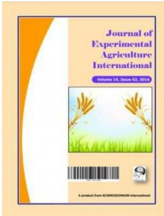

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Zoning of Water Deficiency Risk for Conventional Cotton in Mato Grosso

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Authors' contributions

This work was carried out in collaboration among all authors. Author ESS designed the study, performed the statistical analysis and wrote the first draft of the manuscript. Authors JHCJ, FAL and RSSA contributed the analyses of the study and reviewed the following versions. All authors read and approved the final manuscript.

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ABSTRACT

Cotton agroclimatic zoning is an essential tool to establish the most favorable periods for its cultivation, when the environmental conditions are more propitious, in order to reduce risks in agricultural activity. The objective of this work was to develop the zoning of the risk estimation of cotton yield reduction in the state of Mato Grosso, using the FAO method. Cultivars of early, medium and late cycles were considered, with four sowing dates (12/11, 12/21, 1/01 and 1/11) and three available water capacities (60, 140 and 200 mm). Results were specialized by ordinary kriging. The southernmost regions of the state presented the highest reduction risks, due to the lower precipitation in these areas. Sowing period 1 presented the lowest yield reduction risk, and the late-cycle cultivar in season 4 was the one that presented the highest reduction risk. Trough the validation of the obtained results, it can be considered that the methodology adopted in this work to verify the risk of yield decrease proved to be efficient.

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1. INTRODUCTION

The Mato Grosso state is currently the largest cotton producer in Brazil, according to data from CONAB (National Supply Company), with a production of 880.5 thousand tons in the 2015/16 crop season [1].

Rainfall occurs in the state in the spring-summer season, when agricultural activities are intensified, although precipitation anomalies may occur, resulting in dry-day sequences during the rainy season, with negative interferences in crop yield [2].

Rainfall is one of the most significant and influential meteorological elements in environmental conditions, particularly to the agricultural sector, where it plays a fundamental role in the development of crops and final production [3]. It is considered one of the most influencing factors in cotton development, since, through water deficit, there are significant reductions in growth, development, production per plant and, consequently, in the final productivity. Such severity depends on the stress duration and on the development stage of plants when it occurs [4].

Climate risk zoning is an alternative used to establish more favorable periods for different crops, where environmental conditions are conducive to crop development. When sowing is performed in periods in which climatic conditions are adequate to the crop needs, there is a reduction in risks of losses due to water deficit or surplus in the critical stages of crop development [5].

Simulation models are used to study and define the most favorable sowing times for cotton cultivation in which there is no water restriction. A worldwide methodology to verify the effect of water deficiency on cotton yield was advocated by FAO [6], where the relative yield decrease is estimated by considering the relative evapotranspiration reduction and a specific response coefficient.

Once sowing times are defined, with a lower risk of reduced yield, it is possible to define the favorable regions for conventional cotton cultivation and zoning through data interpolation and map generation. In view of the foregoing, the objective of this work was to develop the zoning of the risk estimation of conventional cotton yield considering different cycles, sowing times and water storage capacity of the soil in the state of Mato Grosso, as well as the validation of the employed model.

2. MATERIALS AND METHODS

The study area corresponds to the Mato Grosso state, located in Center-West region of Brazil, whose territory is 903,198,091 km^2 [7]. The success of agriculture in the Cerrado region, particularly of cotton, has been driven by favorable climate conditions, flat reliefs, favoring agriculture mechanization, programs to encourage the culture implemented by region states and, specially, intensive use of modern technologies [8].

The daily meteorological data on temperature (maximum, average and minimum), relative humidity, wind speed and precipitation were obtained from the National Institute of Meteorology (INMET). Concerning the precipitation data, these were obtained from the National Water Agency (ANA). In this study, stations that presented a minimum of 10 years of observation were used, totaling 15 conventional INMET stations and 169 ANA rainfall-gauging stations.

Data were organized in ten-day periods and analyzed to verify their homogeneity; data organization in ten-day periods consists in dividing the daily values into 36 groups with ten days each, disregarding the periods in which observations failed, so that the occurrence or not of interruptions (failures) in the climatological series was what determined which tests would be applied.

For the time series that did not present interruption, the Wald-Wolfowitz test was applied for randomization. The application of this test consisted in determining the series median, then comparing the sequence number of values above or below the median, in the chronological order of observations, at the 5% significance level. When series presented an interruption, the Wald-Wolfowitz two-sample test was used, whose application consisted in arranging the data in ascending order, identifying the number of sequences in which data appeared before or after the interruption [9,10,11].

