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Developing an algorithm to geographically estimate the available time for agricultural field spraying in the state of Mato Grosso do Sul

Desenvolvendo um algoritmo para estimar geograficamente o tempo disponível para pulverização agrícola no estado de Mato Grosso do Sul

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Highlights

Soil compaction is influenced by machine traffic and enhanced by soil humidity.
Available time for agricultural mechanization does not consider soil moisture.
Machinery traffic in inadequate soil moisture conditions increases soil compaction.

Abstract

The dimensions of mechanized agricultural systems depend on the edaphoclimatic conditions, crops, and work regimes. This study aimed to geographically estimate the monthly available time and number of favorable hours for agricultural field spraying in the state of Mato Grosso do Sul, Brazil. The meteorological restrictions imposed during unfavorable hours were as follows: ambient temperature above 32 ºC, relative humidity below 50 %, wind speed above 15 km h^{-1}, and volumetric soil humidity above 39 % (equivalent to 90 % of the available water capacity). Mathematical models were then developed considering a period of ten years, which used historical data from the ground monitoring stations of the National Institute of Meteorology within the region. The subsequent algorithm was programmed and installed in a web server to simulate the time required for agricultural field spraying. During the cropping period in the region, there were climatic restrictions on performing agricultural spraying, with relative humidity being the variable with the most significant impact. However, soil moisture conditions restricted the available time for agricultural spraying more than the wind speed, relative air humidity, or ambient temperature.

Key words: Agricultural pesticides. Soil compaction. Weather conditions.

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Resumo

O dimensionamento de sistemas mecanizados agrícolas depende das condições edafoclimáticas, da cultura e do regime de trabalho. O objetivo deste trabalho foi estimar geograficamente o tempo disponível mensal e o número de horas favoráveis à pulverização agrícola no Estado de Mato Grosso do Sul, Brasil. As restrições meteorológicas impostas para o cálculo das horas desfavoráveis foram: temperatura ambiente acima de 32ºC, umidade relativa abaixo de 50%, velocidade do vento acima de 15 km h^{-1} e umidade volumétrica do solo acima de 39% (equivalente a 90% da capacidade hídrica disponível). Os modelos matemáticos foram elaborados considerando um período de dez anos, com base nos dados históricos das estações automáticas do Instituto Nacional de Meteorologia instaladas no Estado. O algoritmo desenvolvido e instalado em ambiente web permitiu simular o tempo disponível para pulverização agrícola no estado de Mato Grosso do Sul. Durante o período de safra na região, há restrições climáticas para a realização da atividade de pulverização agrícola, sendo a umidade relativa do ar a variável de maior impacto. A condição de umidade do solo é mais restritiva para o tempo disponível para a pulverização agrícola do que a velocidade do vento, umidade relativa do ar ou temperatura do ambiente.
Palavras-chave: Compactação do solo. Condições climáticas. Defensivos agrícolas.

Introduction

The technical dimensioning process of mechanized agricultural systems should consider edaphoclimatic conditions, crops, and work regimes. Studying the available and favorable weather conditions for mechanized operations is essential for the correct dimensioning of agricultural machinery sizes and quantities. Additionally, adequate field operational capacities of the machines must be selected accurately to culture the crop during its cycle, which can be a factor in reducing costs considering that rationalization can lead to increased profitability (Mello et al., 2019). Depending on the crop, mechanization within the agricultural production process can account for 20%–40% of the total production costs (Kay et al., 2019; Mello et al., 2019). Furthermore, the variation in the climatic conditions and soil moisture during the cropping period directly interfere with the dimensioning process (Gava et al., 2018).

Agricultural spraying activity is often paused on the field due to inadequate weather or soil in high humidity conditions, which is unsuitable for the transit of agricultural machinery over the soil. Overall, the ideal weather conditions for pesticide applications are established as temperatures below 30°C, relative humidity above 55%, and wind speed between 3 and 12 km h^{-1} (Radons et al., 2022). Agricultural spraying in unfavorable environmental conditions promotes an increase in spray drift. It can lead to considerable environmental damages, such as soil contamination, death of beneficial insects from biological control and even pollinators, contamination of groundwater, as well as economic damage due to waste of phytosanitary products (Baio et al., 2019; Kambrekar, 2020).

Studying climatic variations make it possible to account for unfavorable periods of agricultural spraying throughout the day. The most favorable period for agricultural spraying, which is represented by minimal wind speed and a higher relative humidity index, has generally been found to range between 6:00 p.m. to 11:00 a.m. (Radons et al., 2022). Recently, night spraying has been adopted to minimize losses caused by adverse weather conditions (low air humidity, high temperature, or high wind speed), reducing the risk of drift and losses through evaporation (Tian et al., 2020).

By monitoring climatic variables, the chances of successful spray application increase; however, soil moisture is the most decisive factor for machinery traffic. In addition to causing more significant damage to the crop, compaction mainly occurs due to heavy agricultural machinery transits over soils with low load capacity; this is generally observed under high humidity conditions due to the high rate of skidding (Esteban et al., 2019). Soil compaction is also caused by an increase in density and resistance to penetration due to a decrease in porosity and aeration, thus impairing the growth of the plant root system (Deon et al., 2018).

