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Weather conditions favorable for agricultural spraying in Rio Grande do Sul State[1]

Condições meteorológicas favoráveis para pulverização agrícola no Estado do Rio Grande do Sul

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HIGHLIGHTS:

Altitude showed a moderate negative correlation with wind speed favorability.
Air temperature was the meteorological element with greatest favorability for agricultural spraying in the Rio Grande do Sul State.
The range of the most favorable times for agricultural spraying occurred from 6:00 p.m. to 11:00 a.m.

ABSTRACT: Knowledge of the periods when the meteorological conditions are favorable for agricultural spraying is important in agricultural planning, particularly in fleet dimensioning. This study aimed to determine, on a temporal scale, favorable weather conditions for agricultural spraying in Rio Grande do Sul State, Brazil. In addition, the times and months of the year that have the most and least suitable conditions for agricultural spraying were investigated, as well as the meteorological conditions that are frequently limiting and their relationships with the geographic coordinates and altitude of the location. Hourly data from automatic weather stations in 12 locations were collected, totaling 56,500 days and 1,356,009 hourly observations. Wind speeds greater than 3 km h^{-1} and less than 10 km h^{-1}, air temperatures up to 30 °C, and relative air humidity above 55% were considered favorable. The data were released after descriptive analysis considering the registered frequency and mean. Altitude showed a moderate negative correlation with wind speed favorability. Air temperature was the meteorological element with the greatest favorability for agricultural spraying in the Rio Grande do Sul State, whereas wind speed was the most limiting meteorological element. There were no differences in favorability between the months of the year. The most favorable times were from 6:00 p.m. to 11:00 a.m. and the most unfavorable from 12:00 p.m. to 5:00 p.m. Considering the condition in which air temperature, wind speed, and relative air humidity were adequate for agricultural spraying simultaneously in the Rio Grande do Sul State, 43.2% of the periods were favorable.

Key words: application technology, pesticides, air temperature, relative air humidity, wind speed

RESUMO: O conhecimento dos momentos em que as condições meteorológicas são favoráveis à pulverização agrícola é importante no planejamento agrícola, principalmente para o dimensionamento da frota. Este estudo teve como objetivo determinar, em escala temporal, as condições climáticas favoráveis à pulverização agrícola no Estado do Rio Grande do Sul, assim como as épocas e meses do ano com melhores e piores condições, o elemento meteorológico mais limitante e suas relações com as coordenadas geográficas e a altitude do local. Foram utilizados dados horários de estações meteorológicas automáticas de 12 locais, perfazendo um total de 56.500 dias e 1.356.009 observações horárias. Foram considerados favoráveis os valores de velocidade do vento acima de 3 km h^{-1} e abaixo de 10 km h^{-1}, temperatura do ar ≤ 30 °C e umidade relativa do ar maior que 55%. Os dados foram expostos após à análise descritiva considerando a frequência e a média registrada. A altitude apresentou correlação negativa moderada com a velocidade do vento. A temperatura do ar é o elemento meteorológico com maior favorabilidade para pulverizações agrícolas no Rio Grande do Sul. A velocidade do vento é o elemento meteorológico mais limitante. Não houve diferença de favorabilidade entre os meses do ano. Os horários mais favoráveis ocorreram das 18:00 às 11:00 h e os mais desfavoráveis das 12:00 às 17:00 h. Considerando a condição em que a temperatura do ar, velocidade do vento e umidade relativa do ar foram simultaneamente adequadas para a pulverização agrícola no Rio Grande do Sul, 43,2% dos momentos foram favoráveis.

Palavras-chave: tecnologia de aplicação, defensivos agrícolas, temperatura do ar, umidade relativa do ar, velocidade do vento

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Introduction

The agricultural sector has been subject to heavy criticism due to pesticide application, which, if not properly performed, can cause environmental contamination and harm to human health. Although its use has allowed large-scale agriculture and a stable crop yield per unit area, these activities should be performed from a sustainable development perspective to prevent environmental contamination, health damage to humans and animals, the appearance of pests and pathogens, weed resistance, and increased control costs (Pretty & Bharucha, 2015; Lamichhane, 2017).

Spray drift is the physical movement of airborne pesticide droplets beyond the targeted area of application due to adverse environmental factors in the field (Zhang et al., 2018) and is one of the main sources of environmental contamination. It is characterized by droplets that are emitted by the equipment used in aerial or ground spraying operations that do not reach the desired target and settle on another surface.