The nonparametric Kruskal-Wallis test was applied for the series with two or more interruptions; it is used to test if a sample set comes from the same distribution, at a significance level of 5%. Trough this test, it is possible to test the null hypothesis that all populations have equal distribution functions, against the alternative hypothesis that at least two of the populations have different distribution functions [12].

The interruptions that occur in the climatological series do not make them unfeasible, and no bug filling was performed, since it is not possible to estimate missing data without changing the frequency distribution dispersion scale [13].

After verification of the data homogeneity, the potential evapotranspiration (ETo) (mm d^{-1}) for the 15 INMET stations was calculated using the equation proposed by [14], which considers the following variables: radiation at the top of the atmosphere, maximum, average and minimum daily temperature. This equation is an alternative for estimating potential evapotranspiration in sites with limited data availability, according to [15], and is expressed by the following equation:

$$ETo = 0{,}0023\ (T_{med} + 17{,}8) \times (T_{max} - T_{min})^{1/2} \times Ra \times 0{,}408$$

Where:

ETo: evapotranspiration reference potential, in mm day^{-1};
Tmed: average daily temperature in ºC;
Tmax: maximum daily temperature in ºC;
Tmin: minimum daily temperature in ºC;
Ra: radiation at the top of the atmosphere, in MJ m^{-2} $day-^{1}$.

As the number of stations with precipitation data only (169) was much higher than the stations with data for the calculation of the potential evapotranspiration (15), the ANA rainfall series were grouped by INMET meteorological station. For this grouping, the Thiessen polygon method was used in order to obtain estimates of actual and maximum evapotranspiration for the 184 stations. This method consists in connecting the stations by straight stretches, drawing perpendicular lines to these stretches, passing through the middle a line connecting the two stations. The perpendicular lines are then extended until they find the others [16].

The climatological water balance was performed on a ten-day scale, and only the precipitation data with 75% probability were used; that is, only the precipitation values with 75% confidence that an event corresponding or higher to that would occur were used. For an empirical determination of the rainfall probability, it is enough that the rainfall values are organized in a decreasing manner, along with the probability in ascending order and provided that the following equation is employed, where: *P* = probability; *M* = number of appearance order of the value in the ordered series; *N* = number of data in the series.

$$P = \frac{M}{N+1}$$

The use of rainfall probability values is important due to the variation in rainfall distribution over the years; therefore, for purposes of planning of agricultural activities, the employment of the rainfall frequency distribution is recommended, which is the case of this work, [17]. In addition, it is important to note that the probability of precipitation is higher than precipitation.

The maximum evapotranspiration (ETm) was estimated by the following equation, according to [6]:

$$ETm = ETo x Kc$$

Where:

ETo: potential evapotranspiration (mm day^{-1});
Kc: crop coefficient.

The used Kc values varied according to the cycle phases of the cotton crop, being equal to 0.5 in the initial development, 0.8 in growth, 1.05 in the reproductive period, and 0.8 at the end of the cycle, as proposed by [6].

For the water balance preparation, one early-cycle cultivar (150 days), one medium-cycle (160 days), and one late-cycle cultivar (170 days) were considered. Four sowing periods were simulated for each cultivar (11/12, 21/12, 01/01 and 11/01). The sowing dates were selected according to Embrapa recommendations, following the sowing window of the cotton crop for the state of Mato Grosso [8].

In the water balance calculation, the estimation of the soil water storage and the accumulated potential water loss was performed by using the equation of Rijtema & Aboukhaled [18], which considers the fraction p as a function of the AWC, that is, a water fraction that is readily

Table 1. Fraction p of soil water for cotton and maximum evapotranspiration

ETm mm/day	2	3	4	5	6	7	8	9	10
Fraction *p*	0,875	0,8	0,7	0,6	0,55	0,5	0,45	0,425	0,4

Source: [6]

available in the soil for extraction by plants without impairing growth. For this purpose, the following conditions were taken into account [19]:

When $AWC * (1-p) < ARM \leq AWC$, that is, in the humid zone.

$$ARM = AWC - L$$

When $0 < ARM \leq AWC * (1-p)$, that is, in the dry zone.

$$ARM = AWC * (1-p)e^{\left[\left(p-\frac{L}{AWC}\right)*\left(\frac{1}{(1-p)}\right)\right]}$$

Where:

AWC: available water capacity (mm);
p: fraction of available water (mm);
ARM: soil water storage (mm);
L: accumulated potential water loss (mm).

The values of the available water fraction can be seen in Table 1, according to [6]. From these values, a regression was generated in order to determine the values of the fraction p at each site as a function of the potential evapotranspiration.

The general values for the available water capacity (AWC), as a function of soil texture, were 60, 140 and 200 mm [6]. The water accounting of a determined soil layer is determined through climatic water balance, defining the dry (water deficit) and wet periods (water surplus) of a given location [20].

