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Less dependent Brazilian oat cultivars to fungicides during the grain filling stage

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Abstract: The use of resilient oat cultivars combined with the omission of fungicide applications during grain filling stage can enhance food safety while reducing environmental impacts. The objective of this research was to identify Brazilian oat cultivars with greater resilience to fungicides omission by evaluating necrotic leaf area and grain yield, considering the last fungicide application prior to the grain filling stage. Field experiments were conducted from 2015 to 2020, using a randomized complete block design arranged in a 22×4 factorial arrangement, consisting of 22 white oat cultivars (both currently recommended and no longer included in the current Brazilian recommendations) and four fungicide application regimes (no application; one application at 60 days after emergence (DAE); two applications, at 60 and 75 DAE; and three applications, at 60, 75, and 90 DAE), with three repetitions. The assessment of necrotic leaf area and grain yield indicated that URS Altiva, UPFPS Farroupilha and UPFA Gaudéria exhibited the highest resilient under conditions without fungicide application during the grain filling stage. These cultivars therefore represent promising genetic resources for enhancing food security and for use in agroecological and low-input production systems.

Keywords: Agenda 2030; Agroecological systems; Agronomic performance; *Avena sativa*; Disease tolerance; Genetic resources.

Abbreviations: SD_ standard deviation; ^{S}_ superior, represented by one SD above the mean; ^{I}_ inferior, represented by one SD below the mean; R^2_ determination coefficient (%); *_ significant at 5% level by the t-test; AYC_ acceptable year for oat cultivation; FYC_ favorable year for oat cultivation; UYC_ unfavorable year for oat cultivation; GY_ grain yield (kg ha^{-1}); WF_ without fungicide; CF1_ one fungicide application, at 60 days after emergence (DAE); CF_2_ two fungicide applications (at 60 and 75 DAE); CF3_ three fungicide applications (at 60, 75, and 90 DAE); UYD_ unfavorable year for the development of foliar diseases; Min_ average minimum temperature; Max_ average maximum temperature; NLA_ necrotic leaf area assessed at 105 days after emergence;

Introduction

Oats are among the most widely cultivated cool-season crops in southern Brazil, serving multiple purposes, such as soil cover, crop rotation, and food production for animal and human consumption (Reginatto et al., 2021; Rosa et al., 2023). These combined functions, together with increased demand, have driven a substantial expansion cultivation area in recent years (Dornelles et al., 2021; Screminn et al., 2023). However, this increase in oat crop areas combined with genetic uniformity among cultivars has increased the susceptibility to diseases (Murphy et al., 2013; Basso et al., 2022). Among the diseases affecting oats, foliar diseases are greatest concern, as they cause necrosis of leaf tissues, the primary organs responsible for photosynthesis, thereby compromising plant development and grain yield (Dietz et al., 2019; Dornelles et al., 2020). Among foliar diseases, the fungi that cause leaf rust (*Puccinia coronata* Cda. F.sp. avenae) and helminthosporiosis [Drechslera avenae (Eidam) El Sharif] receive the most attention due to their ability to compromise the biological functions of the plant and grain yield (Nazareno et al., 2018; Dornelles et al., 2020).

The management of oat foliar diseases relies predominantly on fungicide applications since genetic resistance is often partial, unstable, or rapidly overcome by evolving pathogen population (Silva et al., 2015; Bhardwaj et al., 2021). Disease severity is generally higher during the flowering and grain filling stages when temperature and humidity conditions are particularly favorable for pathogen development (Basso et al., 2022; Pereira et al., 2023). As a consequence, fungicide use tends to intensify during these stages, sometimes extending applications close to physiological maturity (Jiang et al., 2021; Screminn et al., 2023). Moreover, most fungicides recommended for oat crops have systemic action, favoring the translocation of the pesticide to the grains during the grain filling stage (Rosa et al., 2023; Pereira et al., 2020). Therefore, this poses a potential risk to public health due to the close association between pesticides and emergence of diseases such

as cancer, diabetes, respiratory diseases, and neurological and reproductive disorders (EFSA et al., 2021; Rani et al., 2021). The application of pesticides also has environmental consequences, including soil, water, and air pollution, as well as the death of important ecosystems organisms such as pollinating insects (Pereira et al., 2020; Screminn et al., 2023).

Throughout the crop cycle, plants are exposed to variable environmental conditions and pathogen pressure that may restrict growth and productivity (Jeschke, 2016; Khan et al., 2021). Nevertheless, certain cultivars can withstand, recover from, or adapt to these adverse conditions and are therefore considered resilient. Plant resilience corresponds to the ability to tolerate biotic and abiotic stresses, maintain plant growth and production even under unfavorable conditions (Husen, 2021; Waldron et al., 2021). Considering the context of diseases, some factors contribute to greater expression of resilience in plants, including the presence of resistance and tolerance (Patra et al., 2018; Bakala et al., 2020). Disease resistance involves the plant's ability to limit the entry, development, and reproduction of pathogens, whereas tolerance relates to the plant's ability to maintain growth despite infection (Mansilla-Córdova et al., 2018; Pagán and García-Arenal, 2018). Therefore, properly scheduled fungicide applications can facilitate the identification of more resilient oat cultivars to reduce the use of pesticides and extend the interval between the last application and grain harvest, promoting food security and minimizing environmental damage. The objective of this research was to identify Brazilian oat cultivars with greater resilience to fungicides omission by evaluating necrotic leaf area and grain yield, considering the last fungicide application prior to the grain filling stage.

Results and discussion

Agricultural year conditions and fungicide use in the expression of grain yield

The evaluated crop seasons exhibited distinct meteorological patterns that influenced disease pressure and nitrogen use efficiency. In 2015, high rainfall and temperatures above 18 °C throughout the cycle favored foliar diseases, reducing yield to 2,444 kg ha^{-1} (below the 4,000 kg ha^{-1} potential). Thus, 2015 was classified as an acceptable year for cultivation (AYC) and favorable for disease development (FYD). In contrast, 2016 presented lower, stable temperatures and well-distributed rainfall (Fig. 1), which limited leaf necrosis and optimized N utilization. With a yield of 3,867 kg ha^{-1} (Table 1), 2016 was the only year classified as favorable for cultivation (FYC) and unfavorable for diseases (UYD).

The years 2017 to 2020 were characterized as unfavorable for cultivation (UYC) and favorable for diseases (FYD). In 2017 and 2018, water scarcity during early stages and high temperatures at nitrogen application led to volatilization losses, while subsequent rains during grain filling triggered severe disease outbreaks (Fig. 1). In 2019, high thermal averages and scarce initial rainfall restricted plant growth and nitrogen efficacy. Similarly, 2020 suffered from a prolonged drought after 50 days after emergence, which, combined with high temperatures, severely compromised yield.

