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Agricultural zoning and recommendations for the seeding of wheat (*Triticum* species) in the Central-Southern Mesoregion of Parana State in Brazil

Ana Paula Ferreira Dominoni[1]*, Nathan Felipe da Silva Caldana[1], Leonardo Rodrigues[1], Bruno Wismeck Negrão[1], Vitor Rampazzo Favoretto[2], Victor Ricardo Bodnar[3] and Marcelo Augusto de Aguiar e Silva[1]

[1]Departamento de Agronomia, Universidade Estadual de Londrina, Londrina-PR, 86057-970, Brazil.
[2]Department of Crop Sciences, the University of Illinois at Urbana-Champaign, Turner Hall, 1102 S Goodwin Ave, Urbana, IL 61801, United States.
[3]Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK, 74078, United States.

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Wheat is one of the most cultivated cereals and is essential for human and animal feeding. Since it is a sensible species to the meteorologic conditions, the climate changes can alter all its cultivation areas and practices known in the present agriculture. This paper aims to make the zoning of climatic risk for agriculture for the wheat crop (*Triticum* species) and recommend the planting window for the central-southern Mesoregion of Parana State. The crop's climate risk was evaluated by several variables: Temperature (minimum and average), precipitation, water deficit, and frost. The entire Mesoregion presents aptness for wheat cultivation. The water demand for the species is supplied in all tested scenarios. The risk is also not identified for precipitation. The average temperature in a section of the region is lower than the recommended, but the seeding can be shifted to seasons with increasing temperatures. The entire region presents a high probability of frost occurrence. Because wheat is a winter crop, seeding during this period could be beneficial if late frosts are avoided, mainly during August and September. Thus, seeding is recommended in small intervals in the region, varying from May 21 to September.

Key words: Climate aptness, climate risk, agricultural planning, climate change.

INTRODUCTION

Wheat is one of the most cultivated cereals, always with a high agricultural highlight, because it has significant economic importance (Pires et al., 2019), from the small to the big grower (Bezerra and Stulp, 2019), and for human and animal feeding (Athanassof, 2019). In terms of Brazilian production, the wheat crop has a vast probability of expansion in traditional areas and the country's central region (Manfron et al., 1993). Wheat is

*Corresponding author. E-mail: ana.dominoni@hotmail.com. Tel: +55 43 9980-1546.

approximately 21% of the world's demand for food (Santi et al., 2018). Wheat is a crop of high importance in the composition of sustainable agricultural systems (Fontaneli et al., 2019), one of the most viable crops to the succession and rotation in production systems of grains, vegetables, and fibers in some regions (Barbieri et al., 2019). Thus, contributing to the maintenance of the soil production capacity and the pest and invasive species integrated management (Marsaro Junior, 2016).

In 2019, 2,000 ha were planted in Brazil, with a total production of 5,000 metric tonnes of grains (IBGE, 2020), being the south region of Brazil, accounting for 90% of the national production (ECCO et al., 2020). This cereal's cultivation presents particular aspects and risks because it is a winter crop (Marsaro Junior, 2016).

The agricultural climate zoning can contribute to the expansion of wheat cultivation because it consists of identifying the characteristics and patterns of the climate elements and factors of a country, state, or city that can be determinant in the choice of the crop, agricultural planning, and decision-making of such area (Ricce et al., 2013; Caldana et al., 2019). Thus, in the most distinct scales, the aptness and risk for each area are defined for each determined crop via maps, considering the water and climate demands of each species with agricultural interest gathering information of the farm risk, aptness, and the recommended window for planting and/or harvest. The zoning should be the first information considered in agricultural planning because the meteorological events cannot be controlled (Francisco et al., 2003; Sentelhas and Monteiro, 2009; Caldana et al., 2019).

Paraná is in a climate transition zone, with high variability of altitude and latitude, significant conditioning discrepancies in the weather, and the occurrence of frosts (de Oliveira and Borrozzino, 2018a). The state's central-southern and southwest regions have altitudes that vary from 800 to 1.300 m with negative temperatures and various frost occurrences during the year (Caramori et al., 2001). Studies that highlight the agricultural climate factors are essential for the field cultivations of the region. This study's objective was to make the zoning for the agricultural climate risk for the wheat crop (*Triticum* species), considering the climate changes that occurred in the region and recommend the seeding window in the central-southern Mesoregion of Parana State.

MATERIALS AND METHODS

Study region

Parana's central-southern Mesoregion (Figure 1) has approximately 500 thousand inhabitants (IBGE, 2019). It has an important agricultural production area (de Lima et al., 2006), showing the importance of studies of the meteorological variables. The region has the majority of its area under the "Cfb" climate (subtropical, without a dry season and mild summer), and a small section in lower altitudes with climate "Cfa" (subtropical, without a dry season and hot summer), according to the Köppen classification system of 1936 (Nitsche et al., 2019). It is one of the areas with higher precipitation in Parana State, with total rainfall varying from 1,800 to 2,200 mm (Caldana et al., 2019; Nitsche et al., 2019). Besides, a yield map was made for the cities among the Mesoregion to identify risks and capabilities that zoning can bring to wheat cultivation in the studied area.

Climate variability

For the climate variability and agricultural risk zoning, data were collected from meteorological stations (complete stations) and precipitation (only with rainfall readings) distributed through the area of study and its proximities. This database comprises six meteorological stations of IAPAR (1963-2019, with different starting dates according to the functioning period of each station, observed in Table 1), five stations from SIMEPAR (2000-2019), and 39 rainfall stations from the Parana Water (1976-2019) (Figure 1).

For the precipitation totals, only data from the rainfall stations were used because of the collected data's long age and uniformity (1976-2019). The spatial distribution of the data was made by interpolation, an efficient method for the spatial visualization of climate data. This interpolation was made via isohyets and/or filling the values by adjusted regression statistics and using the inverse distance weighted (IDW) algorithm (Varatharajan et al., 2018). The maps were created by the Software QGIS 3.12. 3 'București'.

The choice of IDW for the precipitation and sunlight data was based on the verification of the data and the number of meteorological stations available in the region because the quality of the estimator can be evaluated via cross-tabulation of the data, that is, comparison between the collected data and their estimated values from the model (Varatharajan et al., 2018).

The data points from the meteorological stations for precipitations were inserted in the Software QGIS 3.12. 3 'București' and transformed into a raster file, with the help of the IDW interpolator. This new file exhibits an adjusted regular surface to these data points of interest with a pixel of the spatial resolution of 1×1 km. Then, isohyets were inserted and their values to better visualize areas with similar precipitation and sunlight and assemble them.