The yield reduction estimates were performed according to the methodology proposed by [6], considering that the yield decreases proportionally to the reduction of relative water consumption, in a certain proportion that depends on the crop under study.

The yield reduction was estimated by the following equation:

$$R = Ky_d \cdot \left(1 - \frac{ETR}{ETm}\right) + Ky_f \cdot \left(1 - \frac{ETR}{ETm}\right) + Ky_m \cdot \left(1 - \frac{ETR}{ETm}\right)$$

Where:

R: yield reduction fraction, decimal;
Ky_d: crop response factor to hydric deficiency in vegetative phase, ten-day period;
Ky_f: crop response factor to water deficit at flowering, ten-day period;
Ky_m: crop response factor to water deficit at maturation, decimal;
ETR: actual evapotranspiration or water consumption, ten-day period in mm; and
ETm: crop maximum evapotranspiration or water demand, ten-day period in mm.

The used Ky values varied according to the phase of the crop cycle, being: 0.20 for vegetative development; 0.50 for flowering; and 0.25 for maturation [6].

The model aims to determine the potential yield penalty due to water deficiency, which occurs by the sum of the products Ky * (1-ETR / ETm) that quantify the yield reduction caused by water deficiency.

In order to characterize the spatial variability of the risk values of yield reduction, the data were analyzed by using geostatistical methods through the calculation of semivariograms.

Since the semivariograms showed a tendency, that is, they did not stabilize in a sill with the distance growing uninterruptedly, a polynomial surface was adjusted, calculated according to [21], with a new adjustment being performed with the residues obtained by the difference between the original data and the adjusted surface.

$$Z * (x,y) = A_0 + A_1X + A_2Y + A_3X^2 + A_4XY + A_5Y^2$$

Where:

Z: attribute value at point X, Y;
X, Y: point coordinates;
An: coefficients to be calculated.

The semivariograms were adjusted for each sowing season, AWC and cultivar cycle, selecting the models that presented the best adjustments, adopting as one of the parameters the spatial dependence degree (SDD) andusing the Gamma Design Geostatistics statistical software. According to [22], the SDD represents the portion of spatial variability that corresponds to chance, and has the following proportions: (a) strong spatial dependence, <25%, (b) moderate spatial dependence, 25-75%; and (c) weak spatial dependence, > 75%.

$$SDD = \left(\frac{Co}{Co + C}\right) \times 100$$

Where:

SDD: spatial dependence degree;
Co: nugget effect;
Co+C: sill.

After analyzing the semivariograms and establishing spatial dependence among the analyzed variables, the spatial variability of the yield reduction for the Mato Grosso state was mapped through the ordinary kriging technique, using the ARCGIS software.

In order to validate the estimates, the yield, precipitation, soil and cultivar characteristics were surveyed in six commercial cotton production plots located in Tangará da Serra, Campo Novo do Parecis and Deciolândia counties in the state of Mato Grosso.

With the collected information, calculations ofthe ten-day period climatological water balance were performed, in the same way as it was done to estimate the risk zoning of yield reduction. This procedure was carried out aiming to verify if the precipitation that occurred during the crop cycle would be a limiting factor for the yield obtained in the commercial plots where the surveys were made. For this purpose, the yields of the commercial plots were compared with the average yield values of the cultivarsin the regions and in the crop analyzed.

3. RESULTS AND DISCUSSION

Table 2 shows the semivariograms parameters of the risk percentage of yield reduction as a function of water deficit, used to analyze the spatial dependence and the reliability of the generated maps.

The SDD values suggested strong and moderate spatial dependence for the regionalized variables (Table 2) according to the classification by Cambardella et al. (1994), considering that all semivariograms presented values between 3.79% and 40.74% for this parameter. This result indicates that the semivariogram has the capacity to represent the data spatial variability in the state of Mato Grosso.

Figs. 1, 2 and 3 show the reduction risk maps of cotton yield for the state of Mato Grosso, using three AWC's (60, 140 and 200 mm). The risk of reduced yield increases from the northern to the southern direction of the state, following the direction of precipitation distribution, since rainfall is associated with air rise and can occur due to factors such as thermal convection and frontal action of masses, as highlighted by [23].

In a study by [24], it was possible to identify that there is an irregular rainfall variability in Mato Grosso, and the average annual precipitation of a rainier core at the north of the state can reach values higher than 2750 mm. These values decrease in the eastern, western and southern directions of the state, resulting in precipitation with maximum values in the summer and minimum values in winter; furthermore, 70% of the rainfall accumulated during the year fall between November and March, corresponding to summer, whose rainier months are concentrated in the January-March interval.

