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Brazilian Oat Cultivars Grown without Pesticides for Use in Agroecologically-Based Production Systems

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HIGHLIGHTS

- Meteorological conditions help control oat foliar diseases.
- Dimensioning the resistance to foliar diseases of oats in grain filling.
- Disease-resistant oat cultivars favor agroecological cultivation.
- Develop more sustainable agricultural systems with food security.

Abstract: Strategies for evaluating oat leaf diseases and using cultivars for pesticide-free growing enable more sustainable managements with food safety. The objectives of this study were to determine the optimal timing for assessing genetic variability of resistance to leaf diseases among Brazilian oat cultivars through analysis of necrotic leaf area; and identify the most suitable cultivars for agroecologically-based production systems through analysis of grain yield and necrotic leaf area using adaptability and stability parameters. The experiment was carried out in Augusto Pestana, RS, Brazil, using a randomized block design with three replications for evaluating 22 Brazilian oat cultivars (recommended and no longer recommended for cultivation) grown under no fungicide applications, from 2015 to 2020. Necrotic leaf area was measured at 60, 75, 90, 105, and 120 days after plant emergence (DAE), using the WinDIAS software (Copyright 2012, Delta-T Devices Limited); grain yield was determined after harvesting grains with approximately 15% moisture. Regarding the necrotic leaf area analysis, the highest genetic variability of resistance to leaf diseases in the Brazilian oat cultivars evaluated was observed between 90 and 105 DAE. Regarding grain yield and necrotic leaf area, the oat cultivars URS Altiva, URS Charrua, UPFPS Farroupilha, and UPFA Gauderia stood out as the most suitable genetic resources for agroecologically-based production systems.

Keywords: *Avena sativa* L.; herbicide; fungicide; food safety; Agenda 2030.

INTRODUCTION

White oat (*Avena sativa* L.) is one of the main species grown in southern Brazil and has become an important alternative for diversifying agriculture and contributing to the economy of the country due to its various purposes [1,2]. Large-scale cultivation of oats increases vulnerability to epidemic risks throughout the crop cycle, especially from pathogens that cause leaf diseases [3,4]. The fungi that cause crown rust (*Puccinia coronata Cda. f.sp. avenae*) and leaf spot [*Drechslera avenae (Eidam) El Sharif*] stand out among the foliar diseases due to their capacity to compromise the plant biological functions and grain yield [5, 6].

The most efficient method to control these diseases and ensure grain yield is the intensive use of fungicides [7, 8]. Increases in the severity of these diseases are favored by high temperatures and air humidity, which are conditions that usually occur during the flowering and grain-filling stages of the crop cycle [9, 2]. This implies the concentration of pesticide applications from these stages until close to the crop maturation stage, favoring the permanence of pesticide residues in oat grains [10, 11].

Considering that most of the oat grains produced are intended for human consumption, contaminated grains raise great concerns about public health, mainly due to the significant connection between pesticides and development of serious diseases, such as cancer [12, 13]. In addition to public health issues, the irresponsible use of pesticides causes environmental damage, including soil, water, and air pollution and loss of several animal species, such as those at the base of the food chain and the pollinating insects [14, 7].

The connection between development of diseases and exposure to pesticides, along with the growing ecological awareness, has caused an increasing demand for food produced through more sustainable processes, resulting in changes in consumer preferences connected to a greater concern for health and the environment [15, 16]. Consequently, the agroindustrial sector and farmers has converted conventional production systems to agroecologically-based or even organic production systems [17, 18]. Agroecologically-based production systems are promising alternatives to conventional practices, as they encompass practices that avoid the use of pesticides, minimize the use of external inputs, and limit application of mineral fertilizers, ensuring productivity with economic returns [19, 20]. Thus, the greater concern with health and consumption of healthier foods results in the need to develop more sustainable cropping systems that ensure food safety [21, 4]. The process of converting agricultural systems requires the evaluation and identification of factors that guide the application of measures that ensure the sustainability of the new system to be implemented [17, 22]. Several factors should be evaluated for this purpose, mainly those related to cultural practices, such as the use of resistant or tolerant cultivars to pests and diseases. The use of these cultivars makes agroecological and organic agriculture even more viable [23, 24].

A large number of white oat cultivars are recommended for cultivation in Brazil; these cultivars differ in cycle, height, genetic resistance to diseases, and responses to environmental changes [25, 26]. Identifying more stable cultivars with greater genetic resistance to leaf diseases and improved capacity to thrive under unfavorable environmental conditions, can promote more sustainable crops and facilitate the transition from conventional to agroecologically-based cultivation systems [15, 26]. These cultivars can be identified through analysis of adaptability and stability parameters that highlight genotypes that are less susceptible to leaf diseases and environmental variations [15, 27]. This analysis can be performed using the Eberhart and Russel model, which measures the response of each genotype to environmental variations based on regression coefficients estimated by an environmental index [28, 29].

The objectives of this study were to determine the optimal timing for assessing genetic variability of resistance to leaf diseases among Brazilian oat cultivars through analysis of necrotic leaf area; and identify the most suitable cultivars for agroecologically-based production systems through analysis of grain yield productivity and necrotic leaf area using adaptability and stability parameters in different agricultural years under no fungicide applications.

MATERIAL AND METHODS

Study area and experimental design

The experiment was conducted between 2015 and 2020, in Augusto Pestana, RS, Brazil (28°26'30'' S and 54°00'58''W). The soil in the experimental area is classified as a Typic Hapludox (Latossolo Vermelho

Distroferrico tipico) [30]. The climate of the region is humid subtropical, according to the Köppen classification. Soil analysis was carried out before sowing, presenting the following chemical characteristics in average years: pH = 6.3; P =34.1 mg/dm^3; K = 198 mg/dm^3; OM = 3.2%; Al = 0 cmol$_c$/dm^3; Ca = 6.5 cmol$_c$/dm^3, and Mg =2.5 cmol$_c$/dm^3. The plant population density used for sowing was 400 viable seeds m^{-2}, according to technical recommendation. Considering an expected grain yield of 3000 kg/ha, 10 kg/ha of nitrogen was applied at sowing, and the remainder was applied as topdressing when the plants were at the fourth expanded leaf stage. Furthermore, 45 and 30 kg/ha of P_2O_5 and K_2O, respectively, were applied at sowing based on the soil chemical analysis results. The control of weeds was carried out by planting soil cover crops in the summer, mainly buckwheat (*Fagopyrum esculentum* L), which has a rapid growth and effective soil cover, protecting against erosion and moisture loss, in addition to high competitive capacity against weeds and ease of decomposition, favoring nutrient cycling for the following crop [31].