Restrictive conditions for activities with field sprayers, such as self-propelled sprayers, must be established by considering weather conditions and soil moisture at the field capacity when the soil becomes plastic, which is regarded as the ability of the soil to deform under pressure and maintain that deformation even after the pressure has been removed. Clay soils under volumetric moisture conditions between 30 % and 40 % (equivalent to 90 % of the available water field capacity) are close to the optimum moisture scenario for compaction (Silva & Ricardo, 2022). The consequences of soil compaction include increased mechanical resistance to root growth as well as modified soil pore size distribution and connectivity, which can ultimately alter water retention, availability, and soil aeration (Lima et al., 2020). The traffic of agricultural machinery in the field in a situation of soil moisture at approximately 95% of the field capacity is prone to soil compaction. In comparison, when this same traffic of machines occurs when the soil is presenting moisture at 65% of the field capacity, there is no longer a significant difference in compaction using the same machinery (Deon et al., 2018). However, the literature does not present the ideal soil moisture for mechanized operations according to the different conditions of textures (Gava et al., 2018).

This study aimed to geographically estimate the monthly available time and number of favorable hours for agricultural field spraying in the state of Mato Grosso do Sul, Brazil.

Material and Methods

Study region

The study region included the entire territory of the state of Mato Grosso do Sul. According to the Köppen classification (Figure 1), the climatic conditions were segmented into three regions with classes: Aw, (savanna tropical) with a dry winter and an average air temperature of the coldest month remaining above 18°C; Cfa, a humid temperate climate with a hot summer, and Cwa, warm weather and dry winter, with an average temperature above 22°C during the hottest month and below 18°C in the coldest month.

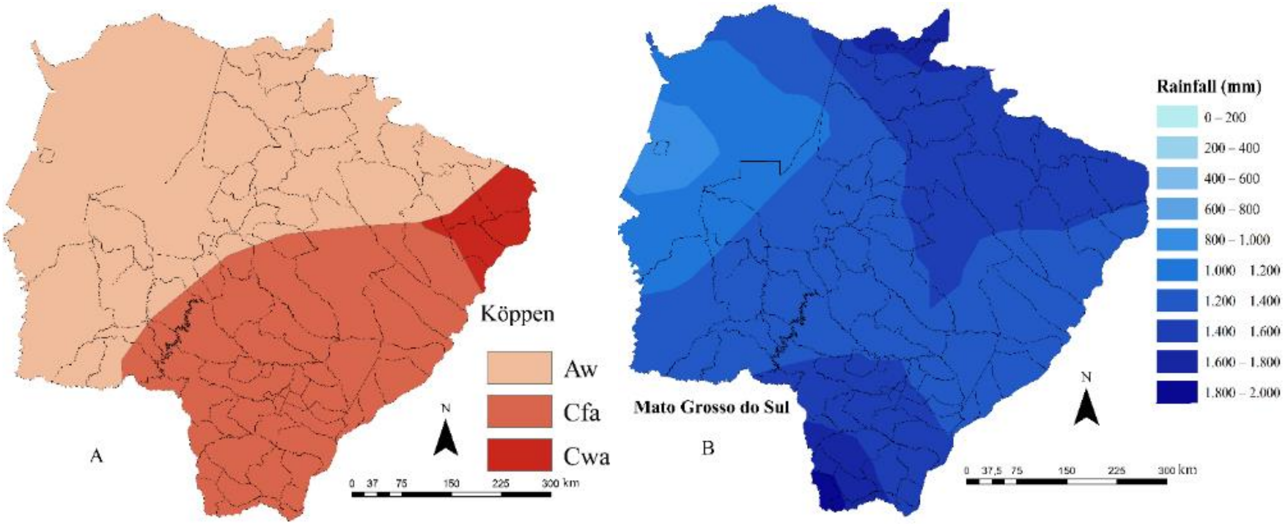

Figure 1. Climate classification (A) and rainfall regime (B) maps in the State of Mato Grosso do Sul, Brazil.

The State of Mato Grosso do Sul is in a region of climate transition, suffering the action of several air masses, which implies sharp thermal contrasts, both spatially and temporally. The area is in a convention zone of several air masses that act in the Brazilian territory.

Data collection

Archived data recorded by the National Institute of Meteorology (INMET) meteorological stations in the state of Mato Grosso do Sul were used. These data were from an hourly historical series of ten agricultural years between September 1, 2008, and August 31, 2018. The stations stored hourly data on the maximum and minimum values for temperature, relative humidity, dew points, atmospheric pressure, wind direction and speed, solar radiation, and rainfall. The locations of the stations are shown in Figure 2.

INMET data were then filtered and transferred to the developed web server algorithm via a programming script. The developed programming system ran Script Programming Language (PHP) and Structured Query Language (MySQL) for database consulting. The following data of interest were received: Hourly historical series of wind speed (m s^{-1}); relative humidity (%); air temperature (℃); rainfall (mm); and dew point (℃), and the developed programming script subsequently calculated all the results.