In Rio Grande do Sul State, Brazil, legislative measures are being adopted to prevent drift occurrences with hormonal herbicides. Considering the negative impacts of drift cases on sensitive crops, the state normative instructions nº 5, nº 6, and nº 9, enacted in the official diary by the Secretariat of Agriculture, Livestock, and Rural Development of Rio Grande do Sul in 2019 aimed at conditioning the sale and use of hormonal herbicides upon meeting several factors, involving all the parties responsible for the use of these tools.

Adverse weather conditions, such as high air temperature, low relative air humidity, absence of wind, or high wind speeds are climatic factors varying on spatial and temporal scales that may increase spray drift and compromise the cultivation of sensitive crops (Ramos et al., 2004; Langenbach & Caldas, 2018). Weather conditions can limit the durability of the spraying equipment, with the appropriate number of days per hour of use constituting an essential factor in the dimensioning of the agricultural fleet (Rosa, 2017). From this perspective, it is essential to know the times when weather conditions are favorable for agricultural spraying, since this information may refine the calculations for fleet dimensioning.

This study aimed to determine, on a temporal scale, the favorable weather conditions for agricultural spraying in Rio Grande do Sul State, Brazil. It also investigated the times and months of the year that have the most and least suitable conditions for agricultural spraying, which meteorological elements are often limiting, and their relationships with the geographic coordinates and altitude of the location.

Material and Methods

The data used in this study were provided in open access by the Brazilian National Institute of Meteorology (INMET) and collected from automatic weather stations located in Rio Grande do Sul State, Brazil. The stations were chosen to encompass the different physiographic regions of agricultural importance in the state, using the available datasets with longer periods. Thus, 12 study locations were selected, with datasets ranging from 4,028 to 5,757 days, disregarding entry errors (Table 1). The total dataset consisted of 56,500 days of observation and 1,356,009 hourly observations.

According to the Köppen climate classification, the state of Rio Grande do Sul presents the Cfa and Cfb climate types, with no defined dry season and hot and moderately hot summers, respectively. The Cfa type prevails in most of the state, whereas the Cfb type occurs in the highest parts of the Serra do Nordeste, Planalto, and Serra do Sudeste highland regions in the state. Among the studied locations, only Bento Gonçalves, Lagoa Vermelha, and Passo Fundo were classified as Cfb (Kuinchtner & Buriol, 2001).

The data were classified according to the time of day and month by analyzing the relative number of points in which air temperature, wind speed, and relative air humidity were favorable for agricultural spraying, considering the limits proposed by Ramos et al. (2004). The general favorability condition was defined when the four meteorological elements simultaneously presented favorable conditions.

The wind speed values were considered favorable at values greater than 3 km h^{-1} (0.833 m s^{-1}) and less than 10 km h^{-1} (2.778 m s^{-1}) (Ramos et al., 2004). In the INMET weather stations, wind speed was measured at a height of 10 m. Thus, it is necessary to mathematically adjust this value to a height of 2 m, according to the vertical wind speed profile (Varejão-Silva, 2006). An air temperature limit of 30 °C was established as favorable for agricultural spraying, and values exceeded this were considered unfavorable. For relative air humidity, data below 55% were considered unfavorable (Ramos et al., 2004).

Table 1. Altitude, geographic coordinates, opening date, percentage of entry errors, and number of operational days in the datasets of the automatic weather stations used for the analysis of meteorological favorability for spraying in Rio Grande do Sul State, Brazil

Location	Altitude (m)	Latitude	Longitude	Opening date	Errors (%)	Operational days
Bento Gonçalves	623	-29.16°	-51.53	12/01/06	3.8	4,596
Camaquã	92	-30.81°	-51.83°	12/12/06	5.5	4,505
Cruz Alta	427	-28.60°	-53.67°	05/31/07	2.6	4,476
Jaguarão	31	-32.53°	-53.38°	01/09/07	4.4	4,532
Lagoa Vermelha	834	-28.22°	-51.51°	03/02/07	3.0	4,545
Passo Fundo	681	-28.23°	-52.40°	11/27/06	1.0	4,732
Rio Pardo	107	-29.87°	-52.38°	10/01/06	7.4	4,482
Santa Maria	103	-29.72°	-53.72°	11/27/01	12.9	5,757
Santana do Livramento	328	-30.84°	-55.61°	11/22/01	22.0	5,159
Santo Augusto	490	-27.85°	-53.79°	12/05/01	21.3	5,196
São Luiz Gonzaga	246	-28.42°	-54.96°	07/25/07	11.3	4,028
Uruguaiana	74	-29.84°	-57.08°	09/28/06	7.2	4,491

The data were released after the descriptive analysis, considering the registered frequency and mean. Relative frequency analysis was performed using the function (Eq. 1):

$$FAV = \frac{n}{N} \quad (1)$$

where:

FAV - favorability for agricultural spraying at the studied time, month, or location;

n - number of occurrences of the favorable condition; and,

N - total of observations evaluated.