The experiment was conducted in a randomized block design with three replications, evaluating 22 Brazilian oat cultivars grown in different agricultural years and under no fungicide applications. The evaluated oat cultivars include currently recommended cultivars (FAEM 4 Carlasul, IPR Afrodite, URS Altiva, URS Corona, URS Brava, URS Guara, URS Taura, UPFPS Farroupilha, UPFA Gauderia, and UPFA Ouro) and those no longer recommended for cultivation in Brazil (URS Estampa, URS Torena, URS Charrua, URS Guria, URS Tarimba, URS 21, URS Fapa Slava, FAEM 007, FAEM 006, FAEM 5 Chiarasul, Brisasul, and Barbarasul). The experimental plot consisted of 5 rows of 5 meters (m) in length, with spacing of of 0.2 m between rows to compose an area of 5 m^2.

Data measurement

Three plants were randomly collected from each plot and the three upper leaves were removed from each plant. This procedure was carried out at 60, 75, 90, 105, and 120 days after plant emergence to analyze necrotic leaf area in all cultivars. Then, the leaves were taken to a laboratory where they were scanned and the resulting images were analyzed using a leaf area reader and the software WinDIAS (Copyright 2012, Delta-T Devices Limited) to determine the extent of necrosis caused by the disease on the total leaf area.

The 3 central rows of each plot were considered as evaluation area for estimating grain yield. Mechanized harvesting was performed when the grains had approximately 15% moisture. The grains were taken to the laboratory for correcting moisture to 13%; then they were threshed and weighed to obtain the grain yield in grams, which was converted to kg/ha.

Statistical analysis

The oat cultivars were classified as superior (^{S}) and inferior (^{I}) regarding necrotic leaf area and grain yield in each agricultural year, considering one standard deviation (SD) above or below the mean (mean±SD). Regarding necrotic leaf area, ^{S} cultivars were those presenting one SD below the mean (mean−SD), whereas ^{I} cultivars were those with one SD above the mean (mean+SD). Regarding grain yield, ^{S} and ^{I} cultivars were those with mean+SD and mean−SD, respectively. The optimal timing for evaluating genetic variability of disease resistance through analysis of necrotic leaf area was determined based on the variance magnitude at each evaluation.

The identification of white oat cultivars with greater adaptability and stability to environmental variations in the agricultural year was carried out by subjecting the data obtained from necrotic leaf area and grain yield to the Eberhart and Russell model, according to the following equation:

$$Y_{ij} = b_{0i} + b_{1i} I_j + \delta_{ij} + \bar{\varepsilon}_{ij} \quad (1)$$

where: Y_{ij} is the mean of genotype i under conditions of environment j, b_{0i} is the overall mean of genotype i, b_{1i} is the linear regression coefficient that measures the response of i-th genotype to environmental variations, I_j is the standardized environmental index, δ_{ij} represents the deviations from linear regression and $\bar{\varepsilon}_{ij}$ is the mean experimental error.

A cultivar is considered stable when $\delta_{ij} = 0$ and unstable when $\delta_{ij} \neq 0$. According to this methodology, adaptability is the capacity of genotypes to benefit from environmental stimuli under particular conditions. A cultivar has a wide adaptability when $b_{1i} = 1$; specific adaptability to favorable environmental conditions when $b_{1i} > 1$; and specific adaptability to unfavorable environmental conditions when $b_{1i} < 1$. The hypothesis testing that the regression coefficients are not significantly different from 1 was evaluated by the t test, whereas the F test was used to analyze the hypothesis that the regression deviations of each cultivar are not significantly different from zero. Additionally, the Scott and Knott test at 5% error probability level was applied to compare the means among cultivars. All statistical analyses were performed using the open-source software GENES [32].

RESULTS

Meteorological conditions

Regarding 2015 (Table 1), the total rainfall volume was slightly higher than the historical average of the last 30 years, with high rainfall depths during early crop growth stage (Figure 1 A). An adequate soil moisture was found during the management of soil nitrogen application due to rainfall depths that occurred before nutrient applications. Environmental conditions ranging from moderate to high temperatures, air humidity, and rainfall depths, concentrated mainly during the early crop cycle, resulted in an unfavorable environment for plant development, butt favorable for the development of leaf diseases. The strong action of the disease resulted in large necrotic leaf areas, affecting grain yield (1,229 kg/ha), which was lower than that expected (3,000 kg/ha) (Table 1). This justified the categorization of 2015 as an unfavorable year (UY) for oat cultivation and favorable year (FY) for leaf disease development.

Table 1. Data on temperatures, relative air humidity (RH), and rainfall depths recorded in the months of oat cultivation, and means for grain yield and necrotic leaf area for the evaluated oat cultivars.