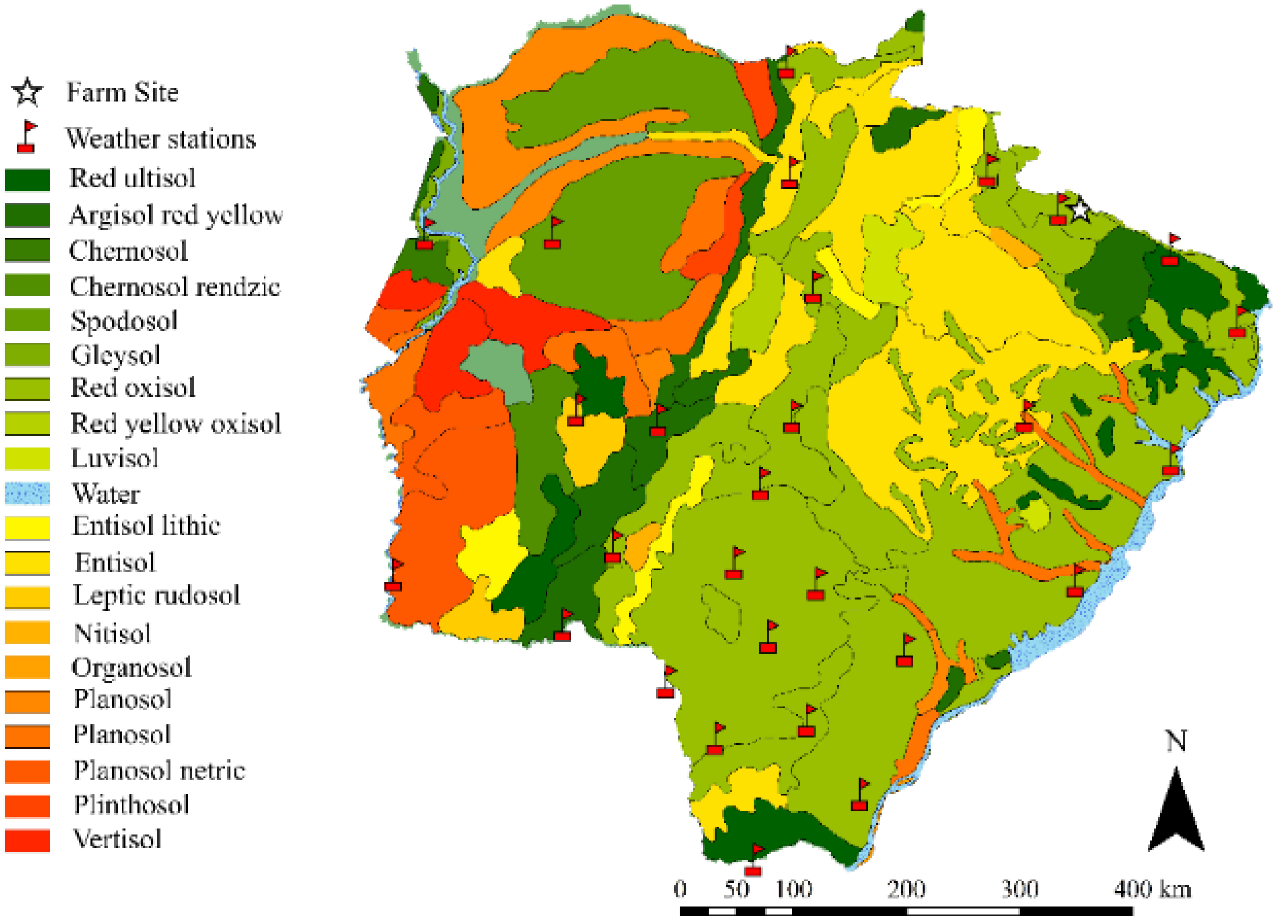

Figure 2. Map of the automatic weather stations in the State of Mato Grosso do Sul (INMET), the soil classification (Empresa Brasileira de Pesquisa Agropecuária [EMBRAPA], 2018), and the site of the Cinco Estrelas farm employed as the case of study.

Development of Web programming script

The available time (AT) for agricultural field operations depended on the total number of hours reserved for machine work and the labor-day period, while excluding unsuitable days (relative to weather and soil humidity restrictions). The following algorithm restrictions were imposed to calculate the field sprayer operations: wind speed higher than 12 km h^{-1} (3.33 m s^{-1}), relative humidity below 50%, and ambient temperature above 32 °C. This study acquired restrictive soil moisture when it exceeded 90% of the water field capacity for mechanized field spraying, which could be classified as a very conservative restriction.

The hourly soil water balance for the historical series was estimated using the formulas inserted into the developed algorithm script (available at http://www.gpvi.com.br/). Thus, evapotranspiration (ETo) was determined using the Penman-Monteith method, which was in conformity with the methodology previously proposed by the

FAO-56 bulletin (Allen et al., 2005). The web script considered the hourly air temperature (°C), relative humidity (%), wind speed (m s^{-1}), and solar radiation (kJ m^{-2}) data. Three variations of soil textures were considered: clay, medium, and sandy (predominant in the region). In most of the study regions, the crop system by minimum tillage is the mainly practiced applied, and in some areas no-tillage practice. Thus, an amount of 2.5 t ha^{-1} of straw covering the soil (Gava et al., 2018) was considered for calculating the water balance, typical for the scenario of study. The script sequence was defined using the programming scheme presented in Figure 3.