The favorability of occurrence was correlated with the geographic coordinates of the studied locations (latitude, longitude, and altitude) by applying Pearson's correlation. Correlation values below 0.30 represent a weak correlation, values from 0.30 to 0.60 represent a moderate correlation, values from 0.60 to 0.90 correspond to a strong correlation, and values above 0.90 represent a very strong correlation (Pereira, 1979). The normality of errors of the data from different locations, months of the year, and times of the day was tested using the Shapiro–Wilk test, and the homogeneity of variances by Bartlett's test. The data were subjected to arcsine square root transformation to meet the assumption of normality. The data were compared using analysis of variance for locations, local time, and months. The means were compared using the Scott-Knott test at $p \leq 0.05$.

Results and Discussion

Altitude and longitude were significantly correlated with the favorability of some meteorological elements for agricultural spraying. Altitude showed a moderate negative correlation with the favorability of wind speeds greater than 10 km h^{-1}; as altitude increased, favorability decreased (Table 2).

Wind speeds less than 3 km h^{-1} showed positive favorability with altitude, while wind speed greater than 10 km h^{-1} had a lower favorability with altitude, which may be correlated with the probable increase in wind speed with increased elevation. According to Costa & Lyra (2012), in Alagoas State, Brazil, higher regions have greater wind speeds compared to regions closer to sea level. For the Paraná State, Oliveira & Borrozzino (2018) also verified a trend toward wind speed increase with the rise in altitude. The north winds are likely mainly responsible for decreasing the favorable spray times, especially under higher altitude conditions. Heldwein et al. (2003), in a study performed in Santa Maria, RS, Brazil, concluded that strong winds occur predominantly from the north.

The longitude of the study area was strongly correlated with air temperature and relative air humidity favorability for spraying. In the Rio Grande do Sul State, longitude is associated with continentality, as the Atlantic Ocean is located to the east of this state. Therefore, greater continentality occurs as longitude lowers. Sartori (2015) highlighted that continentality allows higher solar radiation availability due to lower nebulosity. This increase in air temperature corresponds to a decrease in relative air humidity, which is an unfavorable condition for agricultural spraying.

The condition in which air temperature, wind speed, and relative air humidity were favorable for spraying in Rio Grande do Sul were when they were simultaneously positively related, which occurred in only 43.2% of the periods. There was variation among study locations, with the greatest favorability occurring in Rio Pardo, which did not differ significantly from Santa Maria and Bento Gonçalves. The lowest favorability occurred in Cruz Alta (Table 3). This variation can be explained

Table 2. Pearson's correlation between altitude (m), latitude (°), and longitude (°), and the favorability of air temperature (°C), wind speed greater than 10 km h^{-1}, wind speed less than 3 km h^{-1}, relative air humidity (%), and the four conditions simultaneously (General) for agricultural spraying in Rio Grande do Sul, Brazil

Factor	Air temperature	Wind speed > 10	Wind speed < 3	Relative air humidity	General
	(n = 12)				
Altitude	0.541^{ns}	-0.602*	0.502^{ns}	-0.092^{ns}	-0.029^{ns}
Latitude	-0.094^{ns}	-0.362^{ns}	0.328^{ns}	-0.485^{ns}	-0.065^{ns}
Longitude	0.750**	0.206^{ns}	-0.103^{ns}	0.716**	0.320^{ns}

Pearson's correlation: *Moderate; **Strong; ^{ns} - Not significant at $p \leq 0.05$, t-test

Table 3. Favorability of air temperature, wind speed greater than 10 km h^{-1}, wind speed less than 3 km h^{-1}, relative air humidity, and the four conditions simultaneously (General) for agricultural spraying in different locations of Rio Grande do Sul State, Brazil

Location	Air temperature	Wind speed > 10	Wind speed < 3	Relative air humidity	General
Bento Gonçalves	0.991 a	0.707 d	0.906 b	0.902 b	0.544 a
Camaquã	0.978 a	0.963 a	0.403 f	0.936 a	0.323 d
Cruz Alta	0.969 b	0.654 e	0.660 e	0.843 c	0.250 e
Jaguarão	0.983 a	0.689 e	0.816 d	0.907 b	0.461 b
Lagoa Vermelha	0.994 a	0.600 f	0.974 a	0.864 c	0.489 b
Passo Fundo	0.989 a	0.547 g	0.907 b	0.869 c	0.385 c
Rio Pardo	0.964 b	0.777 c	0.849 c	0.891 b	0.558 a
Santa Maria	0.955 b	0.862 b	0.769 d	0.876 c	0.543 a
Santana do Livramento	0.972 b	0.654 e	0.920 b	0.814 d	0.421 b
Santo Augusto	0.967 b	0.683 e	0.863 c	0.763 e	0.401 c
São Luiz Gonzaga	0.919 c	0.741 d	0.884 c	0.759 e	0.471 b
Uruguaiana	0.933 c	0.626 f	0.801 d	0.792 d	0.332 d
General mean	0.968	0.709	0.813	0.852	0.432
CV (%)	1.62	4.82	5.81	3.53	11.99