Two air masses operate in Mato Grosso (continental equatorial air mass and Atlantic polar air mass), which affect the distribution and amount of rainfall in the Mato Grosso territory. The equatorial air mass is present between spring and summer; due to the thermal effect and the high humidity contained in Amazon, it moves towards the country interior from the northwest to the southeast direction, thus causing rainfall. The Atlantic polar mass is characterized by polar air accumulation, which acts more frequently in the winter, in the southern-northern direction, favoring temperature decrease and drought [25,26]. However, it is worth mentioning that when considering the period in which cotton is cultivated, the continental equatorial air mass is the one that most exerts influence in its development for being responsible for the rainfall in this period.

Considering the occurrence of three large biomes in Mato Grosso: Amazonia, Cerrado and Pantanal, it is possible to verify the variation in rainfall distribution throughout the state. The highest rainfall averages are found in the Amazon biome, located in the extreme northwest and north areas, and the lowest values are located in the extreme southwest and south areas, corresponding to the Pantanal biome [25]. This rainfall variation in these biomes

Table 2. Parameters of spherical model semivariograms used for the spatialization of the risk values of yield reduction (%) in the state of Mato Grosso

Variables	Parameters				
	Nugget effect	**Sill**	**Range (km)**	**r^2**	**SDD (%)**
AWC 60 SP1 Early	50.49	7.50	78.90	0.624	12.93
AWC 60 SP1 Medium	39.85	24.40	312.28	0.710	37.97
AWC 60 SP1 Late	30.62	17.42	305.61	0.769	36.26
AWC 60 SP2 Early	50.03	7.10	68.90	0.633	12.42
AWC 60 SP2 Medium	34.46	23.70	324.50	0.706	40.74
AWC 60 SP2 Late	39.45	6.70	71.12	0.587	14.51
AWC 60 SP3 Early	24.67	15.42	302.27	0.707	38.46
AWC 60 SP3 Medium	25.04	12.98	303.39	0.615	34.13
AWC 60 SP3 Late	18.55	9.30	301.16	0.724	33.39
AWC 60 SP4 Early	21.41	2.76	65.56	0.501	11.41
AWC 60 SP4 Medium	22.43	3.85	71.12	0.521	14.64
AWC 60 SP4 Late	13.38	8.95	321.17	0.594	40.08
Variables	**Parameters**				
	Nugget effect	**Sill**	**Range (km)**	**r^2**	**SDD (%)**
AWC140 SP1 Early	58.00	34.30	298.94	0.676	37.16
AWC140 SP1 Medium	45.39	26.60	316.72	0.781	36.94
AWC140 SP1 Late	58.26	10.10	84.46	0.600	14.77
AWC140 SP2 Early	74.83	12.20	67.79	0.612	14.01
AWC140 SP2 Medium	56.80	9.80	75.56	0.657	14.71
AWC140 SP2 Late	48.51	8.10	71.12	0.641	14.30
AWC140 SP3 Early	38.86	6.40	76.68	0.629	14.14
AWC140 SP3 Medium	31.64	2.40	78.90	0.658	7.05
AWC140 SP3 Late	25.84	1.02	71.12	0.606	3.79
AWC140 SP4 Early	33.33	4.70	71.12	0.546	12.35
AWC140 SP4 Medium	28.78	4.29	71.12	0.649	12.97
AWC140 SP4 Late	20.84	2.80	75.56	0.595	11.84
Variables	**Parameters**				
	Nugget effect	**Sill**	**Range (km)**	**r^2**	**SDD(%)**
AWC 200 SP1 Early	67.64	9.00	75.56	0.534	11.74
AWC 200 SP1 Medium	69.43	0.80	70.01	0.491	11.39
AWC 200 SP1 Late	56.36	21.80	323.39	0.759	29.00
AWC 200 SP2 Early	49.52	31.00	322.39	0.700	38.49
AWC 200 SP2 Medium	64.90	9.10	67.79	0.551	12.29
AWC 200 SP2 Late	59.23	10.70	65.56	0.530	15.30
AWC 200 SP3 Early	55.71	8.00	70.01	0.635	12.55
AWC 200 SP3 Medium	37.64	5.40	62.23	0.477	12.54
AWC 200 SP3 Late	31.53	5.72	86.68	0.528	15.35
AWC 200 SP4 Early	35.15	5.30	68.90	0.532	13.10
AWC 200 SP4 Medium	34.13	5.30	60.01	0.416	13.44
AWC 200 SP4 Late	26.10	4.70	78.90	0.467	15.25

AWC: available water capacity (mm); SP: seeding period; EARLY, MEDIUM, LATE: crop cycle (days); r^2: coefficient of determination of semivariogram; SDD: spatial dependence degree

corroborates with the obtained results, since in the region corresponding to the Pantanal biome the greatest yield reduction risk was found, with the lowest risk in the Amazon biome.