Air temperature and relative air humidity are closely related to the emergence and progression of the main oat foliar diseases. Leaf rust, caused by the fungus *Puccinia coronata Cda. F.sp. avenae*, is the main oat disease and is most damaging at average temperatures above 18 ºC and at high relative air humidity (above 90%) (Nazareno et al., 2018). Yellow spot, caused by the fungus *Drechslera avenae (Eidam) El Sharif*, is favored by the occurrence of high air humidity and temperatures ranging from 18 to 28 ºC. Additionally, air temperature and relative air humidity have effects on the development of plants and crop yield. Relative air humidity is an important factor for grain yield, as it regulates the leaf blade transpiration rate can affect the water balance in crops (Ferrante and Mariani, 2018; Chia and Lim, 2022).

Air temperature also significantly affects crop yield. Milder temperatures and proper radiation favor tillering and grain filling. However, the occurrence of temperatures below 2 and 3 °C near the flowering stage can damage leaves and stems, causing flower sterility (Marolli et al., 2017; Mantai et al., 2021b). Low temperatures combined with frost during grain formation can arrest grain growth, resulting in grains of low industrial quality (Mantai et al., 2016). The occurrence of mild temperatures during the vegetative stage is considered essential for increasing the number of grains per panicle (Castro et al., 2012; Scremin et al., 2020).

Additionally, rainfall is the meteorological variable that most affects crop yield, as it is directly connected to plant development and has a significant effect on the efficiency of nitrogen utilization (Kraisig et al., 2020; Mantai et al., 2021a). Large rainfall volumes are not necessarily required to ensure high oat crop yield, but well-distributed rainfall throughout the crop cycle favors adequate soil moisture contents for the crop development processes (Marolli et al., 2018; Reginatto et al., 2021).

Descriptive statistics of necrotic leaf area and grain yield of oat cultivars

The means of necrotic leaf area under the different fungicide application conditions (Table 2), showed significant plant tissue damage by leaf necrosis, mainly under absence of fungicide application, except for the agricultural year 2016, which presented natural disease control conditions. The effect of applying fungicides is evident, resulting in decreased necrotic leaf area as the number of agrochemical applications was increased throughout all evaluated agricultural years. However, a similarity of necrotic leaf area among most cultivars was found between the treatments with two and three fungicide applications in the years with a strong disease pressure.

Overall, the cultivars that showed reduced means of leaf necrosis in a specific year, indicating a superior performance (*S*), did not consistently maintain this classification (Table 2). However, the cultivars that were consistently classified as superior under the different fungicide application conditions, regardless of the agricultural year, were URS Brava, URS Estampa, and FAEM 4 Carlasul, followed by URS Altiva and IPR Afrodite.

Table 1. Temperatures, air humidity, and rainfall depths during the oat crop cycle and means of grain yield and necrotic leaf area, according to the agricultural year.

Month	Temperature (°C)			Air humidity (%)			Rainfall (mm)		GY	NLA	Class	
Month	Min	Max	Mean	Min	Max	Mean	30 years*	Occurred	(kg ha^{-1})	(%)	Plant	Diseases
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	2,444	32	AYC	FYD
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	3,867	5	FYC	UYD
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	1,862	72	UYC	FYD
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	2,013	92	UYC	FYD
September	13	25	19	58	94	76	149	184				
October	16	25	20	47	92	70	227	243				
Total	-	-	-	-	-	-	920	781				
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	1,622	78	UYC	FYD
September	11	24	17	48	91	69	149	99				
October	15	28	21	47	90	68	227	236				
Total	-	-	-	-	-	-	920	751				
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	1,306	93	UYC	FYD
September	12	25	18	60	94	77	149	48				
October	14	30	22	44	91	67	227	52				
Total	-	-	-	-	-	-	920	1,056				

Min= average minimum temperature; Max= average maximum temperature; *= historical rainfall depth from May to October of the last 30 years; GY= grain yield; NLA= necrotic leaf area assessed at 105 days after emergence; AYC= acceptable year for oat cultivation; FYC= favorable year for oat cultivation; UYC= unfavorable year for oat cultivation; FYD= favorable year for the development of foliar diseases; UYD= unfavorable year for the development of foliar diseases.

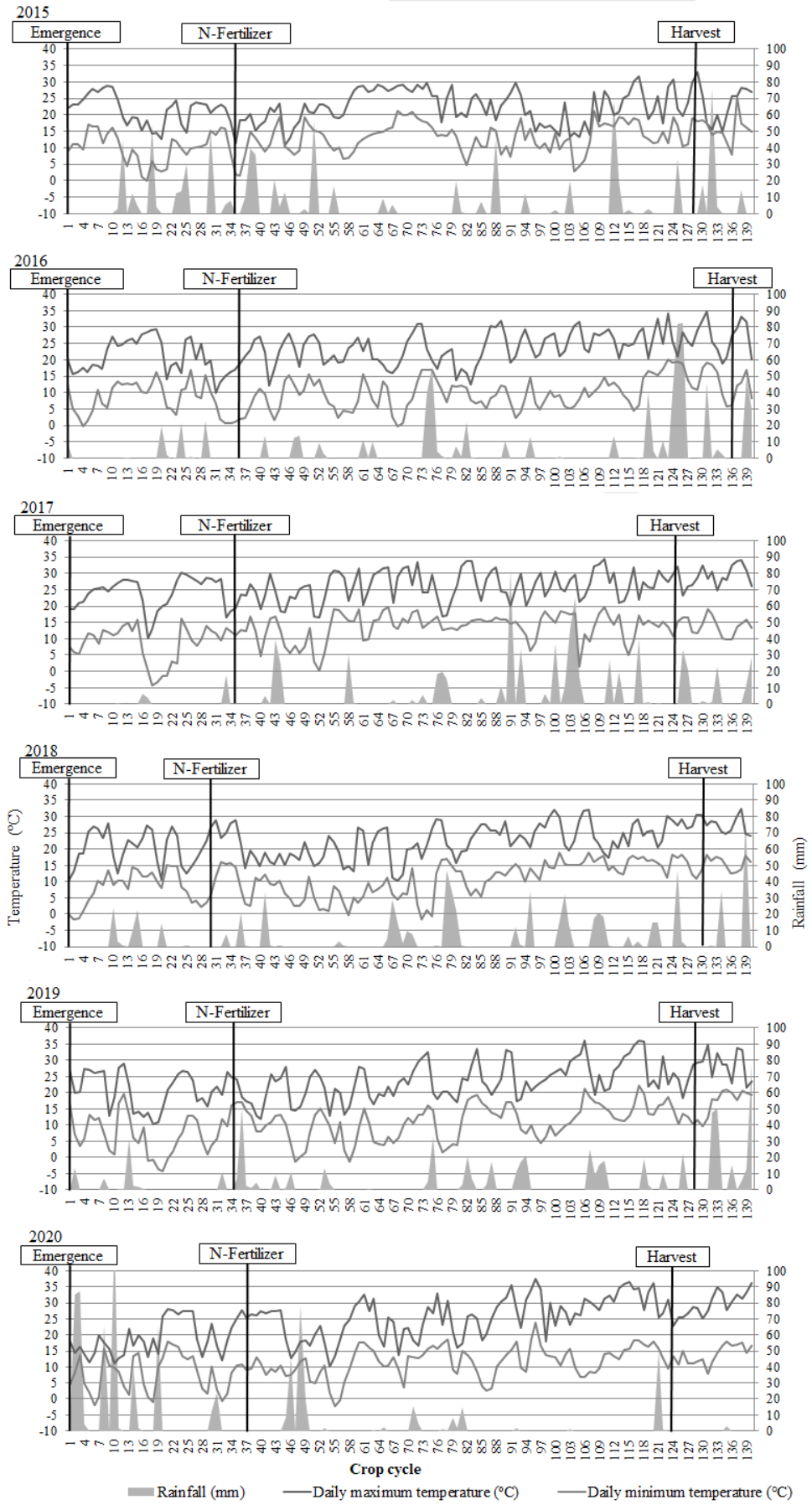


Fig. 1. Rainfall and minimum and maximum temperatures during the oat crop cycle

Table 2. Means of necrotic leaf area (%) in oat cultivars, evaluated at 105 days after emergence, under different fungicide application conditions.