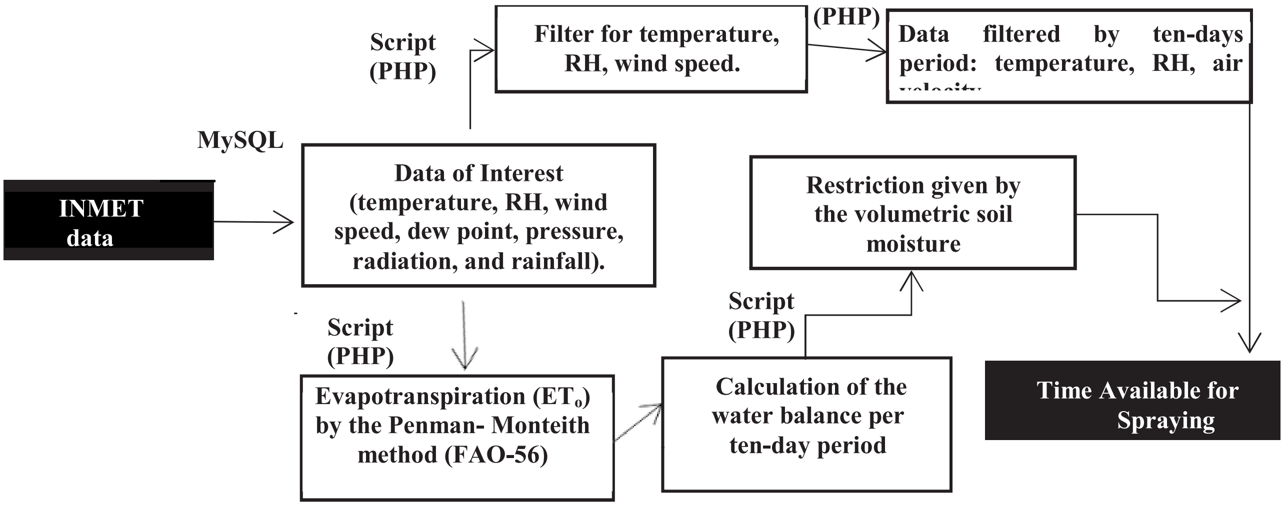

Figure 3. Schematic representation of the calculations sequence for setting the Available Time of field spraying.

Elaboration of the maps

Geographic information system software ArcGIS 10.5 (ESRI, Redlands, CA, USA) was used to process the maps. The adopted interpolation methodology was the Kernel Density, which is an effective data interpolation method that uses nonparametric statistics. Kernel density estimation is a valuable method for analyzing meteorological data, particularly for visualizing the probability density function of the data. This technique works well for data sets with a continuous distribution, such as temperature or wind speed measurements (Shi et al., 2019). The probability of an event reoccurring or being exceeded was calculated through the Kimball method, in which the percentage of AT to crop spraying occurring or being exceeded was given. This equation calculated the empirical probabilities as $F= M/(N+1)$, where F was the frequency, M was the order number, and N was the number of years observed. Maps were subsequently generated with 50 %, 75 %, and 90 % probabilities of AT being exceeded during the early months. AT restriction maps were generated for each agricultural spray event.

Validation with farm data

The validation procedure of the AT calculated by the programming script was contrasted with field information from Cinco Estrelas Farm, located in the municipality of Cassilândia/MS. Meanwhile, farmer-cropped soybeans (*Glycine max*) and corn (*Zea mays*) were used as second crops for the 2019 and 2020 agricultural years. This farm was located in the Cerrado biome, in the North-East of MS State (18º48'15 "S; 52º26'38 "W) (Figure 2). Additionally, the soil on the farm was classified as dystrophic red latosol, an oxisol (EMBRAPA, 2018), with an average clay content of 440 g kg^{-1}. The average annual rainfall was 2,196 mm, while the average temperature was 22.5°C. The climate of the region was characterized according to the Köppen classification as tropical, with a dry season in winter (Aw). Its average altitude was 815 m, with a predominantly smooth relief and slopes ranging between 1% – 2 %.

The characteristics of the applied self-propelled sprayer were based on the Jacto Uniport 2500 Star (Pompéia, Brazil) available on a farm and cropped land of 1,050 ha. The planning of the sprayer activities during the crop season is shown in Figure 4.

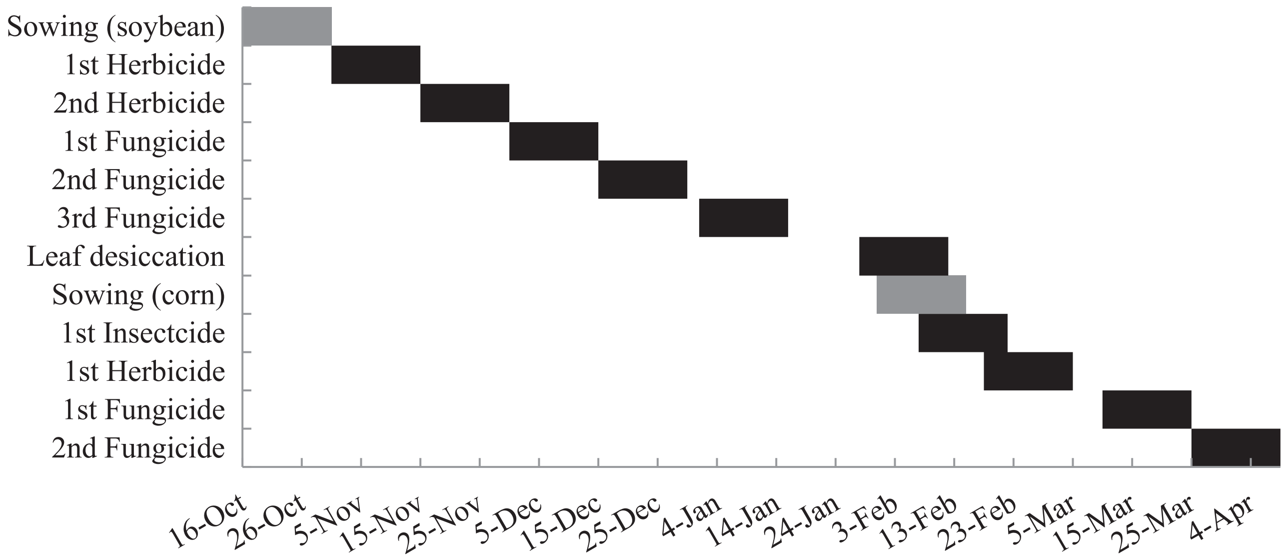

Figure 4. Representation of the spraying activities for the first (soybean) and second (corn) crops.