Means followed by the same letter in the column do not differ from each other according to the Scott-Knott test at $p \leq 0.05$; CV - Coefficient of variation

by the different favorability values of the meteorological elements in each location.

Air temperature was the meteorological element with the greatest favorability for agricultural spraying in Rio Grande do Sul State, and the most limiting at São Luiz Gonzaga and Uruguaiana. Since the Rio Grande do Sul state is located in a region of subtropical and temperate climates (Kuinchtner & Buriol, 2001), such behavior is justified, since it is possible that air temperature is a limiting factor in tropical climate regions.

Wind speed greater than 10 km h^{-1} was the most limiting meteorological element for spraying. In Passo Fundo, only 54.7% of the points showed favorable conditions for spraying (Table 3). In contrast, in Camaquã, only 40.3% of the points had wind speeds of less than 3 km h^{-1}, allowing for spraying. Amarante et al. (2002) highlighted that the average wind speed in Passo Fundo, indicated by the potential to generate wind energy, is superior to that of Camaquã. This difference is probably due to the higher altitude in Passo Fundo, which moderately correlates with favorability (Table 3).

Although 12 locations have been evaluated, the ideal would be for this information to be collected on a more detailed spatial scale, since the meteorological elements have great spatial variation. Currently this is not possible because of the limited availability of weather stations. At the operational level, the ideal would be for weather stations to be installed on all farms, a condition that is still far from being achieved in the studied region.

The effect of relative air humidity on spray drift occurrence was reported by Nuyttens et al. (2006) as a larger factor than wind speed. Higher wind speed values result in greater spray drift. However, these authors concluded that the effect of wind speed on the amount of drift was less pronounced than the effect of relative air humidity. Cunha et al. (2016) concluded that relative air humidity was the most limiting weather element to spraying in Uberlândia, in Minas Gerais State. The presence of a high vapor pressure deficit in the air, a condition associated with low relative air humidity, may decrease the size of the droplets sprayed, making them more susceptible to wind drag (Maciel et al., 2017). Fornasiero et al. (2017) established that changes in droplet size and the use of spray adjuvants are tools that can help prevent spray drift.

Relative air humidity showed intermediate favorability, limiting the application times of phytosanitary products up to 24.1%, such as in São Luiz Gonzaga, where the verified favorability was 0.759 (Table 3). This location showed no significant difference from the Santo Augusto station. The other four locations that showed lower favorability for spraying due to low values of relative air humidity were farther from the Atlantic Ocean, corroborating the previously reported affirmation by Sartori (2015).

The night and morning hours showed greater favorability for agricultural spraying, whereas there was less favorability in the afternoon (Table 4). The most favorable hours occurred from 6:00 p.m. to 11:00 a.m., and the more unfavorable hours from 12:00 p.m. to 5:00 p.m. These results suggest that night application is recommended, although the factors related to spraying must be observed. There are particularities in relation to plant nyctinasty, pesticides that are not recommended for nocturnal spraying, and the behavior of some pests.

Air temperature can directly or indirectly influence the occurrence of spray drifts. At high temperatures, the vapor pressure deficit and the vertical thermal gradient tend to be

Table 4. Favorability of air temperature, wind speed greater than 10 km h^{-1}, wind speed less than 3 km h^{-1}, relative air humidity, and the four conditions simultaneously (General) for agricultural spraying at different times of the day in Rio Grande do Sul State, Brazil