Cultivar	NLA 2015 (FYD)				NLA 2016 (UYD)				NLA 2017 (FYD)			
Cultivar	**WF**	**CF_1**	**CF_2**	**CF_3**	**WF**	**CF_1**	**CF_2**	**CF_3**	**WF**	**CF_1**	**CF_2**	**CF_3**
URS Altiva	69	30	7	2^S	7	6	3	0^S	98	63^S	57^S	57
URS Brava	53	14^S	7	2^S	7	7	3	2	99	71	61	58
URS Guará	76	20	9	0^S	6	6	5	4	98	70	62	55
URS Estampa	35^S	22	19	10	13	8	7	3	99	69	66	53
URS Corona	98	90	80	22	9	3	2	2	99	60^S	59^S	58
URS Torena	69	41	18	16	4^S	2^S	1^S	0^S	99	67	64	56
URS Charrua	63	24	10	4	18	4	2	0^S	98	64	60	57
URS Guria	62	16	8	8	8	3	1^S	1	98	72	71	62
URS Tarimba	59	28	17	11	20	11	6	3	98	68	67	66
URS Taura	89	26	17	16	13	5	3	0^S	99	65	57^S	56
URS 21	65	30	17	16	14	4	2	2	98	84	66	63
FAEM 007	88	69	28	24	15	5	4	1	99	74	67	65
FAEM 006	97	56	14	14	18	12	3	1	99	73	69	48^S
FAEM 5 Chiarasul	96	60	14	12	4^S	3	2	2	98	68	68	66
FAEM 4 Carlasul	75	33	16	14	3^S	2^S	1^S	0^S	98	65	53^S	43^S
Brisasul	37^S	34	10	10	6	3	2	1	99	65	60	59
Barbarasul	86	82	13	4	5	4	2	1	99	68	62	55
URS Fapa Slava	52	46	24	17	32	8	4	0^S	98	71	68	60
IPR Afrodite	94	33	4	4	5	4	2	0^S	99	58^S	56^S	42^S
UPFPS Farroupilha	64	28	4	4	8	6	4	3	99	68	63	55
UPFA Ouro	30^S	6^S	5	5	10	5	4	3	98	79	72	62
UPFA Gaudéria	27^S	15^S	13	8	6	4	2	1	98	75	72	68
Mean	67	37	16	10	11	5	3	1	99	69	64	57
SD	22	22	16	7	7	3	2	1	0	6	5	7

Table 2 (continued).

Cultivar	NLA 2018 (FYD)				NLA 2019 (FYD)				NLA 2020 (FYD)			
Cultivar	**WF**	**CF_1**	**CF_2**	**CF_3**	**WF**	**CF_1**	**CF_2**	**CF_3**	**WF**	**CF_1**	**CF_2**	**CF_3**
URS Altiva	100	99	78^S	77	98	89	56^S	56	96	94	90	85
URS Brava	100	100	75^S	73^S	96	91	68	45^S	93	92	81^S	81^S
URS Guará	100	100	100	88	100	92	86	55	99	98	98	97
URS Estampa	100	88^S	84	56^S	98	77^S	49^S	46	99	98	79^S	82^S
URS Corona	100	100	95	92	97	93	81	55	97	94	90	89
URS Torena	100	100	98	81	97	88	59^S	55	94	93	92	92
URS Charrua	100	100	92	88	99	87	79	54	98	93	90	88
URS Guria	100	100	93	90	99	98	78	74	98	96	93	90
URS Tarimba	100	100	100	86	95	94	90	68	93	91	90	86
URS Taura	100	98	93	86	98	89	52^S	39^S	93	93	90	88
URS 21	100	100	98	93	98	89	67	59	99	91	91	90
FAEM 007	100	100	99	93	95	85	70	68	98	96	95	95
FAEM 006	100	100	91	89	99	88	77	75	100	99	96	92
FAEM 5 Chiarasul	100	100	86	72^S	99	88	87	50	99	98	97	96
FAEM 4 Carlasul	100	100	82	79	95	85	76	23^S	96	95	90	87
Brisasul	100	100	83	81	90	68^S	66	65	97	95	94	92
Barbarasul	100	100	84	81	97	87	64	61	97	96	92	85
URS Fapa Slava	100	100	76^S	75	99	98	81	70	96	95	92	81^S
IPR Afrodite	100	92^S	82	81	93	75^S	73	55	95	92	89	85
UPFPS Farroupilha	100	100	99	98	92	90	73	68	93	92	90	86
UPFA Ouro	100	97	84	83	85^S	70^S	56^S	54	100	96	94	88
UPFA Gaudéria	97^S	96^S	92	84	99	80	70	65	97	92	91	90

Cultivar	NLA 2018 (FYD)				NLA 2019 (FYD)				NLA 2020 (FYD)			
Cultivar	WF	CF_1	CF_2	CF_3	WF	CF_1	CF_2	CF_3	WF	CF_1	CF_2	CF_3
Mean	100	99	89	83	96	86	71	57	97	95	91	88
SD	0	3	8	9	7	8	11	12	5	5	4	4

WF= without fungicide; CF_1= one fungicide application, at 60 days after emergence (DAE); CF_2= two fungicide applications (at 60 and 75 DAE); CF_3= three fungicide applications (at 60, 75, and 90 DAE); SD= standard deviation; ^{S}= superior, represented by one SD below the mean; FYD= favorable year for the development of foliar diseases; UYD= unfavorable year for the development of foliar diseases.

According to the means of grain yield of oat cultivars under the different fungicide application conditions (Table 3), 2016 stood out, presenting cultivars with higher grains yields than that expected (4,000 kg ha^{-1}), even under absence of fungicide application. This reinforces the occurrence of ideal conditions for cereal cultivation. In general, oat cultivars present increases in grain yield as the number of fungicide applications on a calendar basis is increased.

Some cultivars presented similar grain yield means between the treatments with two and three fungicide applications, as found for necrotic leaf area (Table 2), which may indicate the potential of more significant reductions in the number of fungicide applications.