Therefore, through the obtained results, the relationship between water availability and cotton yield is evident, mainly due the oscillation of precipitation in time and space.

By adopting AWC values corresponding to 60 mm (Fig. 1), it is possible to observe a variation in the reduction risk between 0 and 75.71%. For the AWC of 140 mm (Fig. 2) the variation was between 0 and 67.3%, and for 200 mm AWC (Fig. 3) the observed interval was within 0 and 60.31%. The variation of these values is essentially due to the different available water capacities, sowing times and length of the cultivars cycle. However, it is observed that reduction risk is lower in soils whose available water is 200 mm, due the lower water restriction to the plants.

In a study by [27], whose objective was to determine the agroclimatic zoning of the peanut crop for the Upper Paraguay Basin region, in the state of Mato Grosso, a smaller restriction for peanut cultivation was observed in soils with higher AWC's, a similar result to those obtained in the present work. The lower restriction risk in soils whose AWC's are higher is a consequence of greater soil water storage in these soils, allowing late cultivation.

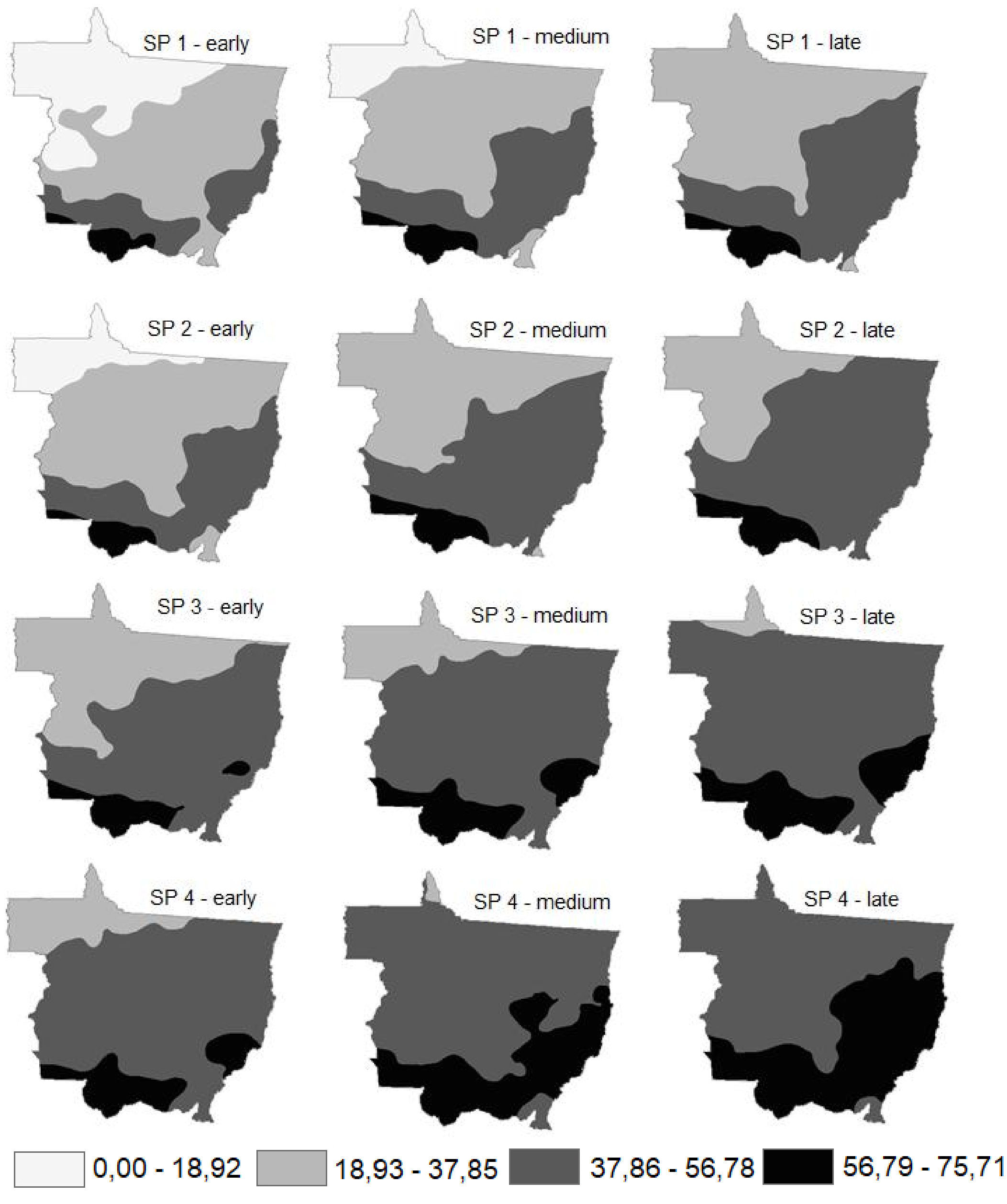

Fig. 1. Maps of the reduction risk of conventional cotton yield (%) for the state of Mato Grosso, under AWC of 60 mm. AWC: available water capacity (mm), SP: sowing period, early, medium, late: crop cycle (days)

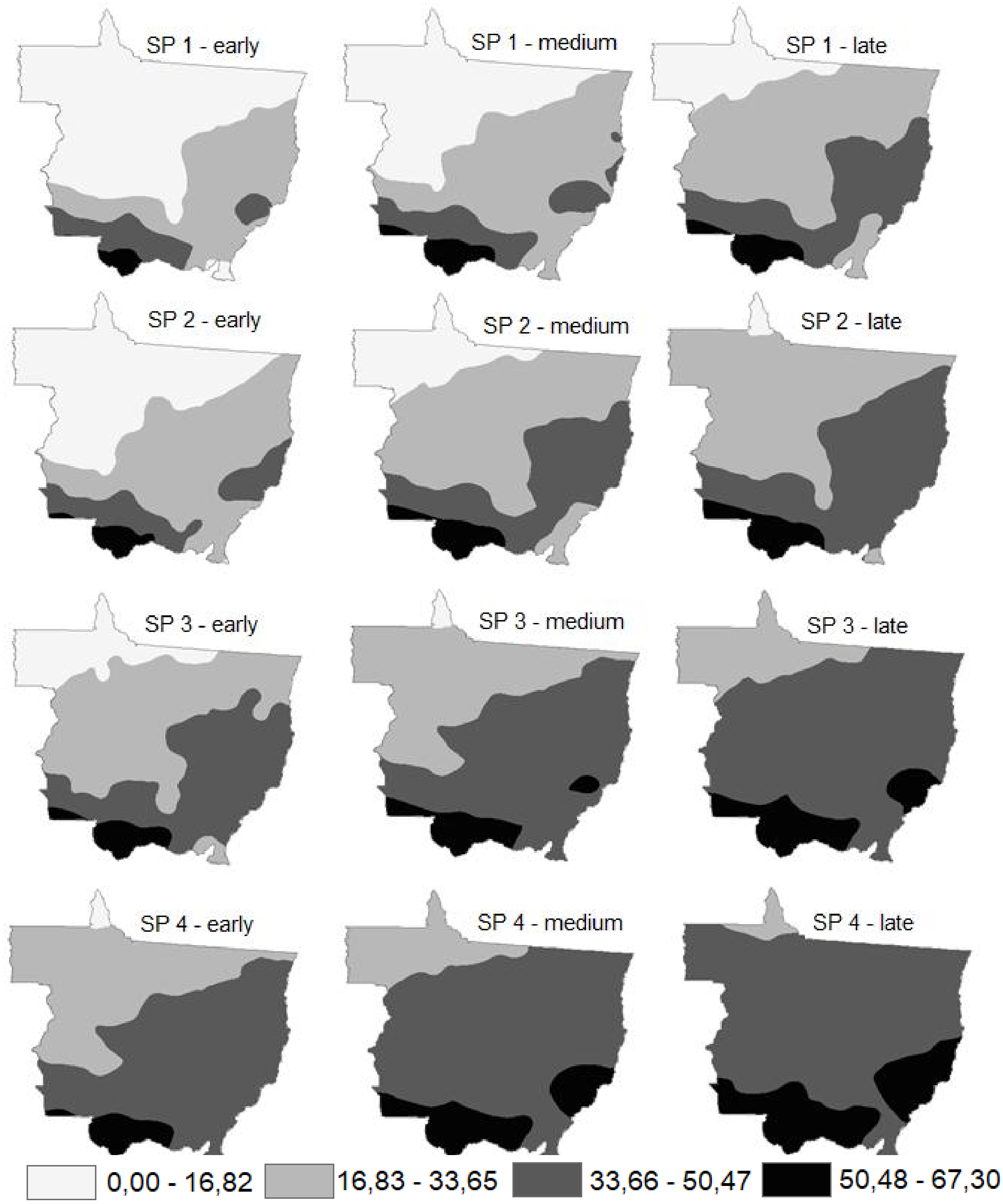

Fig. 2. Maps of the reduction risk of conventional cotton yield (%) for the state of Mato Grosso, under AWC of 140 mm. AWC: available water capacity (mm), SP: sowing period, early, medium, late: crop cycle (days)