Month	Mean temperature (°C)			Mean RH (%)			Rainfall (mm)		GY	NLA	Class	
	Min	Max	Mean	Min	Max	Mean	last 30 years*		(kg/ha)	(%)	P	D
2015												
May	13	23	18	68	96	82	161	181				
June	10	21	16	67	96	82	141	228				
July	11	21	16	67	95	81	131	211				
August	13	25	19	58	93	76	111	86	1229	70	UY	FY
September	13	21	17	57	94	76	149	127				
October	15	25	20	47	92	70	227	161				
Total	-	-	-	-	-	-	920	994				
2016												
May	11	21	16	65	95	80	161	55				
June	5	19	12	54	94	74	141	10				
July	9	22	15	60	92	76	131	80				
August	9	23	16	60	92	76	111	160	3206	11	FY	UY
September	8	23	16	53	90	72	149	56				
October	12	25	19	53	91	72	227	326				
Total	-	-	-	-	-	-	920	687				
2017												
May	14	22	18	72	92	82	161	434				
June	11	22	16	64	92	78	141	146				
July	8	24	16	43	89	66	131	10				
August	11	24	18	54	91	73	111	117	1146	99	UY	FY
September	15	27	21	60	91	76	149	161				
October	14	27	20	56	92	74	227	304				
Total	-	-	-	-	-	-	920	1172				
2018												
May	13	26	20	59	93	76	161	63				
June	7	19	13	67	95	81	141	104				
July	9	20	15	66	95	81	131	80				
August	6	20	13	58	93	76	111	107	923	100	UY	AF
September	13	25	19	58	94	76	149	184				
October	16	25	20	47	92	70	227	243				
Total	-	-	-	-	-	-	920	780				
2019												
May	14	22	18	68	96	82	161	202				
June	12	24	18	50	92	71	141	55				
July	8	19	13	55	94	74	131	90				
August	8	22	15	48	92	70	111	69	736	94	UY	FY
September	11	24	17	48	91	69	149	99				
October	15	28	21	47	90	68	227	236				
Total	-	-	-	-	-	-	920	751				

Cont. Table 1

2020												
May	9	22	15	57	95	76	161	173				
June	11	21	16	72	94	83	141	291				
July	8	19	13	68	95	81	131	336				
August	10	23	16	58	93	76	111	156	982	97	UY	FY
September	12	25	18	60	94	77	149	48				
October	14	30	22	44	91	67	227	52				
Total	-	-	-	-	-	-	920	1056				

Min = minimum; Max = maximum; * = average rainfall over the last 30 years; GY = grain yield; NLA = necrotic leaf area evaluated at 105 days after emergence; FY = favorable year; UY = unfavorable year; P = plant; D = disease.

The year 2016 (Table 1) had lower temperatures, which were relatively stable throughout the crop cycle. The total rainfall volume was lower than the historical rainfall average, but it was adequately distributed (Figure 1 B). Temperatures and rainfall depths were mild throughout the crop cycle. These weather conditions were not favorable for leaf disease development, thus resulting in a decrease in the mean necrotic leaf area for the oat cultivars. Lower rainfall depths occurred before and after soil nitrogen application, reducing leaching losses, which favored greater absorption and use of the nutrient by the plants (Figure 1 B). The mean grain yield in 2016 was 3,206 kg/ha (Table 1), which was higher than that expected (3,000 kg/ha), probably due to the supply of N. This high grain yield denoted that 2016 was FY for oat cultivation and, therefore, UY for leaf diseases, although the crops grew under non-application of pesticides.

The air temperatures in 2017 were high and highly unstable throughout the crop cycle, mainly during the vegetative stage, with some occurrences of negative minimum temperatures. Rainfall depths were significantly low during the crop cycle, especially during the early crop stages, with more significant depths recorded during the grain filling stage. Conditions of low soil moisture and high air temperatures also did not favor soil nitrogen application management (Figure 1 C), contributing to nutrient losses by volatilization. All these prevailing conditions favored high means of leaf necrosis, decreasing grain yield (1,146 kg/ha), which was significantly lower than that expected (3,000 kg/ha) (Table 1). These results contributed to classify 2017 as UY for oat cultivation (UY) and FY for leaf diseases.

Regarding 2018, the rainfall volume was below the 30-year historical average (Table 1), and although it was adequately distributed throughout most of the crop cycle, it was concentrated more towards the end of the crop development stage. These rainfall prevailing conditions and increased air temperatures favored greater leaf disease severity, which was confirmed by high means of leaf necrosis (Table 1). Furthermore, the soil moisture conditions were not suitable for soil nitrogen applications, which compromised the efficiency of N absorption and transformation necessary for optimal grain yield (Figure 1 D). The results of grain yield and necrotic leaf area contributed to classify 2018 as UY for oat cultivation and FY for leaf disease development.

Lower air temperature means were recorded in July and August 2019. Although these conditions favored the restriction of the development of leaf diseases, the high temperatures during the other months of the year created a favorable environment for fungi. The rainfall volume was below the historical average, however, adequately distributed throughout most of the crop cycle, except during the beginning of crop development, resulting in unfavorable conditions for soil nitrogen applications. High rainfall depths were recorded after soil nitrogen application (Figure 1 E), which may have contributed to N leaching and runoff, thus resulting in a decreased grain yield. The means found for grain yield and necrotic leaf area favored the classification of 2019 as UY for oat cultivation (UY) and FY for leaf diseases.

A large rainfall volume was recorded in 2020 during the early crop development stage. The initial conditions were favorable for soil nitrogen application management; however, a prolonged dry spell occurred from 50 days after sowing, compromising the tillering, elongation, and grain filling stages of the crop, directly affecting grain yield (Figure 1 F). Higher temperatures were also recorded during these crop stages, favoring the progress of leaf diseases (Table 1). The combination of these factors favored a decreased grain yield and increased necrotic leaf area, which justifies the classification of 2020 as UY for oat cultivation and FY for leaf disease development.