Local time	Air temperature	Wind speed > 10	Wind speed < 3	Relative air humidity	General
12:00 a.m.	1.000 a	0.740 a	0.774 a	0.974 a	0.487 a
1:00 a.m.	1.000 a	0.745 a	0.766 a	0.981 a	0.484 a
2:00 a.m.	1.000 a	0.749 a	0.757 a	0.985 a	0.479 a
3:00 a.m.	1.000 a	0.752 a	0.752 a	0.988 a	0.479 a
4:00 a.m.	1.000 a	0.757 a	0.748 a	0.990 a	0.480 a
5:00 a.m.	1.000 a	0.757 a	0.745 a	0.991 a	0.477 a
6:00 a.m.	1.000 a	0.757 a	0.744 a	0.993 a	0.480 a
7:00 a.m.	1.000 a	0.740 a	0.763 a	0.992 a	0.482 a
8:00 a.m.	0.999 a	0.691 b	0.802 a	0.983 a	0.474 a
9:00 a.m.	0.996 a	0.641 c	0.846 a	0.953 a	0.462 a
10:00 a.m.	0.983 b	0.625 c	0.874 a	0.893 b	0.448 a
11:00 a.m.	0.959 b	0.621 c	0.894 a	0.802 c	0.418 a
12:00 p.m.	0.931 c	0.633 c	0.903 a	0.702 d	0.378 b
1:00 p.m.	0.903 d	0.640 c	0.906 a	0.619 e	0.338 b
2:00 p.m.	0.885 e	0.641 c	0.904 a	0.567 f	0.308 b
3:00 p.m.	0.878 e	0.647 c	0.897 a	0.549 f	0.296 b
4:00 p.m.	0.887 e	0.657 c	0.883 a	0.567 f	0.304 b
5:00 p.m.	0.909 d	0.690 b	0.854 a	0.624 e	0.337 b
6:00 p.m.	0.940 c	0.746 a	0.810 a	0.729 d	0.396 a
7:00 p.m.	0.976 b	0.782 a	0.776 a	0.833 c	0.445 a
8:00 p.m.	0.993 a	0.774 a	0.772 a	0.895 b	0.468 a
9:00 p.m.	0.997 a	0.752 a	0.779 a	0.930 a	0.475 a
10:00 p.m.	0.999 a	0.739 a	0.779 a	0.951 a	0.477 a
11:00 p.m.	0.999 a	0.736 a	0.777 a	0.964 a	0.482 a
CV (%)	1.62	4.82	11.7	3.53	14.84

Means followed by the same letter in the column do not differ from each other by the Scott-Knott test at $p \leq 0.05$ of error; ^{ns} - Not significant at $p \leq 0.05$ of error; CV - Coefficient of variation

higher (Varejão-Silva, 2006). In contrast, spray drift is strongly increased under low relative air humidity and high vapor pressure deficit (Nuyttens et al., 2006; Maciel et al., 2017). When the vertical air temperature gradient is increased, a condition that represents atmospheric instability, the convective flow may lift small spray droplets, causing them to remain longer in suspension increasing their susceptibility to the effects of wind (Fritz, 2006), which even at lower speeds can potentialize the occurrence of spray drift. The average air temperature at all locations was favorable in 96.8% of the points (Table 3). The condition of greater air temperature favorability occurred from 8:00 p.m. to 9:00 a.m., greater than half of the day, while the more restrictive range extended from 2:00 p.m. to 4:00 p.m. (Table 4).

Wind is one of the main meteorological elements involved in the occurrence of spray drift, and ways to overcome its influence or the suitability of application times to lower wind speed periods are strategies that allow for scheduling and optimization of field operations (Abi Saab, 2004). The average favorability of wind speeds greater than 10 km h^{-1} at different locations also varied with the time of the day. The period from 9:00 a.m. to 4:00 p.m. had the lowest wind speed favorability for spraying (Table 4). The most favorable conditions occurred from 6:00 p.m. to 7:00 a.m. This result was expected, as atmospheric radiation balance influences wind speed, and at times of negative radiation balance, such as at night, the wind speed tends to be less. During the day, this balance will be positive, correlating with a higher wind speed. The seasons of the year and region also influenced the wind speed. In Brazil, the beginning of summer is marked by weaker winds as spring generally has stronger winds (Biscaro, 2007), which coincides with the implantation of the main summer annual crops in the Rio Grande do Sul State.

The greatest variation in favorability throughout the day was observed for relative air humidity (Table 4). The least limiting values occurred from 9:00 p.m. to 9:00 a.m., whereas the most limiting values were concentrated between 2:00 p.m. and 4:00 p.m.

The spraying of pesticides in a windless situation or with very low wind speeds (below 3 km h^{-1}) are equally harmful to those carried out at wind speeds above 10 km h^{-1} (Azevedo & Freire, 2006). In situations with calm winds, pesticide molecules can ascending in the atmosphere due to convective currents and thermal inversions, which occur when there is a formation of a warmer air layer close to the ground that is retained by a cooler upper layer. In these cases, it is difficult to deposit the drops, especially the finer ones, which are suspended in the most heated air layer, and the product is lost mainly by evaporation and does not reach the desired location, impairing the action of the products, possibly resulting in damage to the environment and off-target deposition (Enz et al., 2014; Bish et al., 2019). The favorability for wind speeds less than 3 km h^{-1} varied greatly between the studied locations, with the least favorable meteorological element being only for Camaquã and Santa Maria (Table 3). Favorability due to low wind speed (below 80%) was observed from 7:00 p.m. to 7:00 a.m. (Table 4). After sunset, at night, and early in the morning, the loss of energy from the surface due to the emission of long-wave radiation is accentuated, with the possibility of thermal inversion, an adverse situation in pesticide spraying. Thermal inversion is a greater threat in sprayings with volatile herbicides, as they can be suspended in the atmosphere and when deposited in sensitive cultures, can cause damage after the inversion conditions return to normal (Bish & Bradley, 2017; Oseland et al., 2020).