The Shuttle Radar Topography Mission (SRTM) base was used to apply meteorological values into the maps using the relief and altitude geographical factors on a 30 m scale. These factors were used because they influence the air temperature. This method is needed to spatially distribute and regionalize the data to the areas with no record for temperature with higher precision.

Due to the spatial distribution of the average temperature and frost data measured, the multiple linear regressions were adjusted, articulating the meteorological stations' values with the altitude, latitude, and longitude geographical factors. Thus, obtaining the estimative equations like $y = a + x.lat + y.long + z.alt$. This equation is applied in the geoprocessing Software Arcgis on the SRTM file, enabling map generation with a spatial resolution of 30 m.

The method used for the frost probability was based on the historical series of minimal temperature registered inside of the meteorological shelter. The chances of occurrence of a temperature equal to or lower than 1.0°C were calculated (Freitas et al., 1985) and then applied to the equation $y = a + x.lat + y.long + z.alt$.

Three bases to apply the regression were created, one from SRTM for altitude, and the ones from latitude and longitude, embracing the 30 m scale. Using the "Raster Calculator" tool, the data were spatialized, and the value was generated for each pixel of each analyzed variable.

The occurrence of the first (autumn) to the last (spring) frost was estimated. The method identifies the frost at the soil surface when the shelter's minimum temperature is equal to or less than 2.0°C. Analyzing the data series per station, when the daily temperature

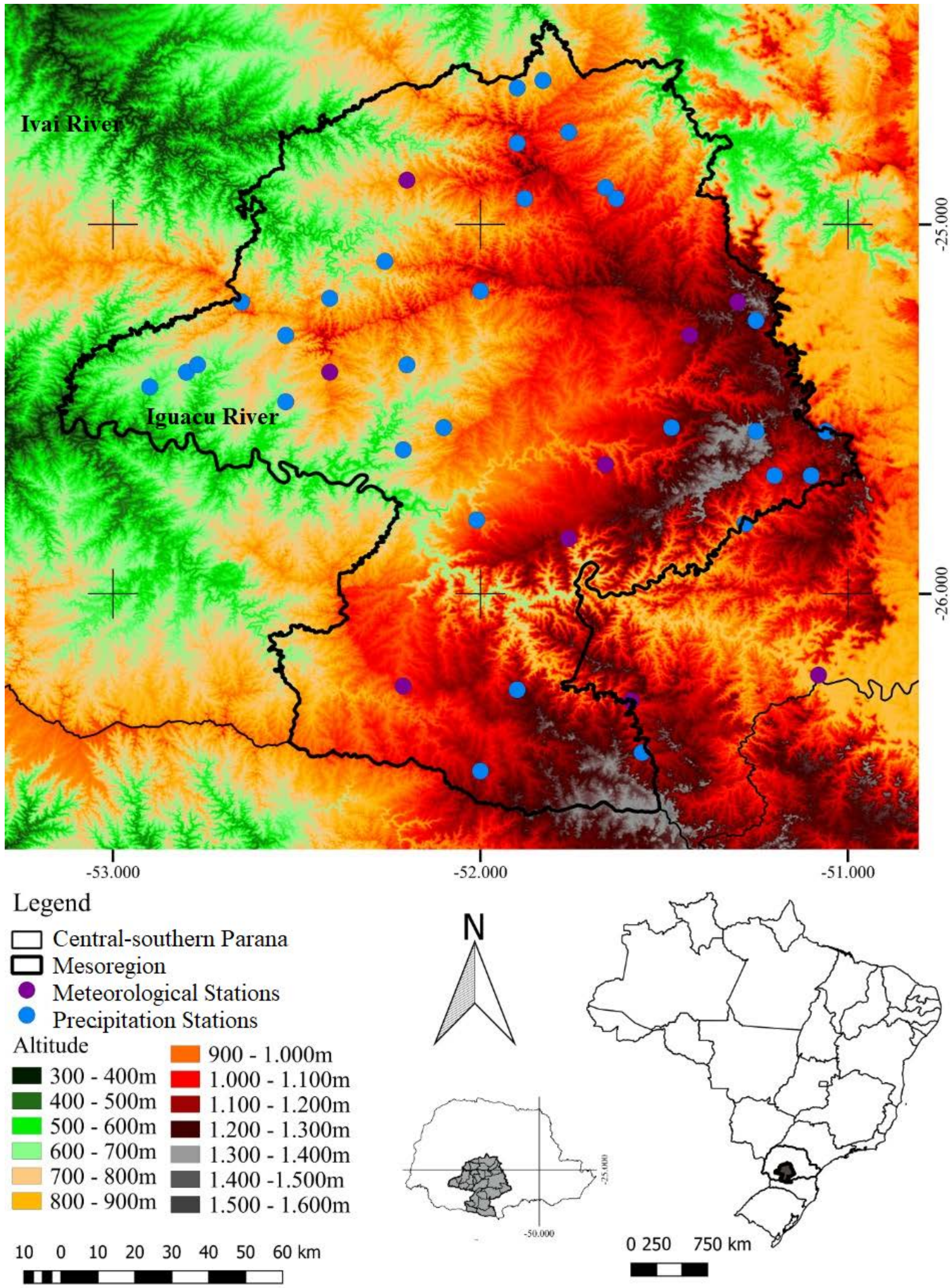

Figure 1. Location of the study area and the meteorological and precipitation stations.

fulfills the conditions earlier mentioned, the value of "1" is associated. If not, the value "0" was given. Then, the probabilities of occurrence of at least one frost are calculated for every ten days (Wrege et al., 2004).

Adopting this procedure, if in a particular ten days period occurred one or more frosts that period was labeled as "1" regardless of the number of occurrence of frosts. If not, it was labeled "0". Based on the sequences of "0" and "1" of each station's historical series, the

Table 1. Information from the meteorological stations in the study.

