicide metsulfuron-methyl was used at a dose of 4g ha^{-1}.

In determining the necrotic leaf area (NLA, cm²), three plants were randomly collected in each plot. In this evaluation, the total leaf area was first sized and then the necrosis area was sized. Therefore, the necrotic leaf area was dimensioned in cm² and %. Plants were collected 105 days after emergence, a time considered suitable for analysis of leaf necrosis in oats (DORNELLES et al., 2021), a condition considered for all cultivars at different times of fungicide use. From each plant collected, the three upper leaves were removed to evaluate the necrotic leaf area in relation to the total area. The leaves were digitized using the leaf area reader and WinDIAS software (Copyright 2012, Delta-T Devices Limited) determining the area of disease necrosis over the total area. The harvest of the experiment to estimate the grain yield occurred manually by cutting the three central lines of each plot, stage close to the harvest point (125 days), with grain moisture approximately 15%. The plots were tracked with a stationary harvester and sent to the laboratory for correction of grain moisture to 13%, after weighing and estimating grain yield (GY, kg ha^{-1}). The values of minimum, maximum and average air temperature and rainfall were obtained from the automatic meteorological station of the Regional Institute of Rural Development, located approximately 200 meters from the experimental field. The results served as a basis for classification as favorable (FYD) and unfavorable to disease (UYD) year in oat cultivation. The individual performance of cultivars considering the average values of yield and necrotic leaf area took into account the classification in superior (S) and inferior (I) in relation to the average plus or minus the standard deviation. Therefore, superior cultivars for grain yield were those with a value equal to or greater than the mean plus one standard deviation and for necrotic leaf area, superior were those with mean values minus one standard deviation. In compliance with the assumptions of homogeneity and normality of the variables, analysis of variance of the main effects and interaction of cultivars and fungicide application conditions was performed (not shown). The selection of potential variables for multiple linear regression was performed using the Stepwise technique. In this technique, a sequence of regression models in which variables are added and removed is iteratively constructed, selecting the regression that has the greatest relationship with the main variable. The addition and removal of variables is performed using partial F statistics, according to the model:

$$F_j = \frac{QS_R(\beta_j \mid \beta_1, \beta_0)}{QM_E(X_j, X_1)} \qquad \text{(Eq. 1)}$$

in which: QS_R is the regression sum of squares and $QM_E(X_j, X_1)$ is the mean square of the error containing variables X_j and X_1. The variables selected via Stepwise were used to compose the multiple linear regression equation in the simulation of wheat grain yield. This equation is composed of two or more variables in generating an equation as follows:

$$y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + \cdots + b_nX_n + \varepsilon \qquad \text{(Eq. 2)}$$

described in matrix form as:

$$y = \begin{bmatrix} Y_1 \\ Y_2 \\ M \\ Y_n \end{bmatrix}; X = \begin{bmatrix} 1 & X_{11} & X_{12} & \dots & X_{1p} \\ 1 & X_{21} & X_{22} & \dots & X_{2p} \\ M & M & M & \dots & M \\ 1 & X_{n1} & X_{n2} & \dots & X_{np} \end{bmatrix}; b = \begin{bmatrix} b_1 \\ b_2 \\ M \\ b_3 \end{bmatrix}; \varepsilon = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ M \\ \varepsilon_3 \end{bmatrix} \qquad \text{(Eq. 3)}$$

From these matrices, the values of the regression coefficients are obtained, being:

$$\hat{\beta} = (X'X)^{-1}X'Y \qquad \text{(Eq. 4)}$$

and the variance of these coefficients is obtained by the covariance matrix of the vector of regression coefficients:

$$C\hat{o}v(\hat{\beta}) = (X'X)\,\hat{\sigma} \text{ e } \hat{\sigma}^2 = \frac{(Y-X\hat{\beta})'(Y-X\hat{\beta})}{n-p-1} \qquad \text{(Eq. 5)}$$

in which n is the number of equations and p the number of parameters. The hypothesis test is verified: $H_0: \beta_i = 0; vs\ H_a: \beta_i \neq 0$, expressed by:

$$t = \frac{\hat{\beta}_i - \beta_i}{\sqrt{\hat{V}(\hat{\beta}_i)}} \qquad \text{(Eq. 6)}$$

The variables selected by the Stepwise technique were used in the multiple linear regression models, regardless of agricultural year. All analyzes were performed using the Genes software (Quantitative Genetics and Experimental Statistics, version 2015, 5.0).