The operational field capacity was estimated based on the dimensional sprayer data and spray efficiency (Gava et al., 2018). Furthermore, the Operational Field Capacity (OFC) of the agricultural sprayer was calculated using an average field speed of 17 km h^{-1} (4.72 m s^{-1}), an effective boom width of 27 m, and an average field efficiency of 60 %, resulting in an OFC of 27.50 ha h^{-1} as it occurred on the field.

Results and Discussion

The rainy (beginning in spring) and summer seasons were selected to present the results considering that they coincided with the crop period in the agricultural fields of Mato Grosso do Sul. None of the weather variables i.e., temperature, relative humidity, and wind speed in October, November, or December restricted the favorable hours for agricultural field spraying (Figure 5). However, excess soil moisture, with a water-soil capacity greater than 90 %, was found to be restrictive, and the condition increased more prominently with the onset of the monsoon. In December, when there is a greater intensification of spraying in the installed crops, there is a more significant restriction condition due to excess soil moisture, favoring its compaction. Machines require firm soil to provide adequate traction and performance for different mechanized operations (Esteban et al., 2019), and the high humidity level on the soil leads to increased field compaction.

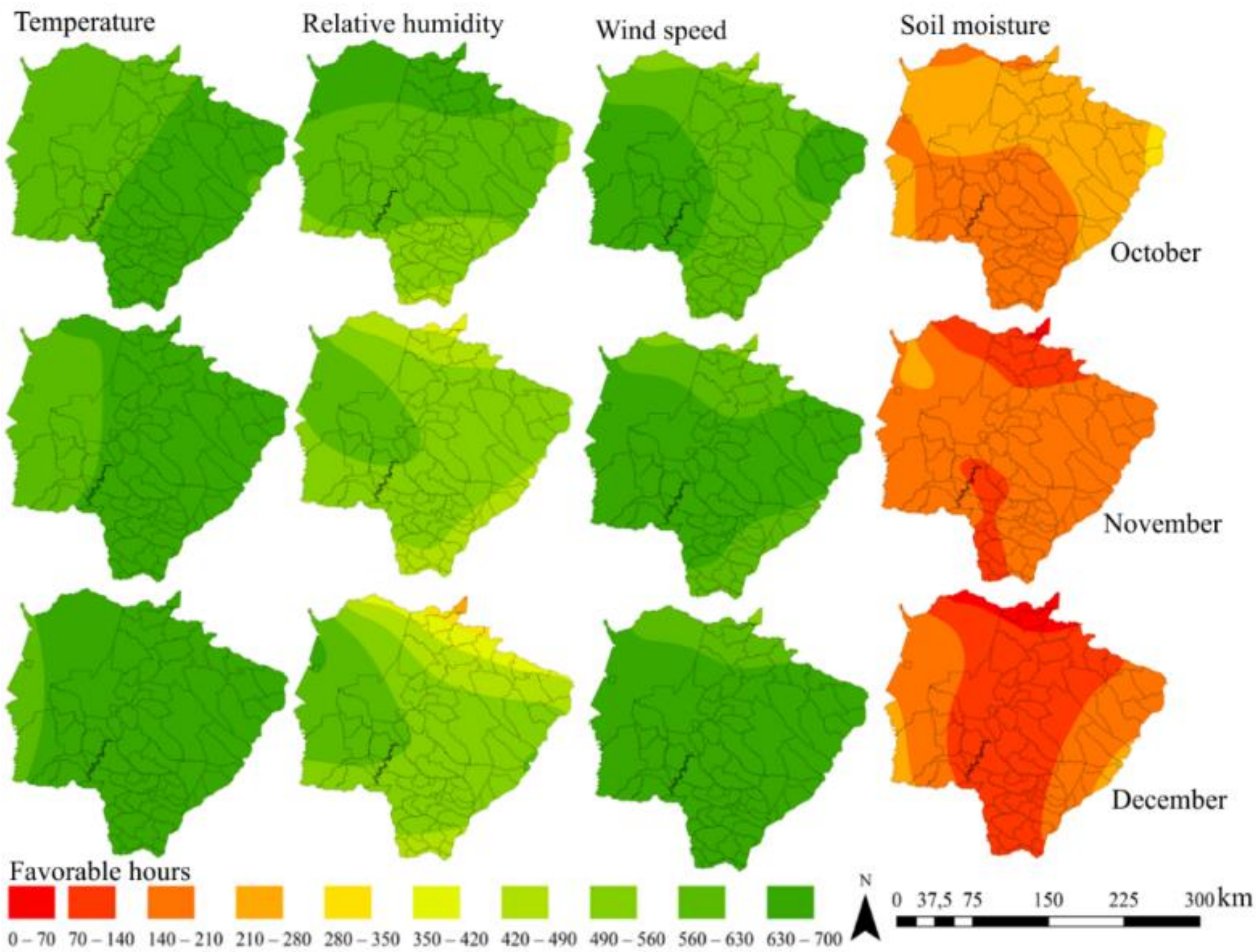

Figure 5. Favorable hours for field spraying according to the constraints of air temperature, relative humidity, wind speed, and soil moisture during spring in the MS State.