Responsible organ	Station (city)	Longitude	Latitude	Altitude (m)	Recording period
IAPAR/SIMEPAR	Cândido de Abreu*	-24.38	-51.15	645	1989 - 2019
IAPAR	Clevelândia	-26.25	-52.21	930	1973 - 2012
SIMEPAR	Entre Rios (Guarapuava)	-25.3	-51.43	1.050	1999- 2019
IAPAR	Fernandes Pinheiro	-25.27	-50.35	893	1963 - 2019
SIMEPAR	Foz do Areia (Pinhão)	-25.85	-51.76	1.020	1999- 2019
IAPAR	Guarapuava	-25.21	-51.3	1.058	1976 - 2019
IAPAR	Laranjeiras do Sul	-25.4	-52.41	880	1974 - 2007
IAPAR/SIMEPAR	Palmas*	-26.29	-51.59	1.100	1979 - 2019
SIMEPAR	Palmital	-24.88	-52.2	930	1999- 2019
SIMEPAR	Pinhão	-25.65	-51.66	1.050	1999- 2019
SIMEPAR	União da Vitória	-26.22	-51.08	736	1999- 2019

*Station with complete data from SIMEPAR, after IAPAR stopped collecting data

accumulated frequency for each station through the year was calculated. The date with 5% of probability at each station was considered the first autumn frost, counting from the beginning to the end of the year. The last spring frost was also determined by an accumulated frequency of 5% probability, but the calculations were done from the end to the beginning of the year (Wrege et al., 2004). As a contribution to agricultural planning, the analysis was made every ten days. Since the risk recommended to agricultural zoning is 20% in the final table, it was only considered periods with a risk higher than this threshold.

The climate water balance (CWB) was obtained by the Thornthwaite and Mather (1955) method, using the equation with the values of various meteorological variables and the soil water capacity (SWC) proportional to the wheat root effective depth. The monthly average of precipitation (extracted from the monthly total of each year) and the monthly average of temperature (obtained from the monthly average of each day for each year). First, the potential evapotranspiration under standard conditions (PEs, mm/month) was calculated by the Thornthwaite method. Then, the potential evapotranspiration was calculated (EP).

Agricultural climate risk zoning

In the conditions of the south region of Brazil, the recommended wheat cultivars present an average cycle between 120 and 130 days (Petrucci et al., 1980). This way, the variables were evaluated considering the period that the cultivar is in the field. The risk factors selected for the agricultural climate risk zoning were:

(a) Annual precipitation: The precipitation was selected from monthly and yearly rainfall data from meteorological series of 39 rainfall stations from the basin. The results were interpolated in a geographical information system to generate maps with data regionalization by IDW. Besides, the precipitation graphic was created with the grouped precipitation by the crop cycle. It was considered a risk of the four-month rainfall below 380 mm (Freitas et al., 1985).
(b) Water deficit (Wd): The Wd was estimated according to the Thornthwaite and Matter (1955) method. It is obtained by the calculation of the climatological water balance to the meteorological stations. The value of 60 mm was used for the SWC, considering that the root system of wheat explores a depth superior to 20 cm of the soil profile (Camargo and Oliveira, 1981). The results were interpolated in the geographic information system (SIG) ArcGis 10.0 to generate the yearly water deficit maps. To the risk of water deficit, it was considered: High risk: Wd>60 mm and Low risk: Wd<60 mm during the cycle (Freitas et al., 1985; Hayes, 2019).
(c) Probability of later frost occurrence used meteorological data of historical series of maximum temperatures observed inside of the meteorological shelters being lower than 1°C; by the risk, the value was applied to a regression in the function of the latitude, longitude, and altitude to map the entire region. Besides the map, to help in the seeding recommendation, the period free of frost by season was estimated (Marsaro Junior, 2016).
(d) Average annual temperature (At): meteorological data was used from the historical series of average temperature observed inside the shelters to estimate the yearly average temperature. The value of At was regressed as a function of latitude, longitude, and altitude for the entire Mesoregion recommended superior to 17°C (Doorenbos et al., 1979).

In the ArcGIS software, to the creation of each map, including the final zoning one, the numerical values from the meteorological stations are transformed in points using each station's geographic coordinates. After the data spatialization, the weather and soil conditions for the species were used to determine the limits of the representative strips for the wheat crop's climate demands. The station values were replaced by "1 Apt" or "2 Restrict" according to the physiological needs for each weather variable analyzed.

The next step was the combination of the gridded images. For each pixel, it was attributed to the values "1" or "2". Suppose the combination for one point was filled by only "1", the pixel was classified as apt. If there is one "2", it will be restricted by a particular variable. If two or more "2" values are registered, the place was labeled as inept.

Then, the uniformity of pixels was made by classifying through the dissolution of vectorial classes. This way, the zoning classes were grouped, creating a regionalization of the aptness for each species. The final zoning map of each crop provides an estimative of the representative area of each risk class, guaranteeing its aptness or not to the spot, beyond the recommendation for the best seeding time according to the agricultural and weather demands during the entire cycle of the crop.