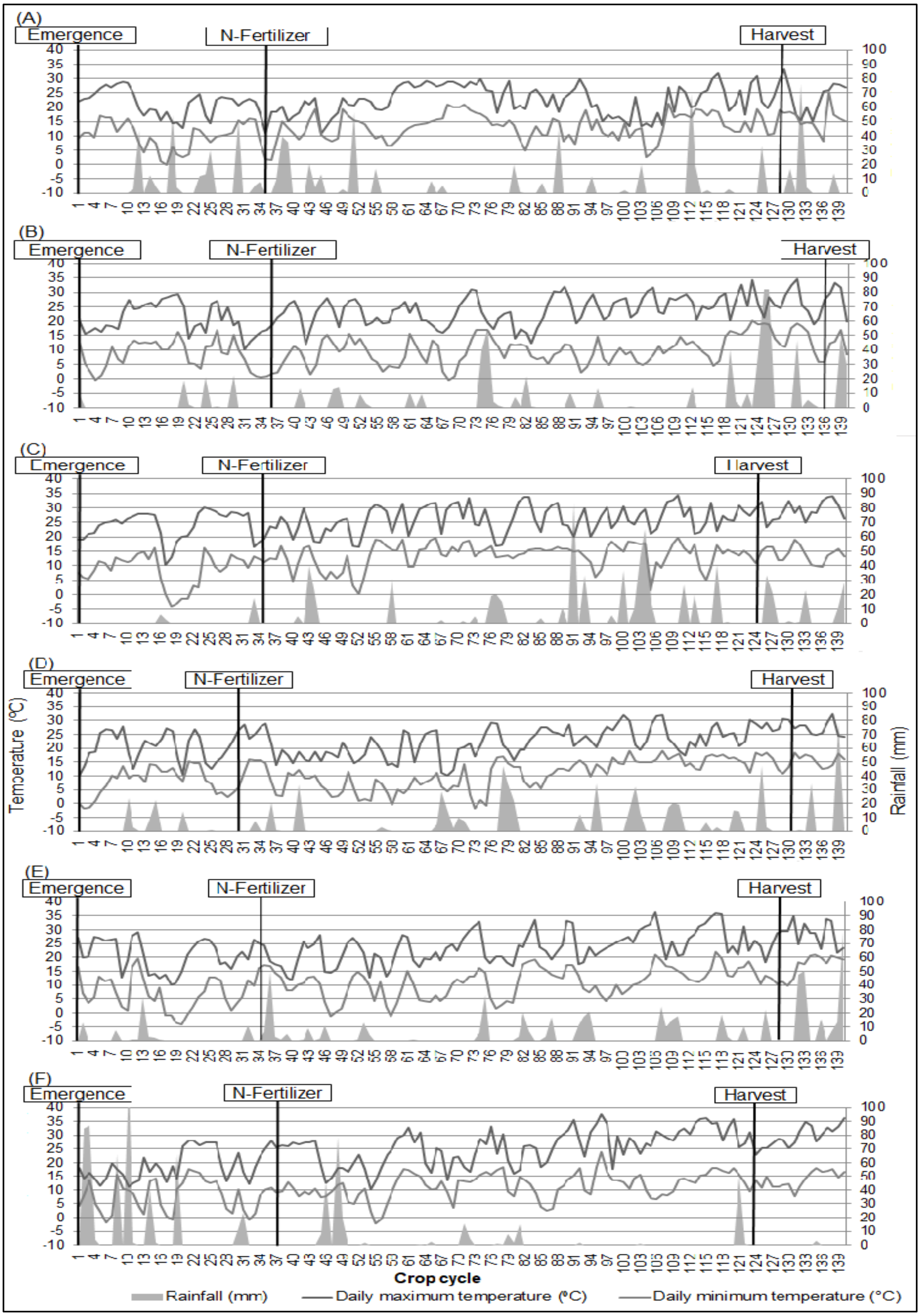

Figure 1. Rainfall depths and minimum and maximum temperatures during oat crop cycles in different agricultural years. (A) 2015; (B) 2016; (C) 2017; (D) 2018; (E) 2019; (F) 2020.

Evaluation of necrotic leaf area

In Table 2, the evaluation of necrotic leaf area at 60 days after emergence (DAE) showed low or no disease action in all agricultural years, denoting unfavorable environmental conditions for the fungus, thus characterizing an inappropriate timing for analysis of genetic variability of resistance to the disease. Considering the different agricultural years, the overall means of leaf necrosis were low at 75 DAE, however, the onset of disease progression was identified from this stage onwards. The results denoted that oat cultivars showed greater susceptibility to the disease when they were at early development stages (elongation), however, this does not represent the most appropriate timing to measure the genetic resistance of oat cultivars to the disease.

Table 2. Necrotic leaf area (%) throughout the crop cycle in oat cultivars grown under no fungicide application.

Oat cultivars	NLA$_{2015(FY)}$					NLA$_{2016(UY)}$					NLA$_{2017(FY)}$				
	60	**75**	**90**	**105**	**120**	**60**	**75**	**90**	**105**	**120**	**60**	**75**	**90**	**105**	**120**
URS Altiva	0	1^{S}	51	69	100	0	0	3	7	39	1	3^{S}	28	98	100
URS Brava	0	1^{S}	36	53	100	0	0	4	7	37	2	5	43	99	100
URS Guara	0	15	54	76	100	0	0	3	6	46	2	6	42	98	100
URS Estampa	0	27	32	35^{S}	100	0	6	9	13	38	1	5	39	99	100
URS Corona	2	16	51	98	100	0	0	4	9	37	1	4	22^{S}	99	100
URS Torena	0	9	53	69	100	0	0	2^{S}	4^{S}	42	2	5	36	99	100
URS Charrua	0	11	49	63	100	0	1	8	18	43	1	4	29	99	100
URS Guria	0	23	51	62	100	0	0	5	8	51	1	6	47	98	100
URS Tarimba	0	25	47	59	100	0	1	9	20	48	1	9	38	99	100
URS Taura	0	23	68	89	100	1	3	6	13	49	2	8	31	99	100
URS 21	0	5	42	65	100	0	1	6	14	44	1	3^{S}	69	99	100
FAEM 007	0	2^{S}	40	88	100	0	3	7	15	38	1	12	49	99	100
FAEM 006	0	4	40	97	100	0	0	8	18	45	2	8	48	99	100
FAEM 5 Chiarasul	0	6	62	96	100	0	1	2^{S}	4^{S}	45	1	4	38	98	100
FAEM 4 Carlasul	0	1^{S}	42	75	100	0	0	2^{S}	3^{S}	41	1	3^{S}	31	99	100
Brisasul	1	4	24^{S}	37^{S}	100	2	4	5	6	36	1	3^{S}	31	99	100
Barbarasul	1	4	45	86	100	0	1	2^{S}	5	52	1	3^{S}	38	99	100
URS Fapa Slava	0	29	46	52	100	0	0	15	32	38	2	5	43	99	100
IPR Afrodite	1	2^{S}	61	94	100	0	0	3	5	34^{S}	1	4	16^{S}	99	100
UPFPS Farroupilha	0	5	38	64	100	0	1	3	8	37	1	3^{S}	38	99	100
UPFA Ouro	0	3	20^{S}	30^{S}	100	0	1	5	10	38	1	3^{S}	60	99	100
UPFA Gauderia	0	12	17^{S}	27^{S}	100	0	1	3	6	26^{S}	1	4	52	99	100
Mean	0	10	44	67	100	0	1	5	11	41	1	5	39	99	100
σ^2	1	64	169	484	0	0	4	9	49	36	0	4	144	0	0