RESULTS AND DISCUSSION

In Table 1, in the oat crop cycle, air temperature and rainfall were higher in 2019 compared to 2020. In addition, 2019 was marked by greater concentration of rainfall throughout the cycle, especially at the beginning of the vegetative stage and in oat grain filling. The results of meteorological conditions (Figure 1) together with information on grain yield under different conditions of fungicide use, classify 2019 as the most unfavorable year for oat cultivation and favorable for the presence of foliar diseases (FYD), unlike 2020, which proved to be more favorable to cultivation and unfavorable (UYD) to diseases (Table 1). This classification is strengthened in view of the statistical comparison of the years of cultivation, in which grain yield was higher in 2020 in all conditions of fungicide use (Table 1).

Milder temperatures decrease the respiration rate, providing greater accumulation of liquid photosynthesis directed to the elaboration of biomass (Marolli et al., 2017). In oats, the base temperature is 4°C, a point that restricts the accumulation of dry matter, ensuring only the survival of the plant (Castro et al., 2012; Mantai et al., 2017). It is noteworthy that plants have an optimal temperature range for biological activities, as it is a meteorological element that also acts on biochemical reactions, with a favorable range between 20 and 25°C in oat crops (Castro et al., 2012).

Table 1. Meteorological data on temperature and precipitation in the oat crop cycle and grain yield in 2019 and 2020.

Month	**Temperature (ºC)**			**Precipitation (mm)**		**Fungicide**				**Class**
	Min	**Max**	**Med**	**20 years****	**Occurred**	**0**	**1 (60)**	**2 (60/75)**	**3 (60/75/90)**	
2019										FYD
May	17.0	20.7	18.9	118.2	125.0	Grain yield (kg ha^{-1})				
June	10.2	22.5	16.3	117.8	248.8	1106	2049	3029	3397	
July	9.5	19.2	14.4	133.4	141.7					
August	14.4	26.3	20.4	92.1	81.5	Necrotic leaf area (cm^2)				
September	12.8	19.9	16.4	136.6	107.5	45*	18^{ns}	11^{ns}	10^{ns}	
October	17.2	27.0	22.1	191.8	180.8					
Total	-	-	-	789.9	885.3					
2020										
May	12.7	21.1	16.9	118.2	56.2					
June	4.8	18.4	11.6	117.8	11.2	Grain yield (kg ha^{-1})				
July	9.0	21.2	15.1	133.4	81.0	3210*	3814*	4052*	4323*	
August	10.2	21.4	15.8	92.1	168.7					UYD
September	8.1	23.2	15.7	136.6	56.2	Necrotic leaf area (cm^2)				
October	13.1	27.3	20.2	191.8	325.7	20	17	10	7	
Total	-	-	-	789.9	699.0					

Meteorological variables	**Values**			**Fungicide**			
	Min	**Max**	**Med**	**0**	**1 (60)**	**2 (60/75)**	**3 (60/75/90)**
	Joint analysis (2019 + 2020)						
Minimum temperature	-1.5	21.7	9.7	Grain yield (kg ha^{-1})			
Average temperature	5.0	26.2	14.8	2158 c	2931 b	3540 a	3860 a
Maximum temperature	9.9	34.6	22.9	Necrotic leaf area (cm^2)			
Precipitation	292.0	673.0	474.0	32 a	18 b	10 c	8 c

NFA=number of fungicide applications; GY=grain yield; FYD= favorable year to foliar diseases; UYD=unfavorable year for foliar diseases; 0=no fungicide application; (60)=one fungicide application at 60 days after emergence; (60/75)= two fungicide applications at 60 and 75 days after emergence; (60/75/90)=three fungicide applications at 60, 75 and 90 days after emergence. Min= minimum value; Max= maximum value; Med= average value. Means followed by the same lowercase letters on the line constitute a statistically homogeneous group by the Skott-Knott model at 5% error probability; **=averages of the last 20 years; *=significant at 5% error probability by the F test; ^{ns}= not significant at 5% probability of error by the F test.