RESULTS AND DISCUSSION

Wheat production is already present in the entire

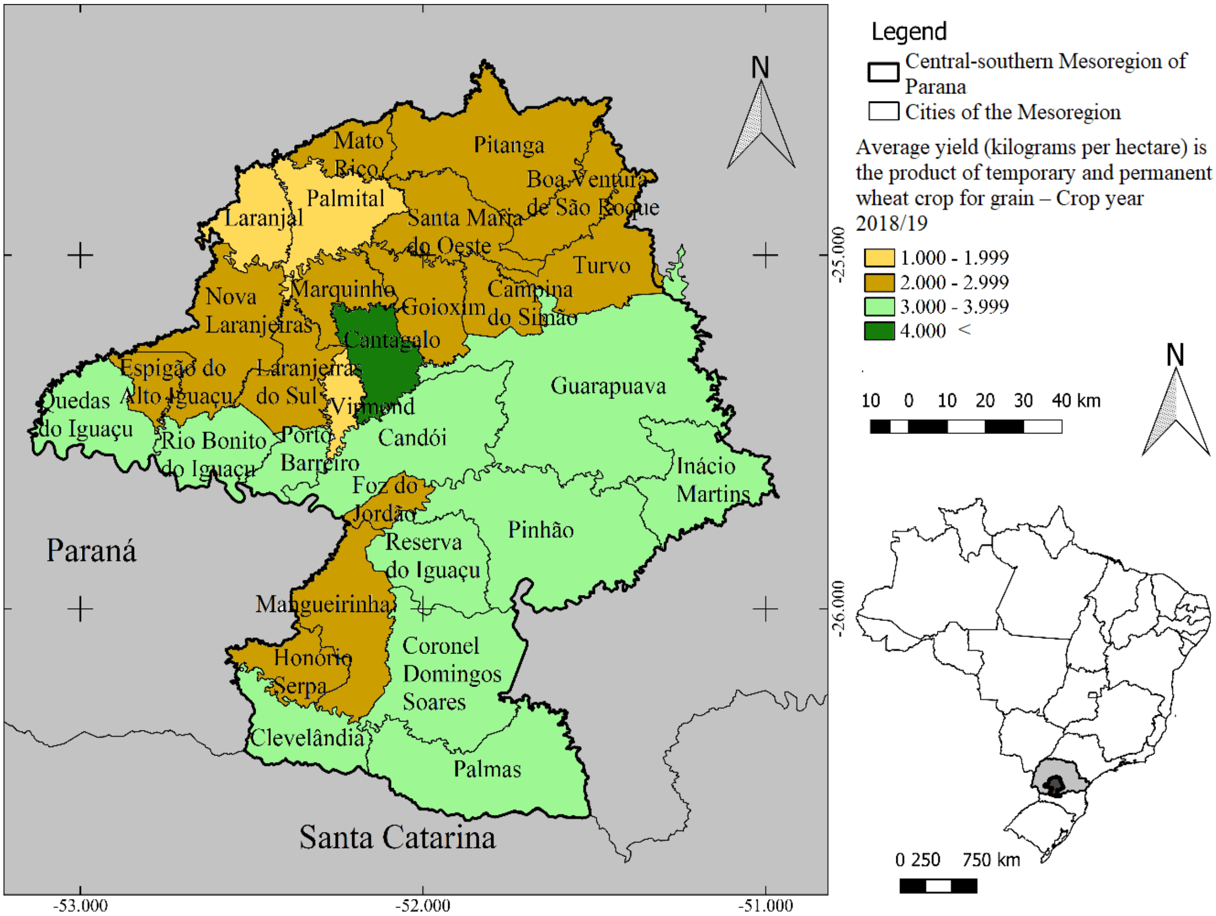

Figure 2. The average yield of wheat in the central-southern Mesoregion of Parana State (2018/2019 crop season).

Mesoregion (Figure 2), mainly in higher altitudes (Figure 1). The average yield of the crop is up to 4,000 kg ha^{-1} in Cantagalo. In the other regions south of Cantagalo, the average productivity is 3,000 kg ha^{-1}. With the agricultural zoning, the area's production can be increased, recommending the seeding window, reducing risk, and helping agriculture financing.

To the wheat zoning, the first risk variable analyzed was the precipitation (Figure 3). The yearly rainfall was analyzed to identify its distribution and regional variation. The rain in the Mesoregion presented regional divergencies. By the annual average precipitation accumulated through the period, it is observed that the north region has oscillating in rainfall amount from 1,860 mm, in the northeast to 2,100 mm in the northwest, at a distance of less than 100 km. These differences are justified by the altitude and the slope of the relief. In the northeast, the altitudes reach 400 m, close to the Ivai River channel, and in the northwest section, it achieves 1,100 m. It needs to be highlighted that the elevation increase from west to east and southwest to northeast is the same as the entry point of the cold fronts and the convective systems in the Parana State (Berezuk and Neto, 2006; Caldana et al., 2019). Thus, contributing to the moist air's forced rise and consequently having a higher precipitated volume in the higher areas.

The west section of the Mesoregion presented the lowest precipitation accumulation, varying from 1,860 to 1,960 mm. In these areas, with high altitudes, the slope of the relief decreases in height, following the atmospheric systems' entryway. However, even in the region's driest areas, they are still with high rain accumulation, only behind the coast and southwest regions of the Parana State (Nitsche et al., 2019).

The highest precipitation total was observed in the central-southern region, the same area that also presented high values of wheat production and yield (Figure 2). The peaks passed the 2,000 mm. The relief in this area increases in a short distance because of the proximity to the Iguacu River channel, also in the way of the development of atmospheric systems.

The risk was not present when analyzing the rain variability and its monthly distribution in the region (Figure 4). Because the crop cycle has 120 days in normal conditions (Pereira, 2018), the average precipitation was grouped by the moving average of every four months to

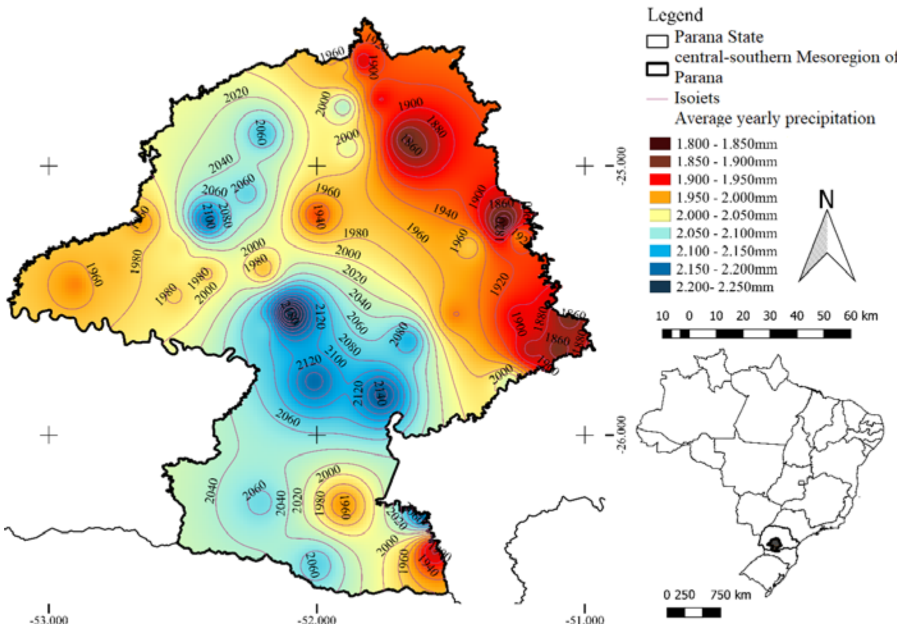

Figure 3. Yearly average precipitation in the Central-southern Mesoregion of Paraná State.