Regarding the cultivars that exhibited superior grain yield performance (*S*), represented by one standard deviation above the mean, those that were classified as superior in a specific year under the different fungicide application conditions did not necessarily maintain this trend. However, the cultivars that were consistently classified as superior (S), meaning those with the best performance, regardless of the agricultural year were URS Altiva, FAEM 007, IPR Afrodite, and UPFPS Farroupilha, followed by URS Corona, URS Guria, and UPFA Gaudéria.

Table 3. Means of grain yield of oat cultivars under different fungicide application conditions.

Cultivar	GY 2015 (AYC)				GY 2016 (FYC)				GY 2017 (UYC)			
Cultivar	WF	CF_1	CF_2	CF_3	WF	CF_1	CF_2	CF_3	WF	CF_1	CF_2	CF_3
URS Altiva	2321^S	2696^S	3487^S	4236^S	2893	3478	4423	4467	1103	1658	1909	2109
URS Brava	1230	2393	3191	3993^S	3298	3795	4112	4225	1024	1539^I	1882	2135
URS Guará	1486	2083	3166	3453	3553	4067	4253	4487	1138	1736	2054	2348
URS Estampa	1555	2393	2822	3302	3266	3625	3671^I	3982	790^I	1413^I	1592^I	1720^I
URS Corona	804	2030	2824	3333	3780^S	4812^S	4983^S	5033^S	976	2093	2424^S	2499
URS Torena	1348	2377	2783	2892^I	2861	3462	3886	4271	859^I	1609	2217	2352
URS Charrua	1616	2662^S	3078	3107	3584	4048	4131	4152	983	1633	2083	2102
URS Guria	1949^S	2681^S	3413^S	3517	2311^I	3296^I	3773	4067	1150	1713	2119	2594
URS Tarimba	1386	1646^I	2672^I	3160	3350	3934	4249	4661	910^I	1303^I	1541^I	2119
URS Taura	863	1813	2152^I	2775^I	2231^I	3366^I	4145	4804	1069	1862	1974	2310
URS 21	1552	2192	3071	3104	3312	3569	3662^I	3755^I	1025	1921	1948	2156
FAEM 007	579^I	1194^I	2922	2923^I	3752^S	4233^S	4861^S	4924^S	1436^S	2399^S	2445^S	2501
FAEM 006	749^I	2035	3264	3660	3461	3929	4134	4543	1340	2126	2444^S	2586
FAEM 5 Chiarasul	727^I	1304	3353	3923^S	3036	3783	4060	4009	1380^S	1911	2228	2432
FAEM 4 Carlasul	1352	2166	3414^S	3514	3802^S	4127	4128	4182	1620^S	2469^S	2857^S	3154
Brisasul	1066	2237	3516^S	3700	3362	3827	4172	4975^S	1031	1683	2058	2106
Barbarasul	680^I	1854	3580^S	3739	3358	4171	4453	4833	1220	1732	1802^I	2139
URS Fapa Slava	1189	1719	3096	3159	2081^I	3373^I	3562^I	3621^I	954	1892	2014	2416
IPR Afrodite	566^I	1527^I	2802	3382	4096^S	4349^S	4687^S	5195^S	1199	1938	2404	2553
UPFPS Farroupilha	1324	2448	3215	3463	3354	3833	4104	4416	1459^S	2394^S	2443^S	2543
UPFA Ouro	1386	2290	2791	3378	2736	3131^I	3413^I	3641^I	1237	1900	2110	2362
UPFA Gaudéria	1308	2163	2601^I	3222	3055	3269^I	3552^I	3614^I	1317	1901	1968	2072
Mean	1229	2087	3055	3406	3206	3794	4110	4357	1146	1856	2114	2332
SD	448	422	354	368	522	413	413	481	213	304	306	287

Table 3 (continued).

Cultivar	GY 2018 (UYC)				GY 2019 (UYC)				GY 2020 (UYC)			
Cultivar	WF	CF_1	CF_2	CF_3	WF	CF_1	CF_2	CF_3	WF	CF_1	CF_2	CF_3
URS Altiva	1535^S	1959	2962^S	3077	1097^S	1409	1892	2356	1143	1228	1476	1484
URS Brava	1477^S	2284^S	3056^S	2933	825	1550	2168	2368	1046	1254	1468	1487
URS Guará	1310^S	2000	2310	3012	746	1186	1963	1903^I	728^I	1403	1440	1465
URS Estampa	1173	2022	2426	3171	719	1712^S	2034	2130	1068	1343	1363	1708^S
URS Corona	1153	1668	2150	2964	702	1142^I	2018	2097	1025	1381	1308^I	1798^S

Cultivar	GY 2018 (UYC)				GY 2019 (UYC)				GY 2020 (UYC)			
Cultivar	WF	CF_1	CF_2	CF_3	WF	CF_1	CF_2	CF_3	WF	CF_1	CF_2	CF_3
URS Torena	1087	1519	2832^S	3039	556	1308	2133	2278	1376^S	1477^S	1674^S	1607
URS Charrua	741	1866	2390	3072	1026^S	1553	2114	2144	1166	1330	1409	1405
URS Guria	670	1774	2219	2573^I	507	1061^I	1719^I	2045	1088	1511^S	1707^S	1729^S
URS Tarimba	635^I	2588^S	2873^S	3159	655	1507	2145	2557^S	568^I	971^I	1414	1489
URS Taura	1078	1863	2856^S	3354^S	645	1468	2043	2232	765	870^I	1275^I	1307^I
URS 21	1099	2057	2144	2456^I	672	1248	1870	2239	753^I	1228	1404	1427
FAEM 007	716	1523	2224	2926	678	1261	1955	1994^I	801	1225	1460	1537
FAEM 006	773	2036	2438	2732	867	1586	1744^I	2038	990	1121	1414	1456
FAEM 5 Chiarasul	803	1369^I	2445	2986	540^I	1527	2273^S	2358	766	1199	1398	1408
FAEM 4 Carlasul	767	1626	2175	2667	572	1320	2114	2197	713^I	789^I	1267^I	1311^I
Brisasul	676	2016	2261	2652	594	1376	1803^I	2194	1009	1367	1478	1428
Barbarasul	729	1626	2446	3125	555	1300	2114	2260	771	1154	1270^I	1207^I
URS Fapa Slava	740	1567	2394	2992	536	1130^I	2173	2266	857	1150	1420	1225^I
IPR Afrodite	690	1861	2484	3441^S	774	1605	2014	2842^S	1103	1516^S	1540	1628
UPFPS Farroupilha	691	1676	2268	2733	747	1283	1713^I	2018	1309^S	1544^S	1645^S	1791^S
UPFA Ouro	797	1218^I	1606^I	2015^I	1031^S	1488	2330^S	2912^S	1281^S	1410	1467	1655
UPFA Gaudéria	975	1236^I	2329	3136	1140^S	2240^S	2282^S	2578^S	1267^S	1398	1625^S	1635
Mean	923	1789	2422	2919	736	1421	2051	2273	982	1267	1451	1509
SD	274	331	330	317	190	252	208	258	227	203	125	170

GY= grain yield (kg ha^{-1}); WF= without fungicide; CF_1= one fungicide application, at 60 days after emergence (DAE); CF_2= two fungicide applications (at 60 and 75 DAE); CF_3= three fungicide applications (at 60, 75, and 90 DAE); SD= standard deviation; ^{S}= superior, represented by one SD above the mean; ^{I}= inferior, represented by one SD below the mean; AYC= acceptable year for oat cultivation; FYC= favorable year for oat cultivation; UYC= unfavorable year for oat cultivation.