Throughout the entire studied historical series, the hottest and rainiest seasons in summer, air temperature, or wind speed had no interference with the favorable hours for agricultural field spraying. These variables never decreased below 500 h per month across the entire state of Mato Grosso do Sul, with soil moisture being the most limited variable (Figure 6). The relative humidity during February and March reduced the number of favorable hours available for field spraying. The favorable hours were reduced to 250 h per month in the North-East of the state, starting from the South-West region and following the Pantanal and North-Central areas. It was reasonable for the farmers to modify the droplet size or use adjuvants to reduce the effects of spray drift when spraying under low relative humidity conditions. There must also be an appropriate choice of these application technology considering that adjuvants could modify the physicochemical characteristics of the application mixture, especially viscosity and surface tension (Santinato et al., 2017).

The soil pressure caused by excess moisture in the sprayer, above the soil, resulted in field compaction. This process occurred during the rainiest months, due to insufficient time for water to infiltrate the soil profile, and therefore, remained in saturated conditions at field capacity for an extended period. Further, aggravating this problematic scenario were the farmers who tend to purchase agricultural machinery with higher operational field capacity than required (Mello et al., 2019). Machines with greater field capacity are generally heavier, increasing the soil compaction problem. In a field experiment performed in Uberlândia, Minas Gerais, a greater appropriate hour for applying pesticides in the months of November to February was found, and lower availability of appropriate hours for field spraying in the months of August and September (Cunha et al., 2016). However, the authors only considered the issue of environmental climate conditions, not considering any restrictions related to occasional problems with the soil.

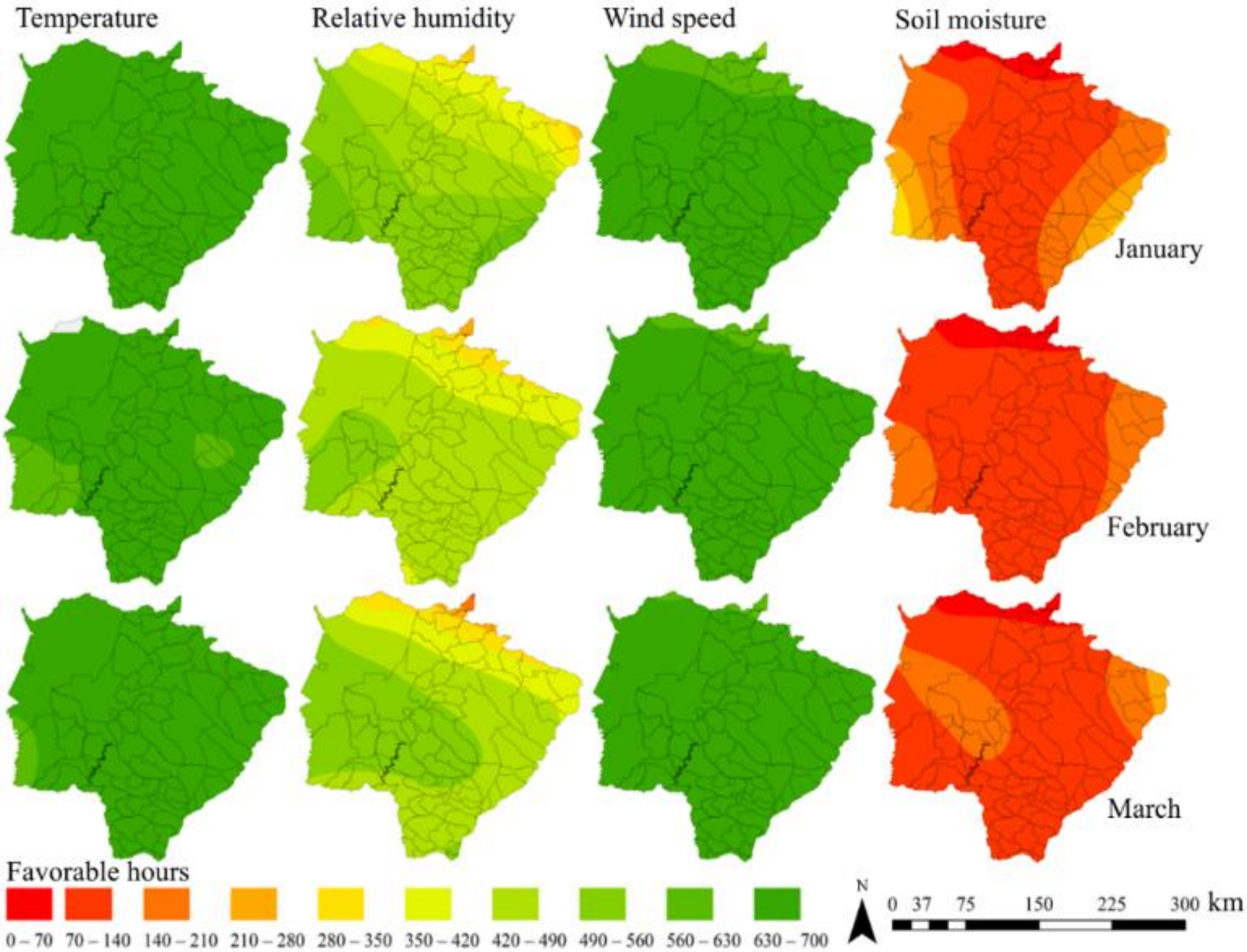

Figure 6. Favorable hours for field spraying according to the restrictions of air temperature, relative humidity, wind speed, and soil moisture during the summer in the MS State.