Oat Cultivars	NLA$_{2018(FY)}$					NLA$_{2019(FY)}$					NLA$_{2020(FY)}$				
	60	**75**	**90**	**105**	**120**	**60**	**75**	**90**	**105**	**120**	**60**	**75**	**90**	**105**	**120**
URS Altiva	1	2	52	100	100	0	4	36	99	100	1	3	31	97	100
URS Brava	1	3	56	100	100	1	5	38	96	100	1	2	21	93	100
URS Guara	1	2	78	100	100	1	4	35	100	100	1	6	34	99	100
URS Estampa	1	5	57	100	100	1	1	49	98	100	0	3	6^{S}	99	100
URS Corona	0	1^{S}	50	100	100	0	2^{S}	43	98	100	1	1^{S}	13	97	100
URS Torena	1	3	54	100	100	1	6	48	97	100	1	4	17	94^{S}	100
URS Charrua	0	3	40^{S}	100	100	0	5	59	99	100	1	2	20	99	100
URS Guria	0	3	77	100	100	1	5	53	99	100	1	4	28	98	100
URS Tarimba	0	4	78	100	100	1	11	56	96	100	1	1^{S}	13	93^{S}	100
URS Taura	1	4	68	100	100	0	8	56	99	100	1	6	15	93^{S}	100
URS 21	0	3	74	100	100	0	8	33	99	100	0	2	17	99	100
FAEM 007	2	10	55	100	100	0	7	33	96	100	1	3	21	99	100
FAEM 006	1	1^{S}	58	100	100	1	18	56	99	100	1	8	15	100	100
FAEM 5 Chiarasul	1	3	45	100	100	0	2^{S}	66	99	100	0	2	18	99	100
FAEM 4 Carlasul	0	2	47	100	100	0	5	53	95	100	0	0^{S}	20	97	100
Brisasul	1	6	50	100	100	1	8	44	91^{S}	100	0	6	24	97	100
Barbarasul	1	2	74	100	100	1	8	60	98	100	0	3	38	98	100
URS Fapa Slava	1	4	41^{S}	100	100	1	8	73	99	100	1	4	16	96	100
IPR Afrodite	1	5	45	100	100	1	6	33	94	100	0	2	15	96	100
UPFPS Farroupilha	1	16	46	100	100	1	9	42	89^{S}	100	0	1^{S}	14	93^{S}	100
UPFA Ouro	2	4	67	100	100	1	12	43	85^{S}	100	1	4	15	100	100
UPFA Gauderia	0	7	47	98	100	1	2^{S}	12^{S}	99	100	0	2	20	97	100
Mean	1	4	57	100	100	1	7	46	97	100	1	3	20	97	100
σ^2	1	9	169	0	0	0	16	196	16	0	1	4	64	4	0

60, 75, 90, 105, and 120 = days after plant emergence, in which the necrotic leaf area was evaluated; σ^2 = variance; ^{S} = superior cultivar based one standard deviation below the mean; NLA = necrotic leaf area (%); UY = unfavorable year for leaf diseases; FY = favorable year for leaf diseases.

The evaluation of unfavorable year (UY) for oat crops and favorable year (FY) for leaf disease development showed that the highest variance was found at 90 DAE, except for 2015. The evaluation carried out at 105 DAE showed low or no variability among cultivars for necrotic leaf area, which caused impairment close to or equal to 100%. However, unfavorable weather conditions for plant development in these years may also have caused an acceleration in the crop cycle due to high temperatures, or even plant death due to inadequate soil moisture. This makes the analysis of the impact of the disease on the leaf area challenging, as the effects caused by fungi can be confused with those caused by weather conditions.

Regarding 2015 and 2016, which were considered favorable and unfavorable years for leaf disease development, respectively, the highest variance among cultivars was found at 105 DAE. The year 2016 stood out for presenting low means of necrotic leaf area and reduced disease progress, resulting in natural control of disease due to milder temperatures throughout the crop cycle. Thus, the period between 90 and 105 DAE is considered the optimal timing for analyzing the genetic variability of resistance to the main leaf diseases among Brazilian oat cultivars.

Regarding the expression of necrotic leaf area in oat plants grown in 2015, the cultivars with the highest resistance to leaf diseases and, therefore, classified as superior based on one standard deviation below the mean (mean−SD) were Brisasul, UPFA Ouro, and UPFA Gauderia. Regarding 2016, which had unfavorable environmental conditions for leaf disease progress, the cultivars classified as superior were URS Torena, FAEM 5 Chiarasul, and FAEM 4 Carlasul. The superior oat cultivars in the following years were: URS Altiva, URS Corona, URS 21, FAEM 4 Carlasul, Brisasul, Barbarasul, IPR Aphrodite, UPFPS Farroupilha, and UPFA Ouro in 2017; URS Corona, URS Charrua, FAEM 006, and URS Fapa Slava in 2018; UPFA Gauderia in 2019, which presented the lower necrotic leaf area at 75 and 90 DAE; and URS Tarimba and UPFPS Farroupilha in 2020 for presenting the lowest necrotic leaf area at 75 and 105 DAE.

Overall, the cultivars that showed lower means of necrotic leaf area in one year did not necessarily maintain the same ranking under other situations. The cultivars that were consistently superior were FAEM 4 Carlasul and UPFA Gauderia (in five evaluations) followed by URS Corona, Brisasul, UPFPS Farroupilha, and UPFA Ouro (in four evaluations).