The compilation of the number of times each cultivar exhibited superiority regarding necrotic leaf area and grain yield in the different agricultural years is shown in Table 4. The cultivars that exhibited the highest number of occurrences of superiority for necrotic leaf area were URS Brava, URS Estampa, and FAEM 4 Carlasul, URS Altiva, and IPR Afrodite. Regarding grain yield, the cultivars that exhibited the highest number of occurrences of superiority were URS Altiva, FAEM 007, IPR Afrodite, UPFPS Farroupilha, URS Corona, URS Guria, and UPFA Gaudéria.

The cultivars FAEM 007 and UPFPS Farroupilha, which stood out in grain yield, did not exhibited superior performance in reducing necrotic leaf area. This suggests that an increase in necrotic leaf area can be offset by a higher physiological efficiency of the remaining healthy cells during the photosynthesis process for grain production. This compensatory effect mechanism may indicate a different form of genetic resistance in plants, a concept also supported by Dornelles et al. (2020) in their study on disease resistance variability in Brazilian oat cultivars under the absence and presence of fungicide applications. Overall, URS Altiva, IPR Afrodite, FAEM 4 Carlasul, URS Brava, and UPFA Gaudéria were the cultivars that most consistently exhibited superior performance for lower necrotic leaf area and higher grain yield.

Table 4. Occurrences of superiority for necrotic leaf area (NLA; %) and grain yield (GY; kg ha^{-1}) of oat cultivars in different agricultural years.

Cultivar	NLA superiority						Σ	GY superiority						Σ	Total
Cultivar	2015	2016	2017	2018	2019	2020	Σ	2015	2016	2017	2018	2019	2020	Σ	Total
URS Altiva	1	1	2	1	1	0	6	4	0	0	2	1	0	7	13
URS Brava	2	0	0	2	1	2	7	1	0	0	3	0	0	4	11
URS Guará	1	0	0	0	0	0	1	0	0	0	1	0	0	1	2
URS Estampa	1	0	0	2	2	2	7	0	0	0	0	1	1	2	9
URS Corona	0	0	2	0	0	0	2	0	4	1	0	0	1	6	8
URS Torena	0	4	0	0	1	0	5	0	0	0	1	0	3	4	9
URS Charrua	0	1	0	0	0	0	1	1	0	0	0	1	0	2	3
URS Guria	0	1	0	0	0	0	1	3	0	0	0	0	3	6	7
URS Tarimba	0	0	0	0	0	0	0	0	0	0	2	1	0	3	3
URS Taura	0	1	1	0	2	0	4	0	0	0	2	0	0	2	6
URS 21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FAEM 007	0	0	0	0	0	0	0	0	4	3	0	0	0	7	7
FAEM 006	0	0	1	0	0	0	1	0	0	1	0	0	0	1	2
FAEM 5 Chiarasul	0	1	0	1	0	0	2	1	0	1	0	1	0	3	5
FAEM 4 Carlasul	0	4	2	0	1	0	7	1	1	3	0	0	0	5	12

Cultivar	NLA superiority						Σ	GY superiority						Σ	Total
Cultivar	2015	2016	2017	2018	2019	2020	Σ	2015	2016	2017	2018	2019	2020	Σ	Total
Brisasul	1	0	0	0	1	0	2	1	1	0	0	0	0	2	4
Barbarasul	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1
URS Fapa Slava	0	1	0	1	0	1	3	0	0	0	0	0	0	0	3
IPR Afrodite	0	1	3	1	1	0	6	0	4	0	1	1	1	7	13
UPFPS Farroupilha	0	0	0	0	0	0	0	0	0	3	0	0	4	7	7
UPFA Ouro	2	0	0	0	3	0	5	0	0	0	0	3	1	4	9
UPFA Gaudéria	2	0	0	2	0	0	4	0	0	0	0	4	2	6	10

Σ= sum of the number of occurrences of superiority; Total= total sum of the number of occurrences of superiority for necrotic leaf area and grain yield.

Linear regression of necrotic leaf area as a function of the number of fungicide applications

The linear regression for necrotic leaf area as a function of the number of fungicide applications in favorable years for foliar disease development showed high linear coefficients (b_0) for all evaluated oat cultivars (Table 5). Reduced angular coefficients (b_1) were found during these years, mainly in 2018 and 2020, indicating a lower effectiveness of agrochemical control over the expression of leaf necrosis.

The cultivar UPFA Gaudéria stands out for exhibiting superior performance with a smaller necrotic leaf area in at least three agricultural years, followed by URS Torena, URS Tarimba, FAEM 5 Chiarasul, UPFPS Farroupilha, and UPFA Ouro, which showed superior performance for less necrotic leaf area in at least two years. These cultivars are less dependent on the use of fungicides due to necrotic leaf area probably because they have different disease response mechanisms (Table 5).

Table 5. Linear regression of necrotic leaf area (%) as a function of the number of fungicide applications for growing oat cultivars, evaluated at 105 days after emergence.

Cultivar	NLA 2015 (FYD)		NLA 2016 (UYD)		NLA 2017 (FYD)	
Cultivar	$b_0 + b_1x$	R^2	$b_0 + b_1x$	R^2	$b_0 + b_1x$	R^2
URS Altiva	60-22.4*x	89	8-2.5*x	94	69^{S}-12.8*x	71
URS Brava	43-16.0*x	79	8-1.9*x	91	92-13.5*x	84
URS Guará	62-24.0*x	81	6-0.7x	100	92-13.8*x	88
URS Estampa	33^{S}-7.8^{S*}x	95	12-3.1*x	94	93-14.2*x	87
URS Corona	100^{I}-23.6*x	80	7-2.2*x	75	88-12.4*x	65
URS Torena	63-18.2*x	90	4^{S}-1.2*x	92	91-13.3*x	82
URS Charrua	54-19.1*x	86	15-5.7^{I*}x	78	89-12.7*x	72
URS Guria	49-17.2*x	72	7-2.4*x	73	92-10.8*x	82
URS Tarimba	52-15.5*x	89	19^{I}-5.7^{I*}x	94	90-10.0^{S*}x	66
URS Taura	71-22.7*x	71	12-4.3*x	90	90-13.7*x	77
URS 21	55-15.6*x	80	11-3.8*x	77	96^{I}-14.2*x	93
FAEM 007	87^{I}-23.3*x	92	13-4.2*x	84	92-10.8*x	80
FAEM 006	89^{I}-29.1^{I*}x	89	17^{I}-5.8^{I*}x	95	95-15.7^{I*}x	94
FAEM 5 Chiarasul	90^{I}-29.9^{I*}x	91	4^{S}-0.9*x	97	90-9.6^{S*}x	64
FAEM 4 Carlasul	64-19.8*x	83	3^{S}-0.8*x	96	91-17.6^{I*}x	90
Brisasul	38^{S}-10.4^{S*}x	84	5-1.6*x	87	90-13.4*x	77
Barbarasul	94^{I}-31.9^{I*}x	86	5-1.3*x	99	91-13.7*x	84
URS Fapa Slava	54-12.9*x	95	26^{I}-10.1^{I*}x	80	92-11.8*x	82
IPR Afrodite	79-30.0^{I*}x	83	5-1.5*x	97	89-17.3^{I*}x	81
UPFPS Farroupilha	56-20.3*x	85	8-1.5*x	97	92-13.6*x	85
UPFA Ouro	22^{S}-7.4^{S*}x	63	9-2.0*x	85	95-11.7*x	94
UPFA Gaudéria	24^{S}-5.7^{S*}x	91	6-1.5*x	92	92-9.3^{S*}x	78
Mean	61-19.2x		10-2.9x		91-12.9x	
SD	23+7.5x		6+2.3x		5+2.2x	