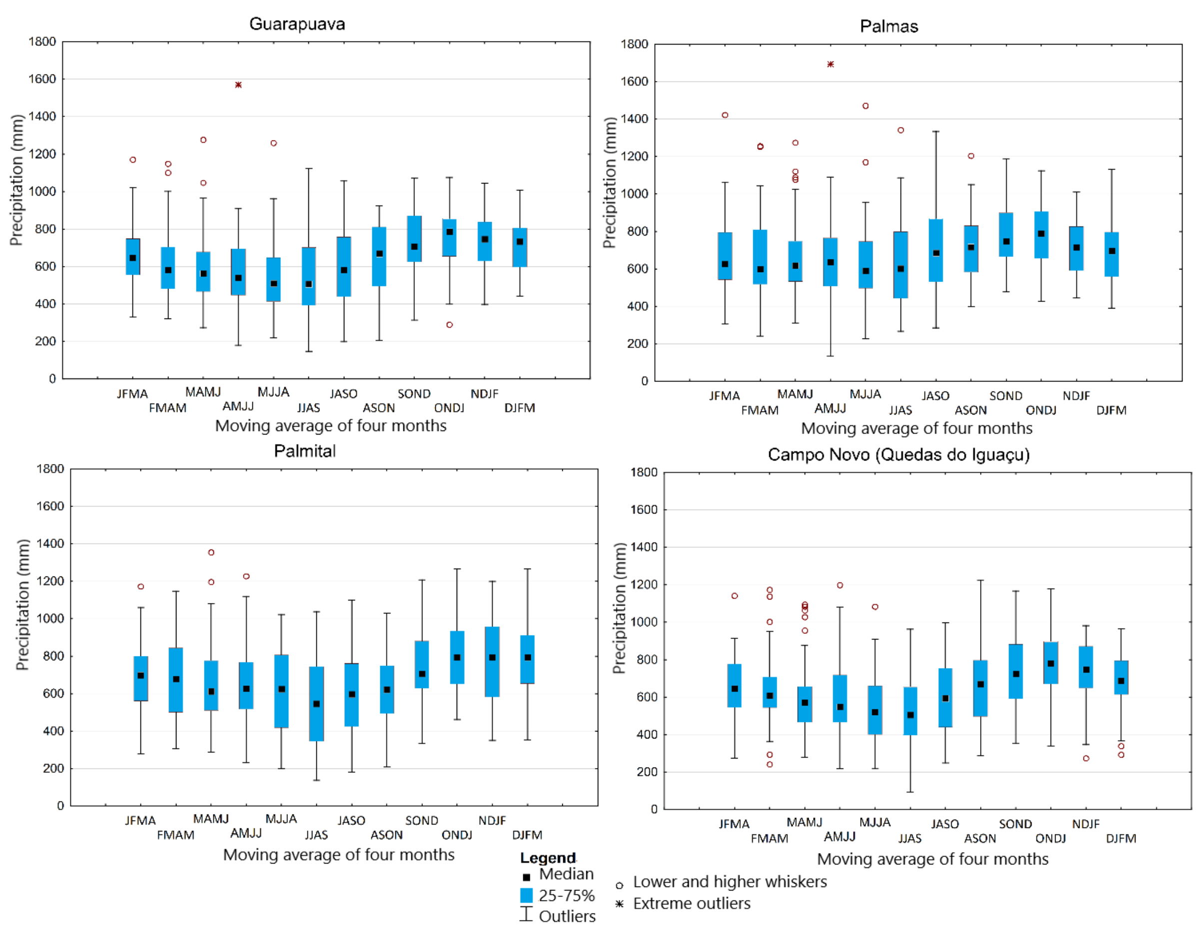

Figure 4. Precipitation by moving average across every four months in the North-Central Mesoregion of Parana.

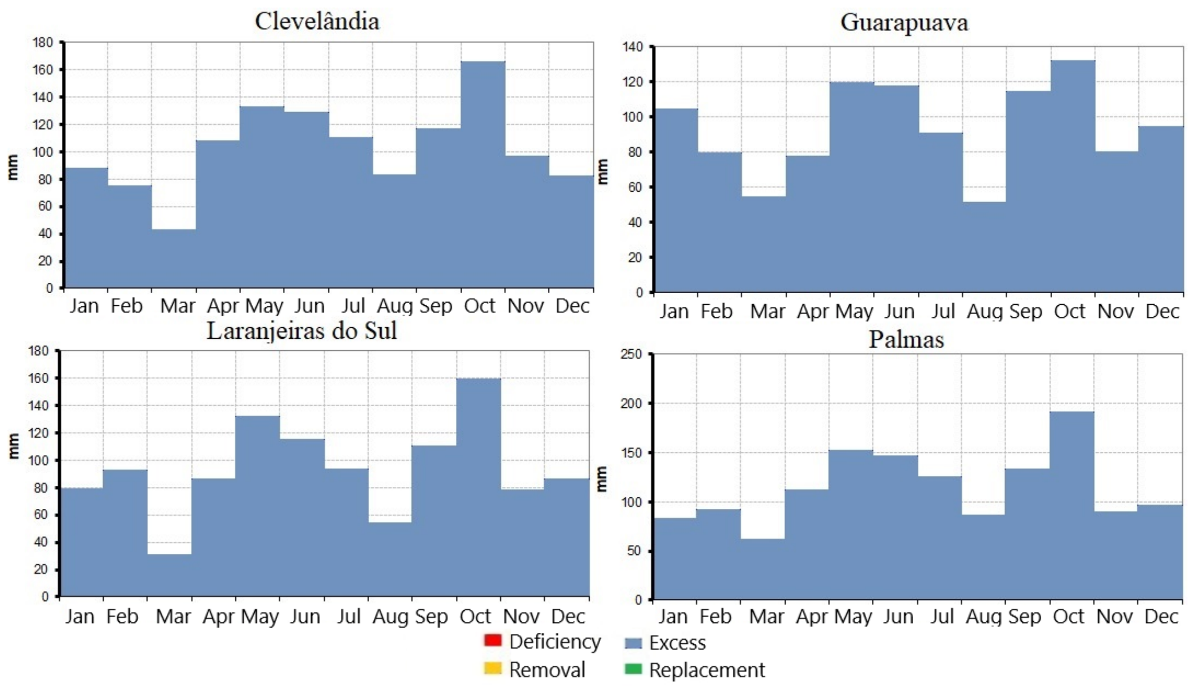

Figure 5. Normal climate water balance to the central-southern Mesoregion of Parana State.

test if the rainfall supplies the crop's water demand during the entire cycle.

The water availability and its management are essential for the wheat crop (Tan et al., 2020) because the maximum yield potential only will be achieved if there is an adequate water supply during the entire crop cycle (Lomas, 1976; Manfron et al., 1993; Xu et al., 2020). Seeding in the wrong window, linked to the water deficit, especially during the critical periods (sowing and reproductive stages), can result in significant yield losses (Bernardo et al., 2019; Hayes, 2019).