The sowing period 1 presented a satisfactory performance, being the season with lower yield reduction risk, particularly for early cycle cultivars. According to [17], it is possible to verify that rainfall in Mato Grosso reaches maximum values in late December and early January, gradually decreasing until the beginning of the dry season, what favored period 1, which corresponds to 12/11. In this sense, the choice of the sowing season is determinant for the success in the search for high yields, which are possible when juxtaposing the development of the crop phenological stages with the favorable climatic environment to the yield expression of the cultivar in use [28].

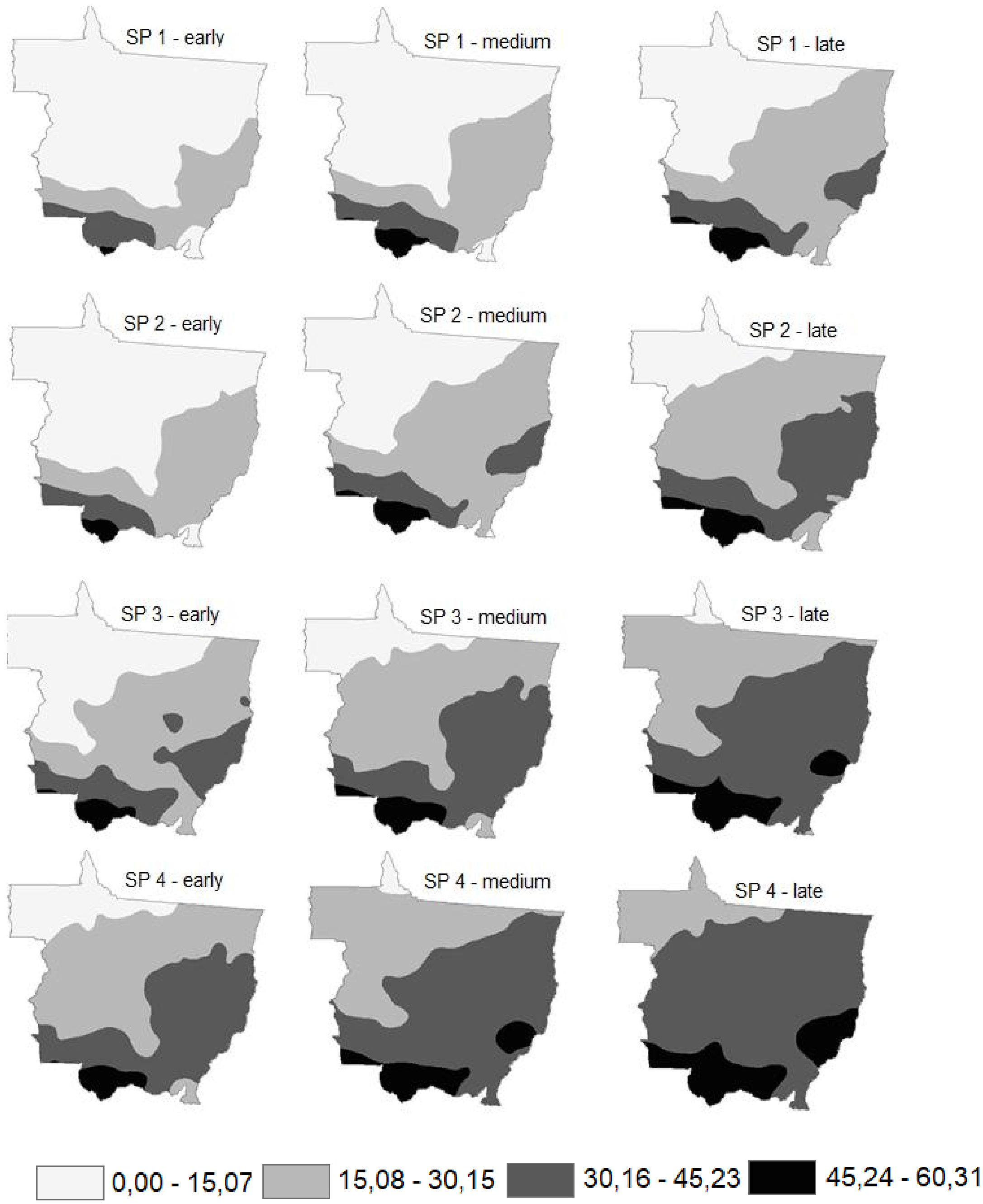

Fig. 3. Maps of the reduction risk of conventional cotton yield (%) for the state of Mato Grosso, under AWC of 200 mm. AWC: available water capacity (mm), SP: sowing period, early, medium, late: crop cycle (days)

In addition, sowing period 1 obtains a lower risk in the regions located to the north and northwest compared to other regions of the state, since, according to [25], the month of December shows a rainfall pattern with maximums located at the extreme north and northwest, in the Amazonian biome, and lowest rates in the south, in the Pantanal biome.