Table 5 (continued).

Cultivar	NLA 2018 (FYD)		NLA 2019 (FYD)		NLA 2020 (FYD)	
Cultivar	$b_0 + b_1x$	R^2	$b_0 + b_1x$	R^2	$b_0 + b_1x$	R^2
URS Altiva	100^{I}-8.7*x	83	99-15.9*x	87	97-3.8x	98
URS Brava	100^{I}-10.4^{I*}x	83	100^{I}-17.4*x	94	93^{S}-4.5^{I}x	84

Cultivar	NLA 2018 (FYD)		NLA 2019 (FYD)		NLA 2020 (FYD)	
Cultivar	$b_0 + b_1x$	R^2	$b_0 + b_1x$	R^2	$b_0 + b_1x$	R^2
URS Guará	100^{I}-3.5x	60	100-14.0x	84	99^{I}-0.5^{S}x	97
URS Estampa	100^{I}-13.4^{I*}x	89	95-18.1*x	92	99^{I}-6.7^{I}x	74
URS Corona	100^{I}-2.6^{S*}x	89	100^{I}-13.9*x	88	97-2.7x	94
URS Torena	100^{I}-5.6x	65	98-15.4*x	92	93^{S}-0.4^{S}x	70
URS Charrua	100^{I}-4.1*x	89	100^{I}-14.2*x	93	98-3.4x	94
URS Guria	100^{I}-3.4x	88	100^{I}-9.23x	87	98-2.7x	98
URS Tarimba	100^{I}-4.0x	60	100^{I}-8.6^{S}x	76	93^{S}-2.0x	91
URS Taura	100^{I}-4.4x	92	100^{I}-21.3*x	93	93^{S}-1.5x	89
URS 21	100^{I}-2.0^{S*}x	83	99-14.1*x	96	97-2.7*x	72
FAEM 007	100^{I}-1.9^{S*}x	68	94-9.7x	93	98-1.1^{S}x	89
FAEM 006	100^{I}-3.9*x	83	97-8.3^{S*}x	94	100^{I}-2.5x	92
FAEM 5 Chiarasul	100^{I}-9.6^{I}x	88	100^{I}-14.6*x	79	99^{I}-0.8^{S}x	99
FAEM 4 Carlasul	100^{I}-8.1*x	85	100^{I}-22.4*x	81	97-3.4x	96
Brisasul	100^{I}-7.2*x	85	84^{S}-78x	69	97-1.6x	97
Barbarasul	100^{I}-7.1*x	86	97-13.0*x	93	99^{I}-4.1^{I}x	88
URS Fapa Slava	100^{I}-9.9^{I*}x	81	100^{I}-10.3*x	91	96-1.7x	88
IPR Afrodite	98^{S}-6.5*x	91	91^{S}-11.4*x	92	96-3.6x	98
UPFPS Farroupilha	100^{I}-0.66^{S}x	83	94-8.7^{S*}x	90	93^{S}-2.1x	95
UPFA Ouro	100^{I}-6.1x	88	82^{S}-10.7*x	92	100^{I}-3.6^{*}x	95
UPFA Gaudéria	98^{S}-4.2*x	92	95-11.2x	93	96-2.1x	87
Mean	99.9-5.7x		97-13.2x		97-2.6x	
SD	1+3.1x		7+4.1x		2+1,5x	

R^2= coefficient of determination (%); *= significant at 5% level by the t-test; SD= standard deviation; ^{S}= superior, represented by one SD below the mean; ^{I}= inferior, represented by one SD above the mean; FYD= favorable year for the development of foliar diseases; UYD= unfavorable year for the development of foliar diseases.

The linear regression for grain yield as a function of the number of fungicide applications showed higher linear coefficients for the cultivars URS Altiva and URS Guria in 2015 (Table 6), as they can achieve grain yields higher than 2,000 kg ha^{-1} under absence of fungicide application. Regarding angular coefficients, the cultivars FAEM 006, FAEM 5 Chiarasul, Barbarasul, and IPR Afrodite showed a superior rate of grain yield increase with each fungicide application. URS Corona, FAEM 007, FAEM 4 Carlasul, and IPR Afrodite stood out in 2016 for presenting the highest linear coefficients, whereas URS Altiva, URS Guria, and URS Taura presented the highest angular coefficients.

The cultivars FAEM 007, FAEM 4 Carlasul, and UPFPS Farroupilha stood out in 2017 for presenting the highest linear coefficients, whereas URS Corona, URS Torena, URS Guria, FAEM 4 Carlasul, URS Fapa Slava, and IPR Afrodite presented the highest angular coefficients, representing a greater grain yield response to fungicide applications.

In 2018, characterized by significant disease effects on oat crops, superior grain yield was found for the cultivars URS Altiva, URS Brava, URS Guará, and URS 21, according to the linear coefficients; the superior cultivars based on angular coefficients were Barbarasul and IPR Afrodite. URS Altiva also presented superiority for grain yield in 2019 for presenting the highest linear coefficient, along with URS Charrua and UPFA Gaudéria, whereas the cultivars URS Tarimba, FAEM 5 Chiarasul, URS Fapa Slava, IPR Afrodite, and UPFA Ouro were superior for presenting the highest angular coefficients. In 2020, with significant limitations for plant development, higher linear coefficients were found for the cultivars UPFPS Farroupilha, UPFA Ouro, and UPFA Gaudéria, whereas the URS Guará, URS Corona, FAEM 007, and FAEM 4 Carlasul presented the most effective responses to fungicide application for yielding the highest angular coefficients. In summary, URS Altiva, URS Charrua, FAEM 007, FAEM 4 Carlasul, UPFPS Farroupilha, and UPFA Gaudéria showed greater superiority among the analyzed cultivars for presenting higher linear coefficients in most of the evaluated years. However, when considering in an overall analysis encompassing both mean values and linear regression coefficients for smaller necrotic leaf areas and higher grain yields over the years, the cultivars URS Altiva, UPFPS Farroupilha, and UPFA Guria stand out.