For the proper development of plants, the presence of soil moisture is essential, so that rainfall is well distributed throughout the crop cycle, a condition that directly influences productivity (Marolli et al., 2018; Kraisig et al., 2021). High rainfall tends to negatively impact the productivity and quality of oat grains, given the decrease in insolation and, consequently, lower net photosynthesis, combined with problems with germination and fungi in the grains, which impact marketing (Sooväli & Koppel, 2011).

Leaf diseases manifest themselves with greater intensity from the flowering stage under conditions of high relative humidity and average temperatures above 20°C (Dornelles et al., 2021). According to Leonard and Szabo (2005), the presence of moisture favors the formation of urediniospores and, consequently, the increase in infection and disease progression. In oats, leaf rust (*Puccinia coronata* Cda. f.sp. *avenae*) and Helminthosporium [(*Drechslera avenae* (Eidam) Sharif)] receive greater attention, as the most severe, causing significant losses in productivity and grain quality (Dietz et al., 2019). This fact is explained by the destruction of much of the leaf tissue of infected plants, interfering with photosynthesis and accumulation of photoassimilates, resulting in the production of light, wrinkled and darkened grains, without quality for the milling and consumption process (Macoski et al., 2020). Due to the severity of foliar diseases in oats, genetic improvement has sought the development of resistant cultivars, however, the resistance obtained is easily overcome in a few years, due to the wide variability of races of the pathogen (Zhuikova et al., 2021). As a result, the use of fungicides becomes the most effective control measure, but with an increase in production costs (Brunetto et al., 2017). Follmann et al. (2016) report that chemical control by the application of fungicides is a necessary measure to guarantee the yield potential and quality of oat grains.

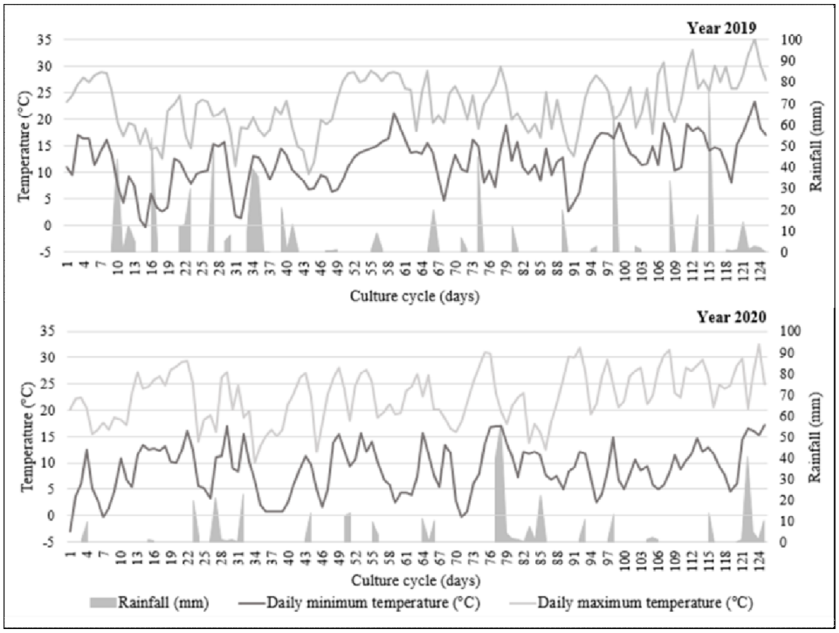

Figure 1. Precipitation and temperature data in the field during the oat crop cycle.

In Table 2, from the joint analysis of the agricultural years, the cultivars FAEM 4 Carlasul, URS Altiva, URS Charrua and URS Guará showed superiority in grain yield due to the absence of fungicide use, with average values around 2500 kg ha^{-1}. Among these cultivars, FAEM 4 Carlasul and URS Charrua also showed superiority with only one fungicide application at 60 days after emergence (DAE), with values above 3100 kg ha^{-1}. In addition, considering a single application at 60 DAE, the cultivar URS Corona was integrated into the superior group, with grain yield around 3400 kg ha^{-1}. These results confirm the potential of these cultivars under conditions of absence or minimal use of fungicide in disease control, with a long interval from application to harvest. The condition with two fungicide applications at 60 and 75 DAE, which also represent a long interval from the last application to harvest, indicated superiority of the cultivars Barbarasul, Brisasul, FAEM 007 and URS Corona, with values close to 4000 kg ha^{-1}. Among these, the sequential applications performed at 60, 75 and 90 DAE, which configure at least 30 days from the last application to harvest, also showed superiority of Barbarasul, Brisasul and URS Corona, followed by IPR Afrodite and URS Altiva. Anyway, although high superiority is observed, they already show a tendency of greater dependence on agrochemicals and greater expression of productivity.