The Guarapuava station was the one that registered the lower medians for the moving four-months because it is located in the driest area of the region. All the medians were above the recommended for the wheat crop (380 mm during the cycle). However, as observed, the occurrence of rain accumulation lower than the recommended can happen, mainly in the four-month periods from the autumn and winter seasons, but the risk is low.

Only four-month periods in Guarapuava did not present a water deficit in the historical series. They were ONDJ, NDJF, DJFM, and JFMA, between the spring and summer seasons. There is the four-month period of SOND with all the medians above 450 mm in the other seasons.

This reduction pattern in rain accumulation during winter in Brazil's south region was identified in various studies (Mendes et al., 2005; Caldana et al., 2018; Jacondino et al., 2019). The occurrence of droughts was also present when the winter for the entire region was analyzed. These periods without rain can seriously damage various crops (Magalhães et al., 2019), showing the necessity to follow the agricultural zoning and arrange the seeding time to periods with lower risks (Gonçalves and Wrege, 2020).

Another way to evaluate if the water demand for wheat is supplied in the Mesoregion is by the average climatological water balance (CWB) (Figure 5). The water availability of a region for a particular crop can be quantified by CWB, highlighting the variations of water excess or deficiency. The studies around CWB should be developed, aiming at the relation between crop and weather, allowing for adjustments of the cultivation to the climate conditions. Besides, they need to present agricultural zoning applications, supplementation irrigation, hydrology, water reserves dimensions, drainage, etc. (Pereira et al., 2002; Dantas et al., 2007).

The central-southern Mesoregion is the third with the most precipitation in Parana State (Nitesche et al., 2019). An average water excess was identified throughout the whole year and through all seasons. The month with the lowest excess was March, presenting less than 40 mm in the Laranjeiras do Sul station. The high evapotranspiration explains the lower values in March in the region through the summer (December, January, February, and March), being the months with high rain volume, however, with high temperatures as well (Nitsche et al., 2019).

Because the evaluated risk was the water deficit of a maximum value of 60 mm during the cycle, the risk was not identified for the region. However, in drought periods,

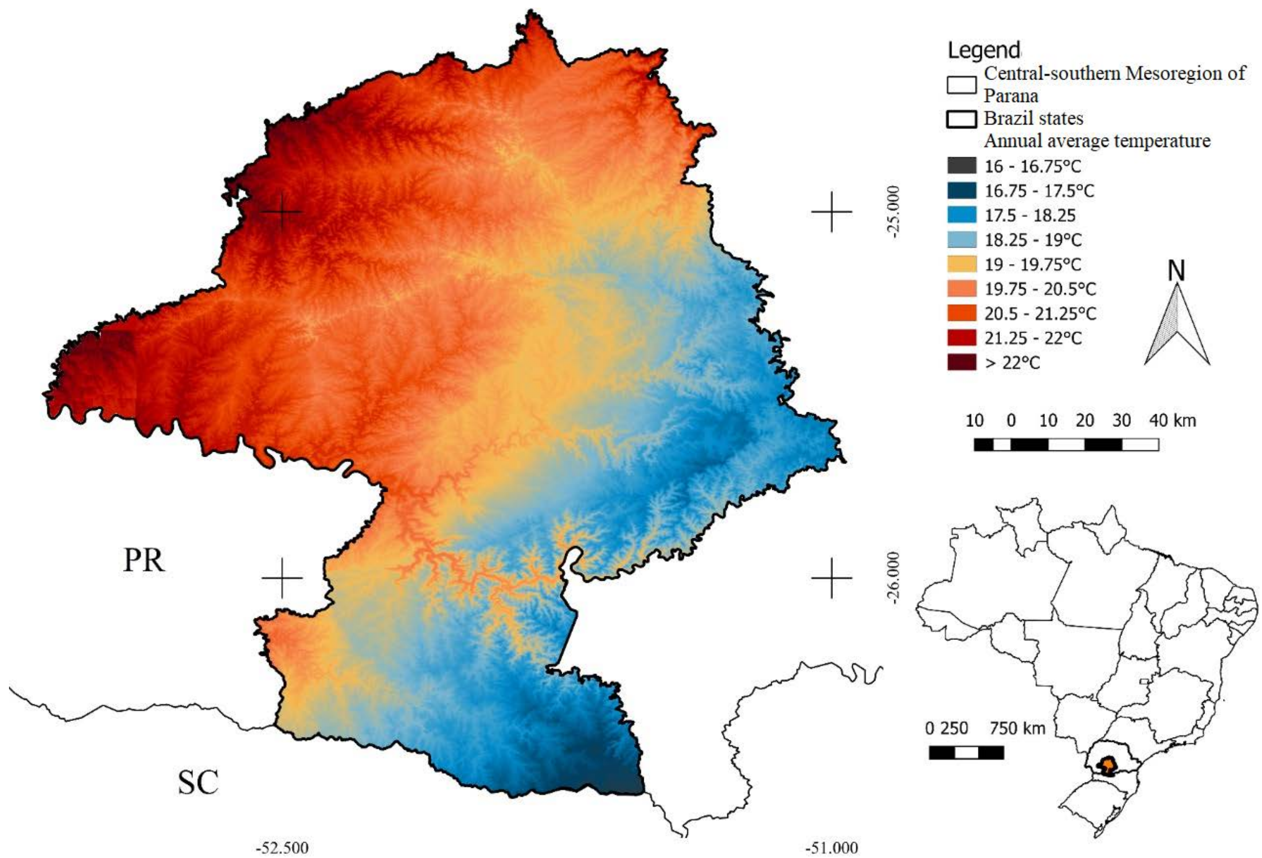

Figure 6. The annual average temperature in the Central-southern Mesoregion in Parana State.

which are frequently identified mainly during the winter time in the South of Brazil, the grower should seek management factors that better suit those periods. According to the water balance and precipitation, the season with the highest water excess and lower risk for planting was the spring.

When the average temperature for the region (Figure 6) is around 17°C, it is considered an optimal average for wheat growth (Doorenbos et al., 1979) because the optimal temperature range falls between 15 and 20°C, and the higher frequency around that range would precipitate on an annual average of around 17°C.

It was identified that the entire west, north, central and southwest regions of the Mesoregion presented average temperatures higher than the recommended of 17°C, with areas being higher than 22°C.

However, the south and east regions presented small areas below the recommended temperature, with temperatures around 16 to 17°C in areas with altitudes higher than 1,100 m (Figure 1). Although, because this is the annual average, it can happen during the year, four-month periods with temperatures more elevated than the crop's demand. Thus, it can be adapted and fit the seeding window during this aptness period.