There was no difference between months when the four meteorological elements were observed simultaneously (Table 5). However, May showed the greatest favorability for agricultural spraying in the Rio Grande do Sul State. November showed a 36.5% favorability of points in which the wind speed, air temperature, and relative air humidity conditions were favorable for agricultural spraying.

The period in which air temperature is the least limiting extends from April to October. Relative air humidity tends to be more favorable only from May to June, which is decisive for general favorability, comprising the four conditions at the same time. Although air temperature was not the most limiting factor in November, wind speed and relative air humidity conditions were the least favorable, making this month the least feasible for agricultural spraying.

At night, wind speeds greater than 10 km h^{-1} played a crucial role in limiting the environmental conditions for agricultural spraying, and the favorability values of air temperature and relative air humidity were less limiting.

Table 5. Favorability of air temperature, wind speed greater than 10 km h^{-1}, wind speed less than 3 km h^{-1}, relative air humidity, and the four conditions simultaneously (General) for agricultural spraying in different months of the year in Rio Grande do Sul State, Brazil

Months	Air temperature	Wind speed > 10	Wind speed < 3	Relative air humidity	General
January	0.913 c	0.716 b	0.855 a	0.842 c	0.432 a
February	0.925 c	0.753 a	0.851 a	0.867 c	0.454 a
March	0.964 b	0.763 a	0.846 a	0.861 c	0.457 a
April	0.982 a	0.786 a	0.839 a	0.844 c	0.454 a
May	0.999 a	0.767 a	0.828 a	0.923 a	0.480 a
June	1.000 a	0.747 a	0.824 a	0.933 a	0.479 a
July	1.000 a	0.718 b	0.803 a	0.897 b	0.447 a
August	0.995 a	0.646 d	0.793 a	0.862 c	0.412 a
September	0.990 a	0.636 d	0.784 a	0.851 c	0.411 a
October	0.984 a	0.632 d	0.777 a	0.845 c	0.406 a
November	0.956 b	0.648 d	0.776 a	0.747 d	0.365 a
December	0.913 c	0.695 c	0.774 a	0.763 d	0.388 a
CV (%)	1.23	2.19	10.81	1.80	12.92

Means followed by the same letter in the column do not differ from each other by the Scott-Knott test at $p \leq 0.05$ of error; ^{ns}-Not significant at $p \leq 0.05$; CV - Coefficient of variation

Conversely, during the day, in most locations studied, relative air humidity represented a greater limitation for agricultural spraying than wind speed, especially between the afternoon and early evening (Figure 1).

Although air temperature was one of the least limiting meteorological factors (Table 3), the differences observed between the studied locations should be considered. The lowest favorability values were observed at 3:00 p.m. for São Luiz Gonzaga and Uruguaiana. In São Luiz Gonzaga, during the afternoon, air temperature becomes even more limiting than wind speed greater than 10 km h^{-1}, thus justifying the importance of evaluating each location, month of the year, and time of the day, with the aim of obtaining a better diagnosis of the actual favorable conditions for agricultural spraying applied to each area of interest.

In most locations, the favorability period below the average extended from August to January. Wind speeds greater than 10 km h^{-1} are the most limiting elements in most locations and months of the year. However, in São Luiz Gonzaga, from November to April, relative air humidity was the most limiting meteorological element (Figure 2). The same occurred in April and November in Santo Augusto, and in May in Santa Maria. Camaquã showed a different behavior, in which relative air humidity and wind speed less than 3 km h^{-1} were the most limiting meteorological elements, except in January and February, when air temperature showed lower favorability than relative air humidity.