URS Taura represents the largest cultivar in terms of cultivation area in Brazil, surpassing by more than 80%. This genotype is highly dependent on the use of agrochemicals to guarantee production, given the high genetic uniformity of the cultivar due to large-scale cultivation and the strong pressure of fungal diseases present in the environment (Table 2). Corroborating the inferiority in almost all conditions of fungicide use for grain yield.

Table 2. Values of grain yield and necrotic leaf area by the number of fungicide applications in the oat cultivars.

Cultivar	**NFA/GY (kg ha^{-1})**				**NFA/NLA (cm^2)**			
	0	**1 (60)**	**2 (60/75)**	**3 (60/75/90)**	**0**	**1 (60)**	**2 (60/75)**	**3 (60/75/90)**
Joint analysis (2019 + 2020)								
Barbarasul	2007	3012	4069^S	4285^S	22	10^S	6^S	6^S
Brisasul	2198	3032	3843^S	4337^S	16^S	16	13	12
FAEM 006	2071	3015	3649	4101	20	15	9	8
FAEM 007	2039	2713	3891^S	3923	15^S	9^S	6^S	6^S
FAEM 4 Carlasul	2548^S	3180^S	3771	3848	26	10^S	8	7
FAEM 5 Chiarasul	1831^I	2387^I	3573	3966	21	8^S	4^S	4^S
IPR Afrodite	2305	3037	3711	4238^S	22	19	8	8
UPFA Gaudéria	2078	2799	3059^I	3418^I	21	12	10	10
UPFA Ouro	1997	2675^I	3085^I	3509^I	39^I	14	11	11
UPFPS Farroupilha	2278	3140	3597	3939	36^I	21	11	11
URS 21	2361	2880	3366	3396^I	24	22^I	17^I	16^I
URS Altiva	2484^S	3070	3738	4351^S	15^S	6^S	5^S	5^S
URS Brava	2191	3094	3618	4092	17^S	9^S	4^S	4^S
URS Charrua	2526^S	3355^S	3604	3629	32	17	10	10
URS Corona	2292	3404^S	3868^S	4178^S	34^I	19	12	12
URS Estampa	2339	2992	3213^I	3525^I	31	22^I	15^I	15^I
URS Fapa Slava	1597^I	2545^I	3256^I	3373^I	34^I	25^I	17^I	17^I
URS Guará	2452^S	2908	3676	3970	32	18	6^S	6^S
URS Guria	2041	2988	3426	3626	34^I	27^I	19^I	19^I
URS Tarimba	2288	2790	3444	3910	32	20	15^I	15^I
URS Taura	1507^I	2589^I	3081^I	3739	22	17	10	10
URS Torena	2043	2919	3334	3581	25	17	11	10
Average	2157	2931	3540	3860	26	16	10	10
Standard deviation	274	249	284	318	7	6	4	4

NFA = number of fungicide applications; GY = grain yield; NLA = necrotic leaf area; 0 = no fungicide application; (60) = one fungicide application at 60 days after emergence; (60/75) = two fungicide applications at 60 and 75 days after emergence; (60/75/90) = three fungicide applications at 60, 75 and 90 days after emergence; ^{S}= superior; ^{I}= inferior.