Sowing period 4 (1/11) was the one that presented the highest yield reduction risk, particularly to the late cycle cultivar, due to the

Table 3. Results and validation information of the FAO method (Doorenbos and Kassam, 1979) for the cotton crop in Mato Grosso

Local	Cultivar	Sowing date	Average cultivar yield kg ha^{-1}	Real yield kg ha^{-1}	Risk Red. (%)
Tangará da Serra	TMG 81 WS	17/1/02	4740.00	4200.00	0.00
Tangará da Serra	FM 954 GLT	17/1/15	4815.00	4500.00	0.00
Tangará da Serra	FM 944 GLT	17/1/25	4620.00	4500.00	0.00
Campo Novo do Parecis	FM 975 WS	17/1/20	5145.00	3378.00	34.00
Campo Novo do Parecis	TMG 47 B2 RF	17/1/20	4080.00	2761.50	33.00
Deciolândia	FM 975 WS	17/1/08	4920.00	4200.00	18.00

decrease in water availability in this period. According to [17], the sowing delay, in relation to water deficit, increases the possibility of the cotton critical phase to occur in the dry season. Thus, when sowing in times when climatic conditions are adequate to the needs of any crop, it is possible to reduce losses risks due to water deficit at the critical stages, which occur in the reproductive phase, when there is a greater water requirement by the crop.

Therefore, one of the determining factors for success in cotton cultivation is the sowing season, which, when performed until the end of December, causes a lower risk of yield losses due to water deficit occurrence.

In general, zoning is a fundamental tool to prevent losses and to increase profits, improving the competitive potential of cotton-growing agricultural enterprises, as observed by [5], in which yield losses were higher than 100%, being evident that the cotton is sensitive to the behavior of environment variables, whether climatic, edaphic or biotic. The yield is directly related to the time and place of sowing, corroborating with the results obtained in this work, in which it was verified that the time and place of sowing might reduce yield in up to 75%.

With the employment of zoning, it is possible to minimize the oscillation effects of climate elements, since such unforeseen climatic variability have always been the main sources of risks to agricultural activity [29]. It was verified that the success of agriculture is related to the anticipated knowledge of the local conditions of soil, solar radiation and rainfall, and their variation along a crop cycle are significant to obtain satisfactory yields, since these factors are determinant for crop success [30].

By analyzing the cultivar cycle effect, it was observed that the late cultivar presented a higher yield reduction risk in relation to the others. This occurred since with the longer cycle of the late cultivar, the chances of the water deficit occurring in a period of low water availability are increased, also considering that the rain plays a fundamental role for agricultural crops and exerts influence in several processes, such as nutrient absorption, transpiration and photosynthesis. It is also necessary to consider that in the same place, in different years, and even at different times of year, the adequate water amount depends on factors such as total rainfall over the days, insolation, wind, temperature, air humidity, plant size or the spacing used in its cultivation, and the ability of the soil in retaining rainwater [9].

Table 3 shows the results of the FAO method validation described by [6]. In Tangará da Serra there was no risk of a reduction in yield during the growing season, however, the three cultivars did not reach the average region yield for the analyzed crop, presenting a variation between 540 and 120 kg ha^{-1}. The occurrence of such differences suggests the interference of other factors that are not related to the occurrence of water deficit, such as the possible incidence of pests and diseases in the crop.

For Campo Novo do Parecis there was a reduction risk of 34 and 33%, and for Deciolândia the risk was 18%, in accordance with the average yield values. Therefore, the methodology proposed by FAO [6] guaranteed satisfactory results to analyze the reduction risk of cotton yieldin the state of Mato Grosso.

In this manner, the definition of the regions and times with the lowest yieldreduction risk constitutes an extremely important information for cotton farmers in the state of Mato Grosso, allowing a more reliable agricultural planning with regard to water availability.

4. CONCLUSION

The sowing period 1 presented the lowest reduction risk of cotton yield, contrarily to season 4, which presented the highest risk. The month of December was considered the most favorable for conventional cotton cultivation in the state of Mato Grosso.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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