Analysis of adaptability and stability for necrotic leaf area

Considering the evaluation at 90 DAE (Table 3), the superior cultivars for presenting smaller necrotic leaf area were Brisasul, IPR Aphrodite, UPFPS Farroupilha, and UPFA Gauderia. The cultivar Brisasul showed specific adaptability, with stability, to unfavorable environments, whereas UPFA Gauderia showed specific adaptability with instability. The cultivar IPR Aphrodite showed a wide adaptability with instability, whereas UPFPS Farroupilha was the only cultivar that showed overall adaptability with stability. Considering the evaluation of necrotic leaf area at 105 DAE, the superior cultivars were URS Brava, URS Estampa, Brisasul, UPFPS Farroupilha, UPFA Ouro, and UPFA Gauderia. The cultivars URS Brava, URS Estampa, and UPFA Ouro showed overall adaptability with instability. Brisasul and UPFA presented specific adaptability to favorable environments, with instability, whereas UPFPS Farroupilha presented overall adaptability with stability.

Table 3. Parameters of adaptability and stability for necrotic leaf area in oat cultivars as a function of agricultural years, without fungicide application.

Oat Cultivars	$NLA_{90\ DAE}$ (%)					$NLA_{105\ DAE}$ (%)				
	b_0	b_1	δ^2	R^2	MS	b_0	b_1	δ^2	R^2	MS
(2015+2016+2017+2018+2019+2020)										
URS Altiva	33b	0.82^{*}	65^{*}	77	281^{*}	78b	1.04	-5	99	7
URS Brava	32b	0.90	-3	93	74	$74c^{S}$	1.05	27^{*}	98	104^{*}
URS Guara	$41a^{I}$	1.14^{*}	135^{*}	78	491^{*}	80b	1.04	14^{*}	98	67^{*}
URS Estampa	32b	0.99	47^{*}	85	227^{*}	$74c^{S}$	1.04	225^{*}	88	700^{*}
URS Corona	31b	0.97	74^{*}	81	308^{*}	$83a^{I}$	0.96	186^{*}	88	583^{*}
URS Torena	34b	1.07	-1	95	80	77b	1.06^{*}	-1	99	17
URS Charrua	34b	0.82^{*}	107^{*}	69	407^{*}	79b	0.93^{*}	6	99	40
URS Guria	$43a^{I}$	1.25^{*}	-6	97	65	77b	1.03	-1	99	19
URS Tarimba	$40a^{I}$	1.30^{*}	39^{*}	92	204^{*}	77b	0.89^{*}	21^{*}	97	87^{*}
URS Taura	$40a^{I}$	1.30^{*}	105^{*}	85	400^{*}	$82a^{I}$	0.92^{*}	83^{*}	93	272^{*}
URS 21	$40a^{I}$	1.17^{*}	252^{*}	69	843^{*}	79b	0.98	-1	99	17
FAEM 007	34b	0.90	37	85	196	$82a^{I}$	0.92^{*}	65^{*}	94	217^{*}
FAEM 006	37a	1.05	11	92	120	$85a^{I}$	0.88^{*}	133^{*}	89	423^{*}
FAEM 5 Chiarasul	38a	1.10	164^{*}	74	578^{*}	$82a^{I}$	1.03	176^{*}	90	552^{*}

Cont. Table 3

FAEM 4 Carlasul	32b	0.92	15	90	131	78b	1.06*	13*	98	64*
Brisasul	29b^{S}	0.75*	35	80	189	71d^{S}	1.08*	161*	91	506*
Barbarasul	42a^{I}	1.15*	76*	85	315*	80a	1.03	79*	95	260*
URS Fapa Slava	39a	0.86	208*	59	710*	79b	0.79*	102*	90	330*
IPR Afrodite	28b^{S}	0.88	200*	61	685*	81a^{I}	1.00	166*	90	522*
UPFPS Farroupilha	30b^{S}	0.87	-17	97	31	75c^{S}	1.00	1	99	28
UPFA Ouro	35b	1.07	252*	65	842*	75d^{S}	1.05	291*	85	896*
UPFA Gauderia	26b^{S}	0.62*	243*	40	814*	75d^{S}	1.11*	316*	85	971*
Mean	35					78				
Standard deviation	5					3				

Means followed by the same letter in the column do not differ significantly from each other by the Scott and Knott test at 5% error probability; DAE = days after plant emergence; $NLA_{90\ DAE}$ (%) = necrotic leaf area evaluated at 90 DAE; $NLA_{105\ DAE}$ (%) = necrotic leaf area evaluated at 105 DAE; b_0 = overall mean of the cultivar; b_1 = linear regression coefficient; δ^2 = regression deviation; R^2 = coefficient of determination (%); MS = mean square of the source of variation; * = significant at 5% error probability by the t-test for regression coefficient and by the F-test for regression deviations and mean square; ^{S} = superior cultivar based on one standard deviation (SD) below the mean; ^{I} = inferior cultivar based on one SD above the mean; SD = standard deviation.

Considering the evaluations at 90 and 105 DAE, the oat cultivars Brisasul and UPFA Gauderia showed the smallest necrotic leaf area with specific adaptability to favorable environments, with instability. In this sense, UPFPS Farroupilha also showed superiority in both evaluations; however, it stood out for maintaining a trend of wide adaptability with stability. These results of necrotic leaf area in both evaluations denoted that these three superior cultivars have the potential to better withstand pressures from pathogens, mainly UPFPS Farroupilha, which had a stable performance and a greater response to environmental stimuli on leaf diseases.

Grain yield

Table 4 shown the means for grain yield of oat cultivars grown under no fungicide application. The cultivars that show superiority for presenting the smallest necrotic leaf areas (Table 3) were not necessarily those that presented the highest grain yields.

Table 4. Grain yield of oat cultivars grown under no fungicide application in different agricultural years.