Considering all the restrictions (weather and soil humidity) given by the variables analyzed for agricultural field spraying, October, November, December, and February were the most critical and presented the lowest AT (Figure 7). The restrictive interaction of these variables drastically reduced the available time when compared individually. The failure of an application could be associated with inadequate technology and non-observance of atmospheric conditions (Tian et al., 2020). For the successful spraying application of pesticides, wind speed should be prioritized, followed by relative humidity and temperature (Baio et al., 2019). However, this study only considered aircraft spraying and per usual, soil moisture was not considered.

The Northern region of the state (Figure 7) had the lowest AT values throughout the year compared with the Southern region. This could have been due to the high altitudes of the areas, which were characterized by a rainier climate and more constant wind gusts. These conditions directly interfered with other meteorological variables (relative humidity and temperature) and with the predominance of clay soil, including Argilosos and Latossolos, in which drainage by excess water was slower.

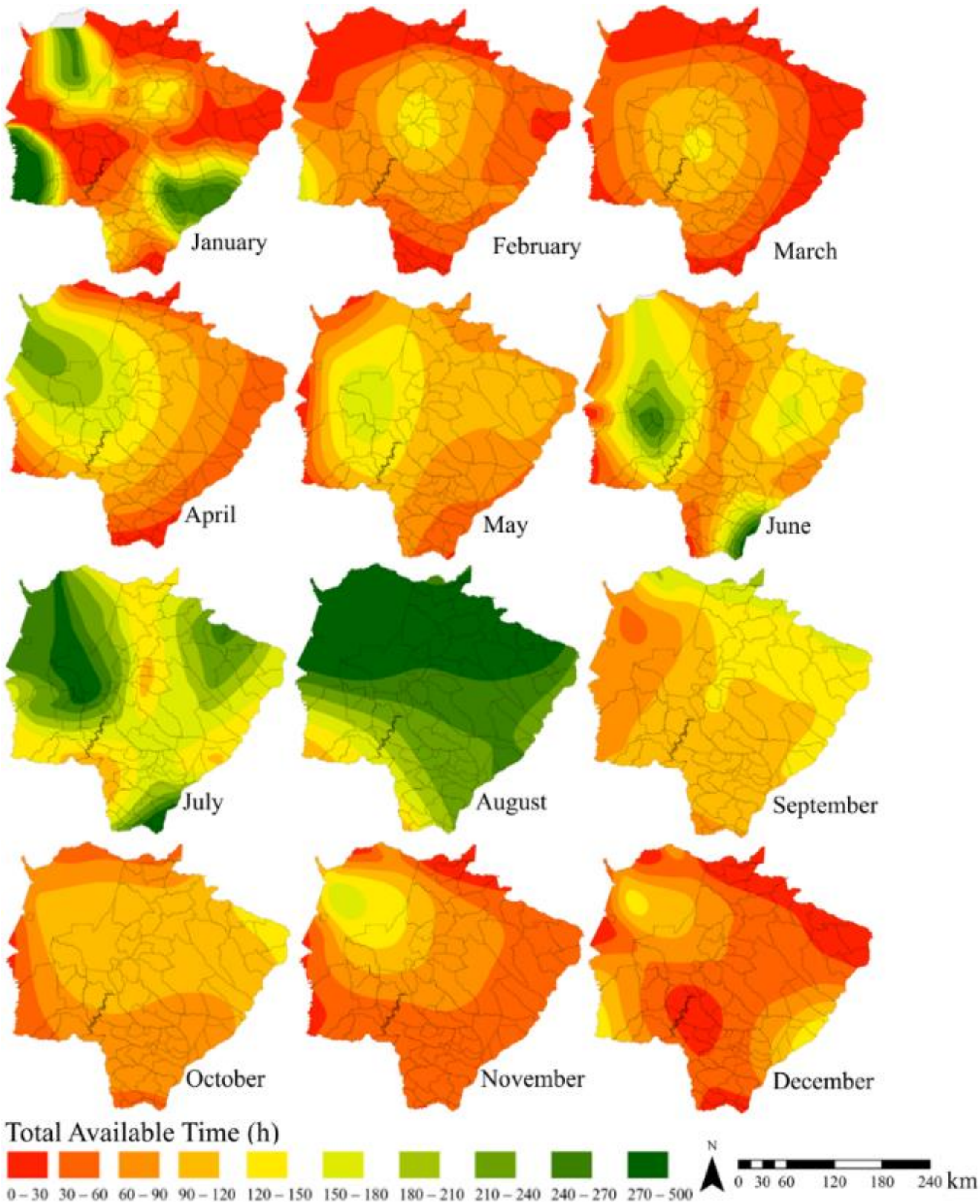

Figure 7. Map of the total monthly Available Time (AT) for agricultural spraying in the State of Mato Grosso do Sul.