The low temperatures and frost occurrence are agricultural and climate factors that are important to developing the zoning and adaptation of the seeding window for wheat. Through wheat development, low temperatures are only beneficial during tillering, when frosts are favorable during the beginning of the development (Manfron et al., 1993). Late frosts, however, mainly after the second month of cultivation, are unfavorable because they can hit the wheat during flowering, bringing as a consequence the abortion of florets, especially in the occurrence of temperatures lower than 1°C (Manfron et al., 1993; Paiva, 2019).

To identify the most sensible areas for the occurrence of frosts, the risk of annual occurrence was mapped, of temperatures lower than 1°C inside the meteorological shelter, which in the South of Brazil, in normal conditions, would bring the turf to -4°C (Vieira Junior et al., 2018). This scenario can carry significant risks, mainly if it occurs in periods like head emergence. Wheat can benefit from lower temperatures during tillering; being frosts good at the beginning of the development because they stop the growth in favor of the root system (Manfron et al., 1993). This way, for the south region, it is recommended that sowing happens during the cold period, even if temperatures are below the threshold for the species (Cunha et al., 2001).

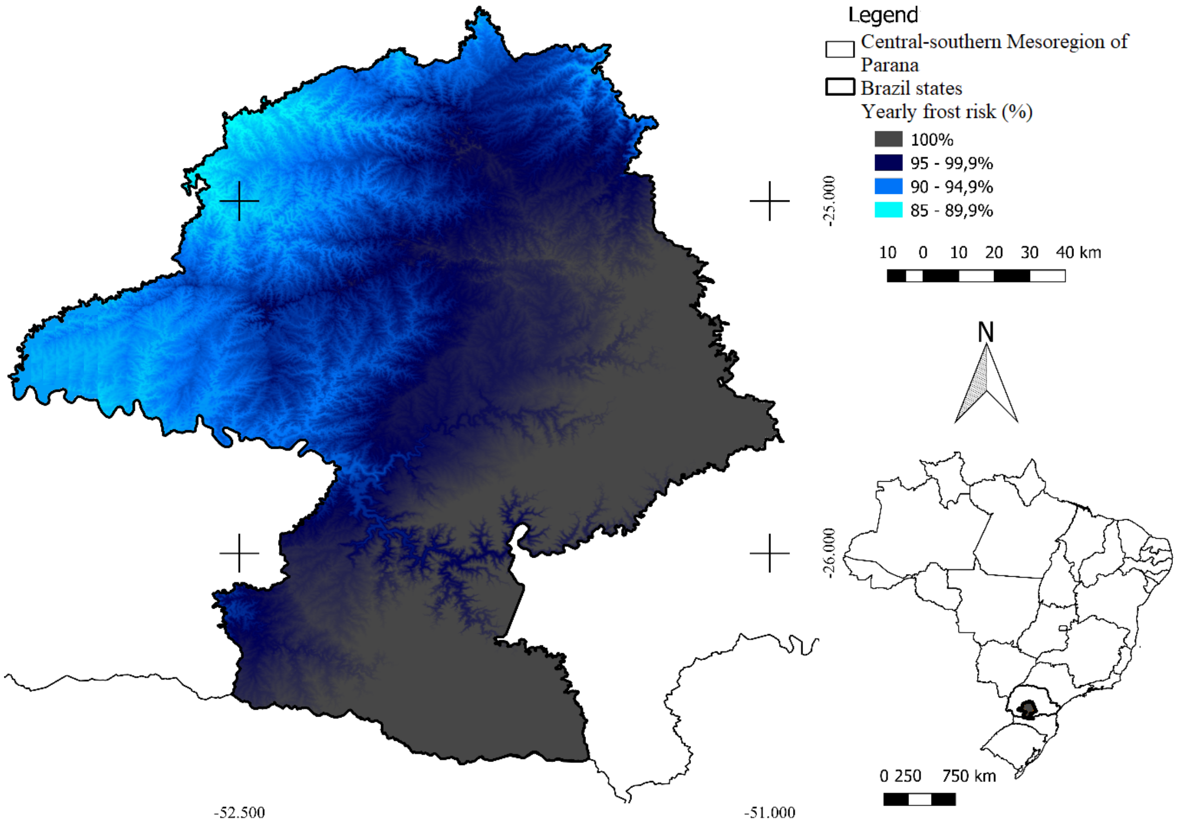

Figure 7. Yearly frost risk level in the central-southern Mesoregion of Parana State.

The Mesoregion has a high frequency of occurrence of low temperatures and frosts. Analyzing the annual risk (Figure 7), all the east and south of the Mesoregion presented a 100% risk of a yearly frost, with at least one occurrence in all analyzed years, embracing cities' regions like Guarapuava, Pinhão, Palmas, and Clevelândia.

Even in the regions with the lowest altitudes, and consequently, higher temperatures, the risk is still low. In the dark blue areas in the map, only a few years in the historical series have not had frosts and have risk levels higher than 95%. In the light blue areas, the risk ranges from 85 to 95%.

The frost regime's knowledge is necessary to subsidize the decision-making process of the animal and plant production sectors (de Oliveira and Borrozzino, 2018b). Information like the number of frosts in each month, the date of occurrence of the first frost in the autumn, and the last frost in spring allows more secure planning of the activities like the adaptation of wheat seeding. It does not comprise the activity with a late frosting when the species is more susceptible (Manfron et al., 1993). So, the period free of frosts was estimated in different locations within the region (Table 2).

Guarapuava and Palmas presented the smallest periods free of frosts, with less than seven months without the registered meteorological adversity. Thus, adapting planting to benefit the crop from the cold weather and frost at the beginning of the cycle, and that the late frost is avoided after two months, the wheat is in the field, and this part of the cycle cannot happen before the last frost.

Having all variables analyzed, the strip, in red in the zoning map (Figure 8), recommends seeding from May 21 until the beginning of August. Because the limit of frost occurrence goes until the end of July, the crop can benefit from the frost period or the low temperatures at the end of the winter season when planted at the beginning of the recommended period.

The second strip, in orange, already presents a higher period with frost occurrence. Thus, a later planting is recommended because late frosts can occur until August. The planting for that area is advised to start from the beginning of June. The same happens with the yellow stripe, with frosts appearing until the end of August, indicating the planting from the second half of June. The small area in green, the coldest of the Mesoregion, and for the state (Nitsche et al., 2019) presented a recommendation starting only in July due to frost occurrences until the middle of September.