Table 6. Linear regression of oat grain yield (GY; kg ha^{-1}) as a function of the number of fungicide applications for growing oat cultivars.

Cultivar	GY 2015 (AYC)		GY 2016 (FYC)		GY 2017 (UYC)	
Cultivar	$b_0 + b_1x$	R^2	$b_0 + b_1x$	R^2	$b_0 + b_1x$	R^2
URS Altiva	2204^{S}+653*x	97	2964+566^{S*}x	91	1204+326*x	93
URS Brava	1338+908*x	99	3393+309*x	92	1093+367*x	97
URS Guará	1499+698*x	95	3641+298*x	94	1226+394*x	96

Cultivar	GY 2015 (AYC)		GY 2016 (FYC)		GY 2017 (UYC)	
Cultivar	$b_0 + b_1x$	**R²**	$b_0 + b_1x$	**R²**	$b_0 + b_1x$	**R²**
URS Estampa	1667+567*x	97	3307+219*x	93	933^{I}+296^{I*}x	86
URS Corona	990+838*x	96	4062^{S}+383x	74	1262+490^{S*}x	80
URS Torena	1594+503^{I*}x	85	2922+465*x	98	996^{I}+508^{S*}x	92
URS Charrua	1882^{S}+488^{I*}x	82	3710+178^{I}x	74	1129+380*x	87
URS Guria	2075^{S}+543^{I*}x	92	2500^{I}+574^{S*}x	92	1183+474^{S*}x	99
URS Tarimba	1263+634*x	95	3411+424*x	98	888^{I}+386*x	97
URS Taura	989+607*x	96	2361^{I}+849^{S*}x	98	1228+383*x	88
URS 21	1649+553^{I*}x	91	3361+142^{I}x	92	1249+341*x	77
FAEM 007	590^{I}+876*x	88	3821^{S}+414*x	92	1709^{S}+324*x	67
FAEM 006	932+996^{S*}x	95	3499+345*x	98	1515+405*x	88
FAEM 5 Chiarasul	581^{I}+1163^{S*}x	93	3242+319*x	76	1466+347*x	95
FAEM 4 Carlasul	1450+773*x	92	3888^{S}+114^{I}x	71	1776^{S}+499^{S*}x	93
Brisasul	1252+918*x	93	3306+518*x	96	1179+359*x	87
Barbarasul	827^{I}+1090^{S*}x	92	3497+470*x	94	1299+282^{I*}x	92
URS Fapa Slava	1197+728*x	90	2437^{I}+480*x	72	1142+451^{S*}x	88
IPR Afrodite	610^{I}+972^{S*}x	98	4036^{S}+363*x	97	1344+452^{S*}x	92
UPFPS Farroupilha	1534+718*x	93	3408+345*x	98	1714^{S}+330*x	71
UPFA Ouro	1489+647*x	98	2780+299*x	98	1364+358*x	92
UPFA Gaudéria	1396+618*x	98	3064+202^{I*}x	94	1465+233^{I*}x	78
Mean	1319+750x		3255+377x		1289+378x	
SD	453+194x		483+168x		241+70x	

Table 6 (continued).

Cultivar	GY 2018 (UYC)		GY 2019 (UYC)		GY 2020 (UYC)	
Cultivar	$b_0 + b_1x$	**R²**	$b_0 + b_1x$	**R²**	$b_0 + b_1x$	**R²**
URS Altiva	1537^{S}+563*x	92	1030^{S}+456*x	98	1185+170*x	94
URS Brava	1666^{S}+513^{I*}x	83	940+524*x	94	1065+183*x	98
URS Guará	1345^{S}+541*x	97	812+424^{I*}x	87	905+274^{S*}x	78
URS Estampa	1238+639*x	98	965+455*x	83	1079+193*x	91
URS Corona	1096+591*x	98	730+506*x	92	976+260^{S*}x	97
URS Torena	1044+716*x	92	669+599*x	93	1203+175*x	93
URS Charrua	889+751*x	97	1122^{S}+391^{I*}x	90	1085+160*x	92
URS Guria	885+615*x	92	542^{I}+527*x	98	1190+211*x	84
URS Tarimba	1134+785*x	78	764+634^{S*}x	97	648^{I}+240*x	91
URS Taura	1115+781*x	98	796+533*x	93	749^{I}+203*x	89
URS 21	1315^{S}+415*x	84	708+532*x	98	862+209*x	84
FAEM 007	747^{I}+733*x	99	775+464*x	91	889+244^{S*}x	90
FAEM 006	1053+627*x	88	1008+366*x	90	978+155*x	99
FAEM 5 Chiarasul	757+762*x	98	744+620^{S*}x	90	873+212*x	83
FAEM 4 Carlasul	871+624*x	98	700+567*x	92	632^{I}+297^{S*}x	93
Brisasul	975+617*x	86	707+522*x	96	1075+196*x	92
Barbarasul	780+800^{S*}x	99	667+592*x	93	846+219*x	92
URS Fapa Slava	785+758*x	99	591^{I}+623^{S*}x	92	953+133^{I*}x	84
IPR Afrodite	787+887^{S*}x	98	866+711^{S*}x	96	1180+150^{I*}x	83
UPFPS Farroupilha	834+672*x	96	803+424^{I*}x	98	1357^{S}+154*x	94
UPFA Ouro	803+404*x	99	966+648^{S*}x	98	1240^{S}+131^{I*}x	97
UPFA Gaudéria	782+757*x	95	1406^{S}+435*x	79	1304^{S}+123^{I*}x	90
Mean	1020+661x		833+524x		1010+196x	
SD	264+125x		197+93x		200+47x	

SD= standard deviation; ^{S}= superior, represented by one SD above the mean; ^{I}= inferior, represented by one SD below the mean; R^2= determination coefficient (%); *= significant at 5% level by the t-test; AYC= acceptable year for oat cultivation; FYC= favorable year for oat cultivation; UYC= unfavorable year for oat cultivation.

Studies have shown that oat cultivars susceptible to the leaf rust fungus can present decreases higher than 50% in grain yield under favorable environmental conditions for the development of this pathogen (Figueiró et al., 2015). Furthermore, the helminthosporiosis (yellow spot) disease reduces grain yield up to 50% under favorable conditions for the fungus (França-Silva et al., 2020). Therefore, the use of cultivars with higher resistance to foliar diseases can contributed to increased grain yield while reducing and/or eliminating the use of pesticides, mainly in agroecological-based cropping systems (Basso et al., 2022). The achievement of the desired standards for white oat crops requires cultivars with high grain yields while meeting the technological standards recommended by the cereal industry, which includes high percentage of caryopsis, a high hectoliter mass, and desirable grain size (Crestani et al., 2010). However, these characteristics may not always be achieved due to climatic factors and the prevalence of fungal diseases (Nerbass Júnior et al., 2008).