In the analysis of the necrotic leaf area, there is a tendency to reduce necrosis with the increase in the number of sequential applications of the fungicide, although for some cultivars, the second application at 60 and 75 DAE shows equal values of necrotic leaf area with three applications at 60 , 75 and 90 DAE. This fact reinforces the possibility of using a maximum of two fungicide applications with these cultivars, ensuring a long interval from application to harvest. Of course, this inference does not take into account meteorological

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conditions more favorable to the disease than those observed in this study, which can increase the pressure of the inoculum on the host. The cultivars that showed superiority in grain yield in the absence of fungicide were not always superior in the expression of lower leaf necrosis, which demonstrates the possibility of compensatory effects of healthy cells in guaranteeing satisfactory yields, representing an element to be observed in terms of resistance to illnesses. This fact was also observed for the other conditions of fungicide use, although some conditions of superiority of productivity are related to smaller necrotic leaf area (Table 2). According to Dornelles et al. (2021) cultivars with greater necrotic leaf area will not always be the ones with lower productivity, suggesting that there may be a compensatory effect from the induction of greater photosynthetic efficiency of the healthy leaf area.

In Table 3, in the analysis of the significance of potential variables using the Stepwise technique, it was observed that the management that involves the number of fungicide applications sequentially over time is a decisive parameter of incorporation in the multiple regression model. In addition, the necrotic leaf area considering the evaluation by necrosis area proved to be qualified for use in the model compared to the percentage of necrosis in relation to the total area of the leaf.

Table 3. Average square values in the identification of potential variables by the Stepwise technique.

Classification	**Variables**	**Average square (2019+2020)**
Number of Fungicide Applications	(NFA, n)	200905863*
Necrotic Leaf Area	(NLA, %)	4279452^{NS}
	(TLA, cm²)	27989469*
Average temperature	(T_{MIN}, °C)	40352403*
	(T_{MED}, °C)	416413^{NS}
	(T_{MAX}, °C)	432526^{NS}
Rainfall	(PRC, mm)	287410351*
Deviation		310304684

NFA=number of fungicide applications; NLA=necrotic leaf area; TLA=total leaf area; T_{MIN}=minimum temperature; T_{MED}=average temperature; T_{MAX}= maximum temperature; PRC=rainfall; *=significant at 5% error probability by the F test; ^{ns}= not significant at 5% probability of error by the F test.

Still in Table 3, considering the meteorological indicators, the minimum average temperature is qualified for inclusion in the multiple regression model along with the rainfall of the oat crop cycle. Therefore, the presented results of this analysis show a conceptual simulation model that follows the following function $GY= f(K_{PRC} +K_{TMIN} +K_{NLA} +K_{NFA})$.

It is important to verify the components that act on the grain yield of crops by changing management techniques, enhancing variables for use in simulation models (Leal et al., 2015). Klering et al., (2016) comment that in the analysis of many variables, the Stepwise technique allows the selection of potential components for simulation by multiple linear regression. These same authors qualified an agrometeorological-spectral model by multiple regression to estimate the yield of irrigated rice grains. Mantai et al. (2016), in this same line of action, simulated oat grain yield by the multiple model, recognizing the panicle harvest index, number of grains and panicle spikelets and nitrogen dose as potential variables, selected by the Stepwise technique. Godoy et al. (2015), in rice, selected copper, nitrogen, iron and acid phosphatase using the StepWise technique for the composition of the multiple model to simulate productivity. It is noteworthy that in a set of independent variables there may be variables that have little influence on the set of dependent variables (Pádua et al., 2015). In these terms, the Stepwise selection method allows choosing the variables with greater explanatory capacity, allowing to arrive at a smaller model with efficiency in the simulation (Almeida et al., 2016).

Table 4 presents the multiple linear regression models for each cultivar involving the variables selected by the Stepwise technique. In this simulation, information obtained in the set of evaluation years was considered, which were: minimum average temperature (T_{MIN}) of 9.7ºC, rainfall of the crop cycle (PRC) of 474mm and number of sequential applications of fungicide (NFA) of 2 applications, at 60 and 75 DAE. For the value of the necrotic leaf area in cm2, the individual response of each cultivar was considered, with two applications, as shown in Table 2. In the presented configuration, the observed (GY_O) and expected (GY_E) productivity results indicate similarity, bringing the possibility of using a qualified simulation model specific to the characteristics of necrosis evolution in each cultivar. It is important to comment on the reduced absolute errors in a model that involves a complex interaction between meteorological variables and the action of the fungus on the size of the leaf lesion and integrating the management of fungicide to control the disease.

Table 4. Multiple linear regression to estimate oat grain yield for each cultivar.