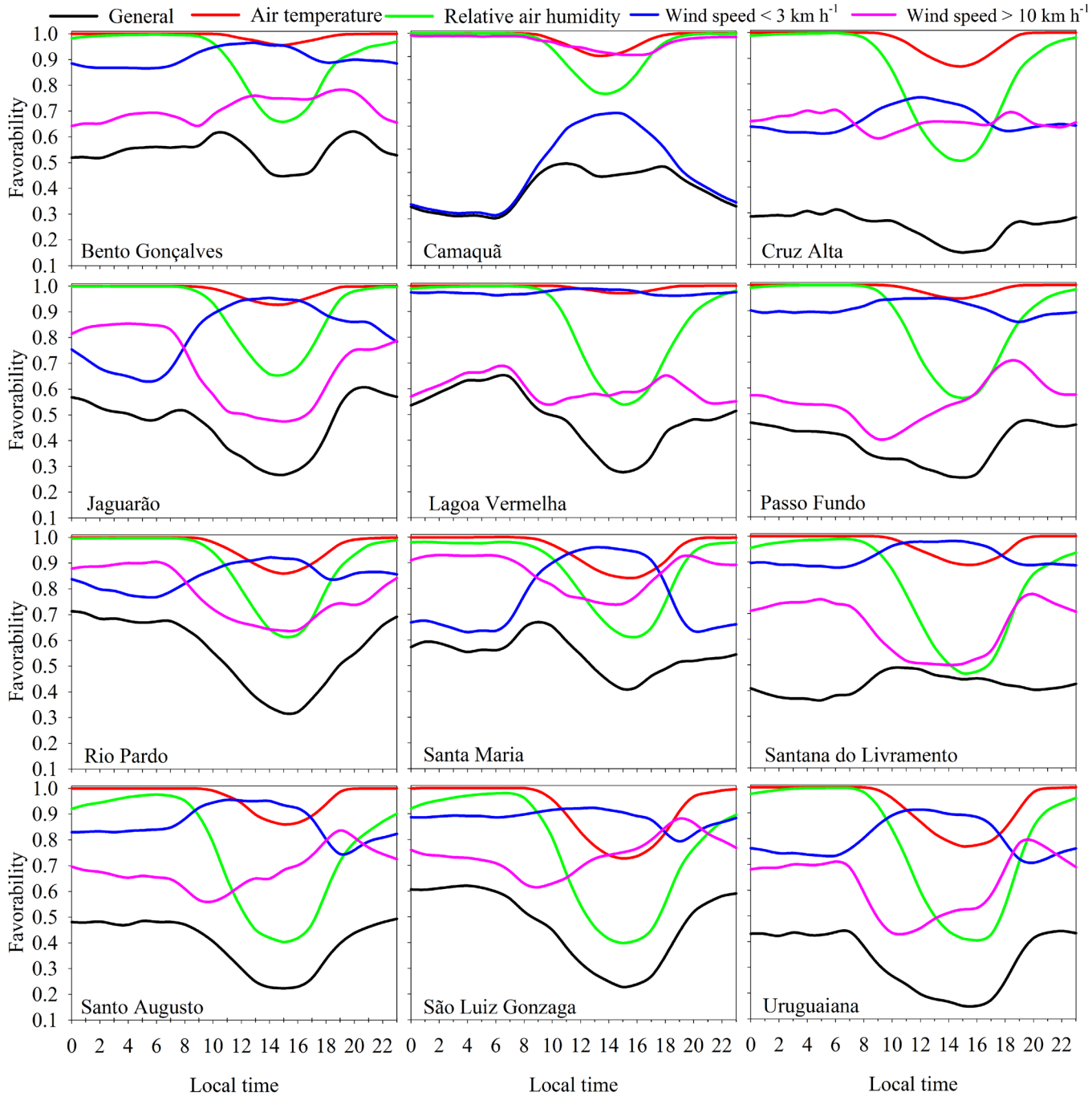

Figure 1. Favorability of air temperature, wind speed greater than 10 km h^{-1}, wind speed less than 3 km h^{-1}, relative air humidity, and the four conditions simultaneously (General) for agricultural spraying at different times of the day and locations in the Rio Grande do Sul State, Brazil