The performance of an agronomic species and its potential for large-scale production is conditioned to the presence of a favorable crop environment, which can, however, favor the incidence and pressure of diseases that directly affect grain quality and yield (Silva et al., 2015; Dornelles et al., 2021). Dornelles et al. (2020) emphasized the significant impact of fungicides on increasing grain yield and controlling leaf necrosis caused by foliar diseases in oat plants. The severity of these diseases is often increased by high temperatures and air humidity, which are conditions frequently observed during the flowering and grain filling stages of the crop (Screminn et al., 2023; Rosa et al., 2023). These factors promote the concentration of pesticide applications during these crop development stages, potentially resulting in pesticides residues in the grains and leading to food safety concerns (Pereira et al., 2023). In this context, Alessi et al. (2018) highlighted the importance of evaluating genetic resistance to diseases and the resilience of oat cultivars for reducing the use of fungicide pesticides and improving food safety. Pereira et al. (2023) also highlighted the significance of identifying oat genotypes that exhibit high performance for traits of agronomic and industrial interest while requiring less fungicide applications, with adaptability and stability, promoting safer production. Considering this scenario, the association between the emergence of disease and the use of pesticides, combined with the growing awareness of ecological issues, has caused an increased demand for food produced through more sustainable processes, reflecting changes in consumer preferences based on their increased concerns about health and the environment (Silva et al., 2015; Rosa et al., 2023).

Materials and methods

Study area and experimental design

Field experiments were conducted in Augusto Pestana, RS, Brazil (28°26'30''S and 54°00'58''W) from 2015 to 2020. The soil in the experimental area is classified Typic Hapludox (Latossolo Vermelho Distroferrico tipico; Santos et al., 2018). The region has a humid subtropical climate, according to the Köppen classification. Soil analysis before planting showed the following chemical characteristics: pH = 6.3; P =34.1 mg dm^{-3}; K = 198 mg dm^{-3}; Organic matter (OM) = 3.2%; Al = 0 $cmol_c$ dm^{-3}; Ca = 6.5 $cmol_c$ dm^{-3}; and Mg = 2.5 $cmol_c$ dm^{-3}.

Planting was carried out in the first half of June, using seed-fertilizer drill. Each experimental plot consisted of 5 rows of 5 m long spaced 0.2 m apart, resulting in an experimental unit of 5 m^2. The population density used was determined according to the technical recommendations for oat crops (400 seeds m^{-2}). Considering the achievement of an expected grain yield of 4 Mg ha^{-1}, 10 kg ha^{-1} of nitrogen was applied at planting, with the remainder applied as topdressing at the fourth expanded leaf stage. Additionally, 45 and 30 kg ha^{-1} of P_2O_5 and K_2O were applied at planting, respectively, based on the P and K contents in the soil.

A randomized block experimental design was used, in a 22×4 factorial arrangement consisted of 22 white oat cultivars and 4 fungicide application conditions, with three replications, under a soybean-oat crop system. Oat cultivars recommended for cultivation in Brazil and oat cultivars no longer included in the current recommendations (for use in crossing blocks in the genetic improvement of the species) were evaluated: URS Altiva, URS Brava, URS Guará, URS Estampa, URS Corona, URS Torena, URS Charrua, URS Guria, URS Tarimba, URS Taura, URS 21, FAEM 007, FAEM 006, FAEM 5 Chiarasul, FAEM 4 Carlasul, Brisasul, Barbarasul, URS Fapa Slava, IPR Afrodite, UPFPS Farroupilha, UPFA Ouro, and UPFA Gaudéria. The fungicide application conditions were scheduled as follows: no fungicide application; one application at 60 days after emergence (DAE); two applications: at 60 and 75 DAE; three applications: at 60, 75, and 90 DAE. The last application (90 DAE) was defined to ensure a minimum 30-day interval between fungicide application and grain harvest, with no pesticide application at the grain filling stage, which was visually identified by the transition of the grains from a milky to a pasty (dough) consistency until the loss of green color in the glumes. This procedure was adopted to eliminate or minimize the risk of chemical residue translocation to the grains.

The fungicide applied was FOLICUR CE at a rate 0.75 L ha^{-1}, (active ingredient: tebuconazole; class: systemic from the triazoles group; formulation: emulsifiable concentrate). Spraying to the plots was carried out using a BD 04 fan nozzle at a pressure of 45 PSI for an application volume of 120 L ha^{-1}. A pH reducer of 30 ml ha^{-1} and Nimbus mineral oil at 0.5 L ha^{-1} were added to all treatments. Weed control involved the application of metsulfuron-methyl Ally at 4 g ha^{-1}, with additional manual weeding as needed. No insecticide applications were required as insect pest populations remained below the economic injury level throughout the study. Regarding diseases, only the foliar pathogens under evaluation were managed as part of the experimental treatments, with no other significant phytosanitary issues observed.

Variables analyzed

The percentage of necrotic leaf area (NLA) was determined using three randomly collected plants from each plot. Plants were collected at 60, 75, 90, and 105 DAE for of all cultivars and fungicide application conditions. The three upper leaves

from each collected plant were removed and evaluated for leaf area. These leaves were taken to a laboratory and digitalized, and the images were analyzed using a leaf area reader and the software WinDIAS (Copyright 2012, Delta-T Devices Limited) to determine necrosis caused by the disease on the total leaf area. The three central rows of each plot were considered for estimating grain yield, with mechanical harvesting performed when grains moisture content was approximately 15%. Grains were taken to the laboratory for moisture correction to 13%, followed by threshing and weighing to obtain the grain yield in grams, which was converted to kg ha^{-1}.

Oat cultivars were classified as superior (*S*) and inferior (*I*) based on their performance regarding necrotic leaf area and grain yield in each agricultural year scenario, 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. Additionally, the cultivars that yielded the best results in terms of necrotic leaf area and grain yield, regardless of the agricultural year, were determined by quantifying the total means classified as superior for each cultivar.

Statistical analysis and multiple linear regression

Necrotic leaf area and grain yield data were subjected to analysis of variance to assess the main and interaction effects between the factors (oat cultivar and fungicide application condition) in each agricultural year (not shown). Subsequently, linear regression analysis was performed, using the equation ($\boldsymbol{Y = b_0 + b_1 x}$), to describe the relationship between necrotic leaf area and grain yield with the number of fungicide applications. The performance of oat cultivars was assessed through analysis of the magnitude of the linear equation parameters, classifying the intercept (b_o) as superior (*S*) and inferior (*I*), which indicates the starting point of the variable in the regression; the angular coefficient (b_1) was also assessed, which indicates the variable's growth rate as a function of the number of fungicide applications. The criterion considered for evaluating these parameters was based on one standard deviation above or below the overall mean. Statistical analyses were performed considering an significance level of 5%, using the free software GENES (Cruz, 2013).

Conclusion

The analyses of necrotic leaf area and grain yield revealed that the Brazilian oat cultivars most resilient to reduced fungicide use, with no application during the grain filling stage, were URS Altiva, UPFPS Farroupilha, and UPFA Gaudéria. Therefore, these cultivars have significant potential as genetic resources for promoting food security or for cultivation in agroecological production systems.

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