Cultivar	**$GY= f(K_{PRC} +K_{TMIN} +K_{NLA} +K_{NFA})$**	**GYo (kg ha^{-1})**	**GY_E (kg ha^{-1})**	**Absolute error**
(2019 + 2020)				
Barbarasul	$GY=5323-4.57_{PRC}-8.66_{TMIN}-4.60_{NLA}+537_{NFA}$	4069	3857	212
Brisasul	$GY=4476-3.2_{PRC}-17.25_{TMIN}-31.30_{NLA}+667_{NFA}$	3843	3730	113
FAEM 006	$GY=5456-4.5_{PRC}-5.09_{TMIN}-53.17_{NLA}+433_{NFA}$	3649	3636	13
FAEM 007	$GY=6072-7.72_{PRC}-15.62_{TMIN}-10.31_{NLA}+653_{NFA}$	3891	3505	386
FAEM 4 Carlasul	$GY=4952-2.84_{PRC}-2.22_{TMIN}-43.19_{NLA}+202_{NFA}$	3771	3648	123
FAEM 5 Chiarasul	$GY=3965-3.13_{PRC}+10.01_{TMIN}-44.51_{NLA}+523_{NFA}$	3573	3423	150
IPR Afrodite	$GY=6412-6.56_{PRC}-11.15_{TMIN}-37.35_{NLA}+448_{NFA}$	3711	3783	72
UPFA Gaudéria	$GY=4775-3.06_{PRC}-3.31_{TMIN}-58.14_{NLA}+218_{NFA}$	3059	3144	85
UPFA Ouro	$GY=3998-2.94_{PRC}+5.50_{TMIN}-18.20_{NLA}+337_{NFA}$	3085	3123	38
UPFPS Farroupilha	$GY=5000-3.12_{PRC}+9.40_{TMIN}-37.47_{NLA}+234_{NFA}$	3597	3677	80
URS 21	$GY=4136-1.00_{PRC}-23.28_{TMIN}-39.59_{NLA}+233_{NFA}$	3366	3242	124
URS Altiva	$GY=3376-1.55_{PRC}-5.80_{TMIN}-9.19_{NLA}+602_{NFA}$	3738	3735	3
URS Brava	$GY=3626-3.63_{PRC}-1.88_{TMIN}+27.91_{NLA}+743_{NFA}$	3618	3471	147
URS Charrua	$GY=5248-3.84_{PRC}-5.20_{TMIN}-22.12_{NLA}+195_{NFA}$	3604	3536	68
URS Corona	$GY=6426-6.2_{PRC}-18.54_{TMIN}-26.08_{NLA}+423_{NFA}$	3868	3834	34
URS Estampa	$GY=4241-3.16_{PRC}-10.49_{TMIN}-6.47_{NLA}+341_{NFA}$	3213	3227	14
URS Fapa Slava	$GY=2701-2.82_{PRC}-7.97_{TMIN}+15.62_{NLA}+700_{NFA}$	3159	2953	206
URS Guará	$GY=5242-4.05_{PRC}+17_{TMIN}-35.98_{NLA}+217_{NFA}$	3676	3691	15
URS Guria	$GY=3061-0.84_{PRC}+1.08_{TMIN}-13.16_{NLA}+451_{NFA}$	3426	3319	107
URS Tarimba	$GY=5780-5.68_{PRC}-12.74_{TMIN}-23.73_{NLA}+421_{NFA}$	3444	3438	6
URS Taura	$GY=4297-5.95_{PRC}+22.64_{TMIN}-2.04_{NLA}+709_{NFA}$	3081	3094	13
URS Torena	$GY=3941-2.91_{PRC}+7.45_{TMIN}-17.17_{NLA}+414_{NFA}$	3334	3274	60
General Average		3541	3487	54

GY= grain yield (kg ha^{-1}); PRC= rainfall (mm); T_{MIN}= minimum temperature (°C); NLA= necrotic leaf area (cm²); NFA= number of fungicide applications (nº); GY_E= estimated grain yield; GY_O= observed grain yield.