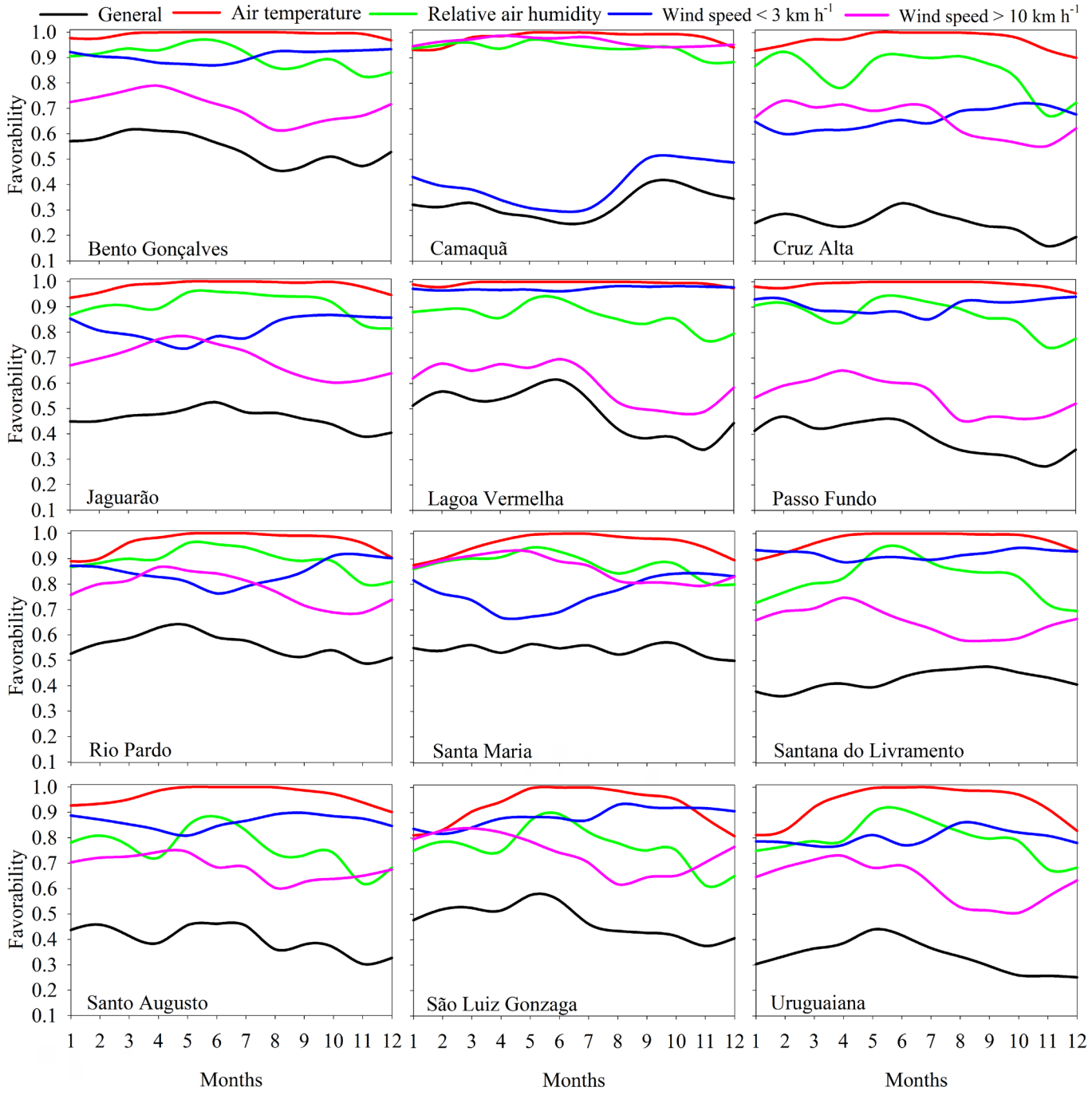

Figure 2. Favorability of air temperature, wind speed greater than 10 km h^{-1}, wind speed less than 3 km h^{-1}, relative air humidity, and the four conditions simultaneously (General) for agricultural spraying in different months of the year and locations in the Rio Grande do Sul State, Brazil

It was verified that meteorological conditions can be limiting for agricultural spraying and should be taken into consideration during the dimensioning of the agricultural machinery fleet and the calculation of the operational capacity of the equipment. Depending on the location and month of the year in which a certain pesticide needs to be applied to the crop, the favorable conditions may be limited to only 15.9% of times, such as in Cruz Alta, in November. Other strategies may be considered to enable the spraying operation, even in relatively unfavorable conditions, such as the use of appropriate spray nozzles, adjuvants, lower volatilization pesticides, green barriers, and other practices aimed at increasing the efficiency of the spray (Fornasiero et al., 2017; Langenbach & Caldas, 2018; Miranda-Fuentes et al., 2018).

Conclusions

1. Altitude showed a moderate negative correlation with wind speed favorability. Longitude was strongly correlated with air temperature and relative air humidity favorability for spraying.

2. Air temperature was the meteorological element with greater favorability for agricultural spraying in the Rio Grande do Sul State. Wind speed was the most limiting meteorological element.

3. There were no significant differences in general favorability between the months of the year.

4. The range of the most favorable times of day occurred from 6:00 p.m. to 11:00 a.m., and the most unfavorable from 12:00 p.m. to 5:00 p.m.

5. Considering the condition in which air temperature, wind speed, and relative air humidity were simultaneously suitable for agricultural spraying in the Rio Grande do Sul State, 43.2% of the periods were favorable.

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