Oat Cultivars	Grain Yield (kg/ha)						nS
	2015$_{(AD)}$	**2016$_{(AF)}$**	**2017$_{(AD)}$**	**2018$_{(AD)}$**	**2019$_{(AD)}$**	**2020$_{(AD)}$**	
URS Altiva	2321^{S}	2893	1103	1535^{S}	1097^{S}	1143	3
URS Brava	1230	3298	1024	1477^{S}	825	1046	1
URS Guara	1486	3553	1138	1310^{S}	746	728^{I}	1
URS Estampa	1555	3266	790^{I}	1173	719	1068	0
URS Corona	804	3780^{S}	976	1153	702	1025	1
URS Torena	1348	2861	859^{I}	1087	556	1376^{S}	1
URS Charrua	1616	3584	983	741	1026^{S}	1166	1
URS Guria	1949^{S}	2311^{I}	1150	670	507	1088	1
URS Tarimba	1386	3350	910^{I}	635^{I}	655	568^{I}	0
URS Taura	863	2231^{I}	1069	1078	645	765	0
URS 21	1552	3312	1025	1099	672	753^{I}	0
FAEM 007	579^{I}	3752^{S}	1436^{S}	716	678	801	2
FAEM 006	749^{I}	3461	1340	773	867	990	0
FAEM 5 Chiarasul	727^{I}	3036	1380^{S}	803	540^{I}	766	1
FAEM 4 Carlasul	1352	3802^{S}	1620^{S}	767	572	713^{I}	2
Brisasul	1066	3362	1031	676	594	1009	0
Barbarasul	680^{I}	3358	1220	729	555	771	0
URS Fapa Slava	1189	2081^{I}	954	740	536^{I}	857	0
IPR Afrodite	566^{I}	4096^{S}	1199	690	774	1103	1
UPFPS Farroupilha	1324	3354	1459^{S}	691	747	1309^{S}	2

Cont Table 4

UPFA Ouro	1386	2736	1237	797	1031[S]	1281[S]	2
UPFA Gauderia	1308	3055	1317	975	1140[S]	1267[S]	2
Mean	1229	3206	1146	923	736	982	
Standard deviation	448	522	213	274	190	227	

[S] = superior cultivar based on one standard deviation (SD) above the mean; [I] = inferior cultivar based on one SD below the mean; FY = favorable year for oat cultivation; UY = unfavorable year for oat cultivation; nS = number of evaluations in which the cultivar showed superiority over the agricultural years.

Overall, the cultivar URS Altiva had the greatest number of highest grain yield means (3), followed by FAEM 007, FAEM 4 Carlasul, UPFPS Farroupilha, UPFA Ouro, and UPFA Gauderia (2). It is important to emphasize the particular environmental conditions in 2016, when the mean grain yield was higher than 3,000 kg/ha and some cultivars even reached 4,000 kg/ha, without fungicide application. This reinforces the great potential of weather conditions to contribute to the natural control of leaf diseases and better use of natural resources by plants to improve crop yields.

Analysis of adaptability and stability for grain yield

Regarding the analysis of adaptability and stability for grain yield (Table 5), the cultivars URS Altiva, URS Charrua, UPFPS Farroupilha, and UPFA Gauderia showed superiority (mean+SD); however, according to the multiple mean comparison test, only URS Altiva was significantly different from the other cultivars. URS Altiva showed specific adaptability to unfavorable environments, with instability in the growing season. Cultivar URS Charrua showed specific adaptability to favorable environments, but also with instability.

Table 5. Adaptability and stability parameters for grain yield of oat cultivars as a function of agricultural years, without fungicide application.

Cultivars	Grain Yield (kg/ha)				
	b_0	b_1	δ^2	R^2	MS
	(2015+2016+2017+2018+2019+2020)				
URS Altiva	1781a[S]	0.69*	198515*	70	631443*
URS Brava	1483b	0.96	53011*	93	194930*
URS Guara	1493b	1.12*	46578*	95	175631*
URS Estampa	1428b	1.00	59774*	93	215219*
URS Corona	1406b	1.24*	69612*	95	244734*
URS Torena	1314c	0.85*	39644*	93	154829*
URS Charrua	1619b[S]	1.11*	57048*	95	202186*
URS Guria	1279c	0.63*	198426*	66	631174*
URS Tarimba	1250c	1.15*	31146*	96	129335*
URS Taura	1108d	0.60*	15230	93	81588
URS 21	1402b	1.05	36175*	96	144420*
FAEM 007	1227c	1.29*	115748*	93	383140*
FAEM 006	1363b	1.11*	68268*	94	240699*
FAEM 5 Chiarasul	1208c	0.99	57153*	93	207356*
FAEM 4 Carlasul	1471b	1.29*	57029*	96	206983*
Brisasul	1289c	1.12*	-292	99	35017
Barbarasul	1118c	1.14*	41696*	96	160986*
URS Fapa Slava	1059d	0.58*	7718	94	59050
IPR Afrodite	1404b	1.41*	132767*	93	434199*
UPFPS Farroupilha	1518b[S]	1.03	42574*	95	163617*
UPFA Ouro	1410b	0.72*	17510*	95	84568*
UPFA Gauderia	1516b[S]	0.82*	6337	97	54907
Mean	1370				
Standard Deviation	145				

[S] = superior cultivar based on one standard deviation above the mean. Means followed by the same letter in the column do not differ significantly from each other by the Scott and Knott test at 5% error probability; b_0= overall mean of the cultivar; b_1 = linear regression coefficient; δ^2 = regression deviation; R² = coefficient of determination (%); MQ = mean square of the source of variation; * = significant at 5% error probability by the t-test for regression coefficient and by the F-test for regression deviations and mean square.

The oat cultivar UPFPS Farroupilha showed overall adaptability to environmental stimuli, with instability. UPFA Gauderia showed specific adaptability to unfavorable environments, with stability. Overall, these four cultivars are noteworthy genetic resources for the production of oat grains in agroecologically-based production systems. The possibility of greater adaptation to significant unfavorable conditions, with stability in grain yield, makes UPFA Gauderia a prominent cultivar. In addition, the analyses of adaptability and stability for necrotic leaf area and grain yield showed superiority of the cultivars UPFPS Farroupilha and UPFA Gauderia.

DISCUSSION

Weather conditions have a significant impact on yield of agricultural crops, mainly oats, which require mild temperatures and low rainfall volume with an adequate distribution throughout the crop cycle [33, 34]. Mild temperatures and high-quality solar radiation favor tillering and grain filling in oat plants. However, air temperatures below 2 °C or 3 °C around the crop flowering stage can damage leaves and stems and cause sterility of flowers [35, 36]. Low temperatures can be also damaging during the grain formation stage, when frosts can cause growth paralysis and result in production of wrinkled and underweight grains [37, 38]. Studies have shown that mild temperatures during the vegetative stage of oat crops-which characterizes the differentiation of spikelet cells-are a decisive factor for increasing the number of grains per panicle [39, 40].