Table 5 shows the general multiple linear regression model, considering the proposal to generate a single regression model to simulate productivity in the set of all 22 oat cultivars, with variables selected by the Stepwise technique, as shown in Table 4. In this configuration, the same values of air temperature and rainfall were also used, with two fungicide applications (60 and 75 DAE) and necrotic leaf area corresponds to the lesion presented in each cultivar, as shown in Table 2. There is an expressive amplitude of absolute error between observed and simulated grain yield for some cultivars, when considering the general model (Table 5). This result indicates greater reliability of simulation by multiple linear regression when considering particular characteristics of each cultivar (Table 4). Although the general model did not present satisfactory results in the simulation of oat grain yield, the individual model per cultivar qualifies the multiple linear regression as a method of great potential for simulation, involving meteorological conditions, injury to the main fungi causing foliar diseases and of fungicide management, proposed in this study. Results of this nature leverage this technique as a statistical model that aggregates linear and non-linear behavior variables, integrating plant indicators, agronomic management and meteorological conditions, representing a more realistic scenario of agriculture.

Table 5. General multiple linear regression model to estimate oat grain yield per cultivar.

Cultivar	**GY = 4654 - 4.02$_{PRC}$ -2.57$_{TMIN}$ -19.27$_{NLA}$ +469$_{NFA}$**	**GY$_O$ (kg ha^{-1})**	**GY$_E$ (kg ha^{-1})**	**Absolute Error**
(2019 + 2020 + 22 oat cultivars)				
Barbarasul		4069	3544	525
Brisasul		3843	3418	425
FAEM 006		3649	3479	170
FAEM 007		3891	3542	349
FAEM 4 Carlasul		3771	3510	261
FAEM 5 Chiarasul		3573	3574	1
IPR Afrodite		3711	3503	208
UPFA Gaudéria		3059	3468	409
UPFA Ouro		3085	3440	355
UPFPS Farroupilha		3597	3448	149
URS 21		3366	3341	25
URS Altiva		3738	3549	189
URS Brava		3618	3576	42
URS Charrua		3604	3460	144
URS Corona		3868	3426	442
URS Estampa		3213	3377	164
URS Fapa Slava		3159	3333	174
URS Guará		3676	3538	138
URS Guria		3426	3286	140
URS Tarimba		3444	3363	81
URS Taura		3081	3459	378
URS Torena		3334	3450	116
General Average		3601	3460	141

GY= grain yield (kg ha^{-1}); PRC= rainfall (mm); T$_{MIN}$= minimum temperature (°C); NLA= necrotic leaf area (cm²); NFA= number of fungicide applications (nº); GY$_E$= estimated grain yield; GY$_O$= observed grain yield.

Currently, several models have been used in order to seek the predictability of agricultural crops, however, not bringing elements of reality effectively. In this context, multiple linear regression has been used as an effective possibility, seeking such conditions (Mercante et al., 2010). It is a statistical model that requires the use of variables that are related to the dependent variable, a condition that can be determined through models that test and select variables that best respond to the elaboration of the multiple regression model, such as the variable selection technique Stepwise (Ribon et al., 2014). Junges & Fontana (2011) used multiple linear regression in the use of agrometeorological and spectral variables to estimate wheat grain yield and confirmed satisfactory results. Also in wheat, Alessi et al. (2021) simulated grain yield at harvest forecast considering ear components in single and fractional nitrogen supply doses, variables selected by the Stepwise technique. Torga et al. (2010), selected promising bean families for grain yield with ideal grain type using multiple linear regression with backward model selection using phenotypic information and molecular markers. Marolli et al. (2018) identified the thermal sum, rainfall, solar radiation, growth regulator dose and biomass cutting moment, qualifying the composition of the multiple linear regression model, in the simulation of oat biomass productivity. Given the importance of estimating the productivity of agricultural crops, it is evident that mathematical models can provide data to qualify forecasting systems, allowing the identification of factors that act throughout the crop development cycle (Rosa et al., 2015).

CONCLUSIONS

The cultivars FAEM 4 Carlasul, URS Altiva, URS Charrua and URS Guará showed superiority in grain yield without fungicide applications. With a single application, at 60 days after emergence, FAEM 4 Carlasul and URS Charrua showed productivity above 3000 kg ha^{-1} and with a long interval from application to harvest.

The variables minimum average temperature, necrotic leaf area and number of fungicide applications were found to be relevant for a multiple linear regression model to simulate grain yield.

The multiple regression model that was developed, considering the genetic individuality of the cultivar integrating meteorological conditions, fungal injury and fungicide management, was efficient for simulating grain yield.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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