Cunha et al. (2001) also made the agricultural zoning and seeding period for wheat in Brazil. For the Parana State, the authors also identified no water deficit risk in

Table 2. Period free of frost (Superior to 20% risk per ten days) in the central-southern Mesoregion in Parana State.

Meteorological station	Period free of frost
Guarapuava	First frost: Ten days from May 3 Last frost: Ten days from August 2
Palmas	First frost: Ten days from May 3 Last frost: Ten days from September 1
Laranjeiras do Sul	First frost: Ten days from June 2 Last frost: Ten days from July 3
Clevelândia	First frost: Ten days from May 3 Last frost: Ten days from August 2

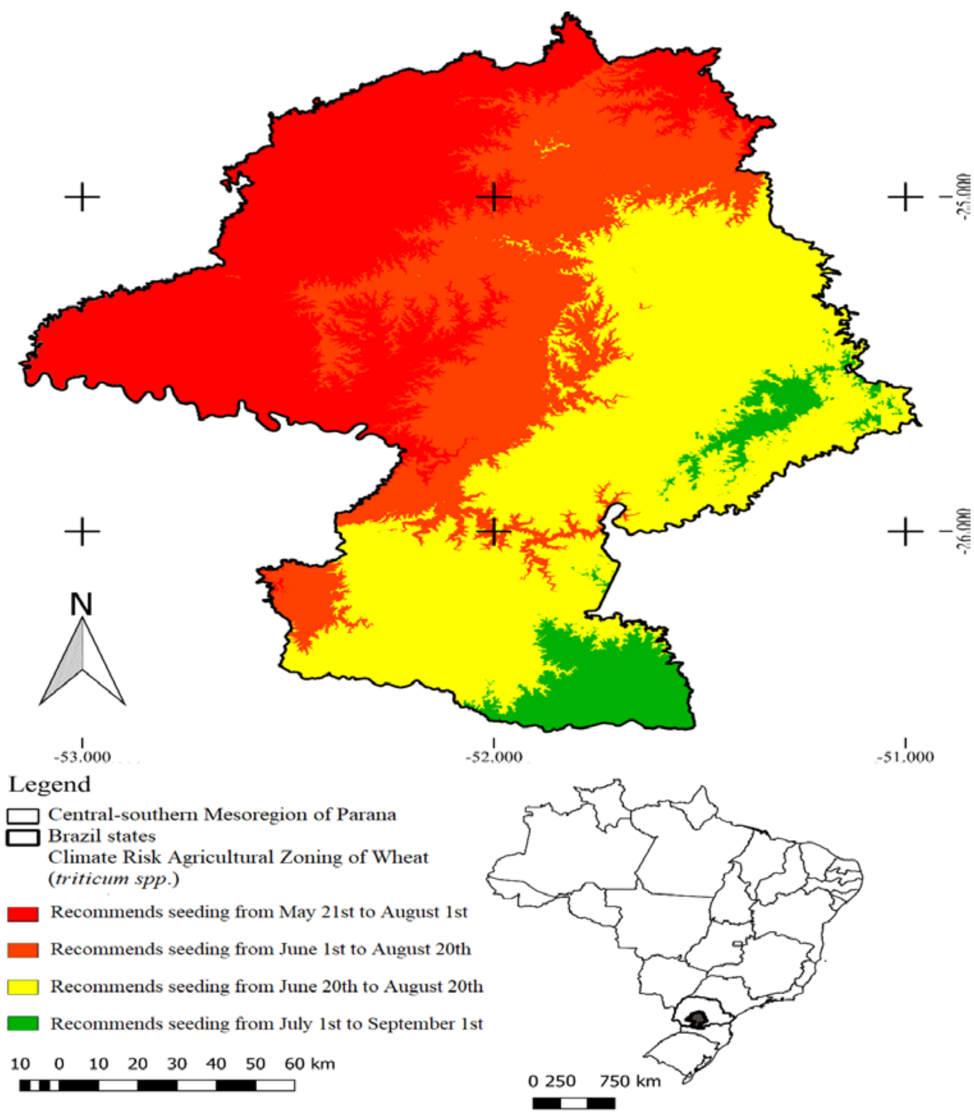

Figure 8. Climate risk agricultural zoning of wheat to the central-southern Mesoregion of Parana State.

the south of the state. The determinant factor for the planting recommendation is the frost. Differing from this study, the authors did not use the relief bases in the map construction, creating abstract lines in the planting recommendation. For the coldest region of Palmas, planting was recommended for the beginning of July. However, the authors did not identify the cold areas in Guarapuava, with similar temperatures and other characteristics found in this study. The rest of the Mesoregion was subdivided into only two classes, even presenting discrepancies in the temperature and the frost regime (Figure 6 and Table 1). The recommendations were from 11 to July 21.

Riede et al. (1998) also made the zoning for the Parana State. Again, the map presented abstractions and not optimal interpretation because it recommends the seeding per city, like the climate conditions, were the same within a city limit. In the central-southern region, because it has significant altitude variations, the attention given to this factor is essential to avoid standardization that can bring risks for the region's agriculture. The authors also divided the region into three classes, with planting varying from June until the end of July.

Santi et al. (2018) seek to identify the impacts of future climate scenarios in the agricultural zoning of wheat in the south of Brazil. They used regional models of temperature increases, varying from 1.4 to 5.4°C. They found that zoning should be continuously updated due to climate changes. In Brazil's southern region, the wheat crop will have its potential planting area reduced, mainly in Parana, in both studied climate scenarios. The period of wheat cultivation indicated by the zoning will be reduced in all south of the country, with the temperature being the main restriction into the number of 10 days periods that are apt to be planted.

Conclusions

(i) The agricultural zoning showed great potential for wheat cultivation in the Parana's central-southern and opened perspectives of new cultivation areas. Thus, increasing its cultivation in the south of Brazil and worldwide areas with a similar climate.
(ii) All the central-southern Mesoregion from Parana State presents aptness for wheat cultivation.
(iii) The water demand of the species is supplied in all tested scenarios, with no month presenting water deficit. The risk is also not identified for precipitation, which showed well distributed during the year and values above the expected for good wheat yield.
(iv) The average temperature in part of the ecoregion is below the recommended. However, the planting can be shifted for seasons that have a temperature increase.
(v) All the region presents high frost probability. Because it is a winter crop, wheat can benefit from the seeding during this period since late frost is avoided, mainly during August and September.
(vi) Seeding is recommended at different intervals through the Mesoregion, varying from May 21 to the beginning of September.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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