Rainfall is the meteorological variable that most affects crop yields, as it is directly connected to plant development and significantly impacts the efficiency in nitrogen use, mainly when considering that N is the macronutrient that most affects crop yields [41, 42]. The management of soil nitrogen applications requires adequate soil moisture and low volumes and intensity of rainfall after application to avoid leaching [43, 44]. Oat crops do not require a large rainfall volume to ensure high crop yield, which was found in the present study, as well-distributed rainfall that favors adequate soil moisture is satisfactory for the processes of crop development [45, 46].

The relative air humidity is also an important factor for the success of oat crops, as it affects the fertilization and fertility of the spikelets [47, 48]. In addition, high air humidity is directly connected to development of diseases, such as crown rust and leaf spot [5, 8]. The parasite that causes crown rust survives in the crop by infecting volunteer plants that remain in the field after harvesting [3, 4]. It is a disease that completes its cycle in 7 to 10 days, when the infection by the pathogen induces several structural, biochemical, and physiological changes in the plant, directly affecting the grain quality and yield [49, 50]. New infections and greater potential damage from the disease are favored under mean temperatures above 18 °C and high relative humidity (above 90%) [51, 5]. The development of the fungus responsible for causing leaf spot is favored by high air humidity and temperatures between 18 °C and 28 °C, causing the development of large or elliptical leaf spots that are brown or purple in color [50, 5]. Leaf blight symptoms can affect up to 100% of the plants and result in decreases in crop yield ranging from 10% to 40% [52, 4]. The disease reaches the panicle when the infection is severe, favoring the occurrence of dark grains and production of aflatoxins, which cause deterioration, compromising the commercialization of the grains, as they are not useful for the food industry [53, 54].

Agroecologically-based food production systems often result in lower crop yields when compared to conventional systems due to a greater disease pressure and control difficulties, however, they can provide higher economic income due to the higher value of the product [55, 56]. Furthermore, there is a growing trend in the consumer market for food free from contaminants, especially those that ensure the safety of food for human consumption [57, 16]. Several studies have reported that conventional systems based on application of pesticides are directly connected to public health problems, such as cancer, diabetes, respiratory and neurological disorders, and reproductive syndromes [58, 13]. Conducting qualified studies focused on understanding the genetic resources available in different crops is important for a better adjustment of the interaction between cultivars and cropping systems [15, 59].

Studies have shown that when oat cultivars susceptible to the fungus responsible for causing crown rust are subjected to favorable environmental conditions for the pathogen development, they can have decreases in grain yield of more than 50% [60, 61]. Considering leaf spot and favorable conditions for the fungus, the decreases in grain yield can range from 10% to 50% [54]. In this context, growing oat cultivars with greater resistance to leaf diseases can ensure high grain yields under reduced and/or no pesticide applications, especially for agroecologically-based crops.

Genetic breeding programs usually seek to develop new cultivars through the use of resistance genes, often using vertical (qualitative) resistance [4, 3]. Vertical resistance is characterized by one or a few genes of greater effect and contributes to the reduction and/or delay in the onset of the epidemic or the progression of the inoculum. However, these cultivars have resistance to specific races of pathogens and remain susceptible to other races that may arise when they are cultivated on a large scale [62, 63]. Thus, the selection pressure on the pathogen promotes the emergence of new races, leading to susceptibility of cultivars a few years after their commercial release [64, 63]. Contrastingly, horizontal resistance provides control against a greater number of pathogen races, as it is based on the incorporation of several genes with smaller effects, showing greater resistance durability for cultivars that are cultivated on a large scale [65]. In this context, the coexistence of the cultivar with the inoculum is necessary, as the beginning of the pathogen's development is a necessary stimulus to trigger the plant's defense mechanisms [4, 66]. These factors slow down the development process of a cultivar, requiring several years of study and, therefore, making it unviable to release new materials in a short period of time [67, 68].

In addition to the development of new cultivars with greater resistance, studies have sought other alternatives for enhancing cultivation conditions without using agrochemicals. The use of resistance inducers and the method of natural disease control through an escape zone are among these alternatives. Resistance inducers are natural or synthetic compounds that can activate defense responses in plants that are similar to those induced by pathogen infections, thus preventing or delaying infection [69, 70]. The escape zone is a natural method for controlling diseases that occurs by identifying low phytosanitary risk zones, i.e., by defining a cultivation period that presents unfavorable weather conditions for the development of fungi (pathogens), mainly during the stages of elongation and the beginning of grain filling [71, 72].

Identifying cultivars that are more resistant to diseases and with greater capacity to use environmental stimuli can be facilitated by using models to estimate adaptability and stability [15, 27]. In this sense, Pereira and coauthors [73] identified soybean genotypes with greater resistance to powdery mildew though parameters of adaptability and stability. Silva and coauthors [15] evaluated the performance of oat cultivars by evaluating grain yield and quality through parameters of adaptability and stability to identify the genotypes more responsive to the reduction in the use of fungicides. Saito and coauthors [74] used these models to identify maize lines with greater resistant to gray leaf spot and leaf wilt.

The current global economic and ecological crises have brought to light the unsustainability of the production pattern of industrial agriculture, which is dependent on chemical inputs and practices that degrade the environment. This highlights the growing need to find alternatives for managing natural resources and social organization that can provide positive responses to the challenges of sustainable agricultural production and the preservation of biodiversity and that are aligned with the Sustainable Development Goals of the 2030 Agenda, enabling the continued sustainable development of humanity [75, 4].

CONCLUSIONS

The optimal timing to assess the genetic variability of resistance to leaf diseases in Brazilian oat cultivars, based on the analysis of necrotic leaf area, is between 90 and 105 days after plant emergence.

The analysis of grain yield and necrotic leaf area through adaptability and stability parameters identified the cultivars URS Altiva, URS Charrua, UPFPS Farroupilha, and UPFA Gauderia as the most suitable genetic resources for agroecologically-based production systems among the oat cultivars evaluated.

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