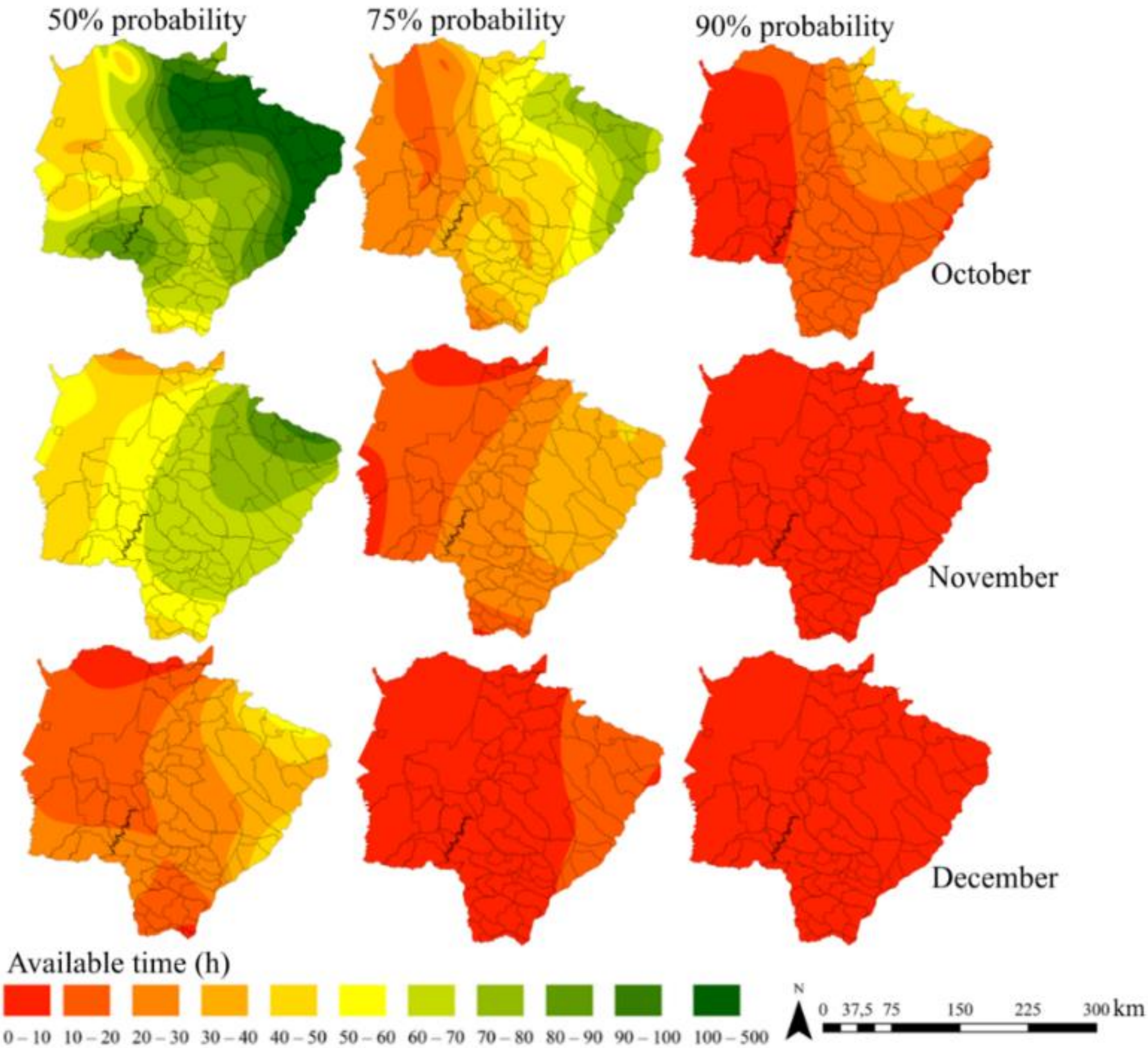

Figure 8. Available Time (h) for mechanized spraying according to the probability of occurrence of being equaled or exceeded during the spring season and according to a ten-year historical series.

During spring, AT began to decrease again, consequently reducing the probability of favorable conditions. For October, November, and December, there was no more than 50 h of AT with a 90 % certainty probability (Figure 8). During these months, AT for mechanized field spraying was in demand in large quantities, with farmers being limited to less than 50 % certainty of the occurrence for a minimum of 100 h throughout the state. In December, the probability of AT occurring over 50 h was below 50 %. Using this study, farmers were able to estimate the number of favorable hours for the use of field sprayers in the region of MS State to quantify the set of agricultural machinery systems to be deployed on the farm.

For January, February, and March (summer), even with a 50 % probability, no more than 50 h were available in total (Figure 9). Under these conditions, agricultural field spraying was limited by soil moisture during the rainy season. Thus, it was impossible to perform agricultural field spraying with a 50 % probability of favorable hours between December and March for almost the entire state. Esteban et al. (2019) previously investigated the effect of soil compaction on the sugarcane root system and subsequently found a change in the area of the crop root system and its distribution throughout the soil profile, thus decreasing crop yield.

Figure 10 illustrated the results of the AT (h) simulation application based on the developed algorithm and the operational rhythm (h) required for a farm in the North-East of the state. According to the AT simulation for the 1,050 ha farm, the hours required to accomplish the operational rhythm in October, November, December, February, and March exceeded the hours available for mechanized field spraying. Therefore, it could be deduced that the farmer performed spraying in conditions of high soil moisture, promoting soil compaction by the tires of the field sprayer.

Thus, it is necessary to adopt technical strategies to accomplish planned operations, such as increasing the number of mechanized agricultural sets or contracting outsourced services. As an additional counterpoint, one significant advantage of aerial spraying was that the machinery did not come into direct contact with the soil of the sprayed field and thus presents itself as an alternative in conditions of impediment, owing to excessive humidity in the field. Consequently, technically dimensioning an agricultural machinery system could be difficult, and the physical conditions of the farm's agricultural system, soil, and climate must be considered.

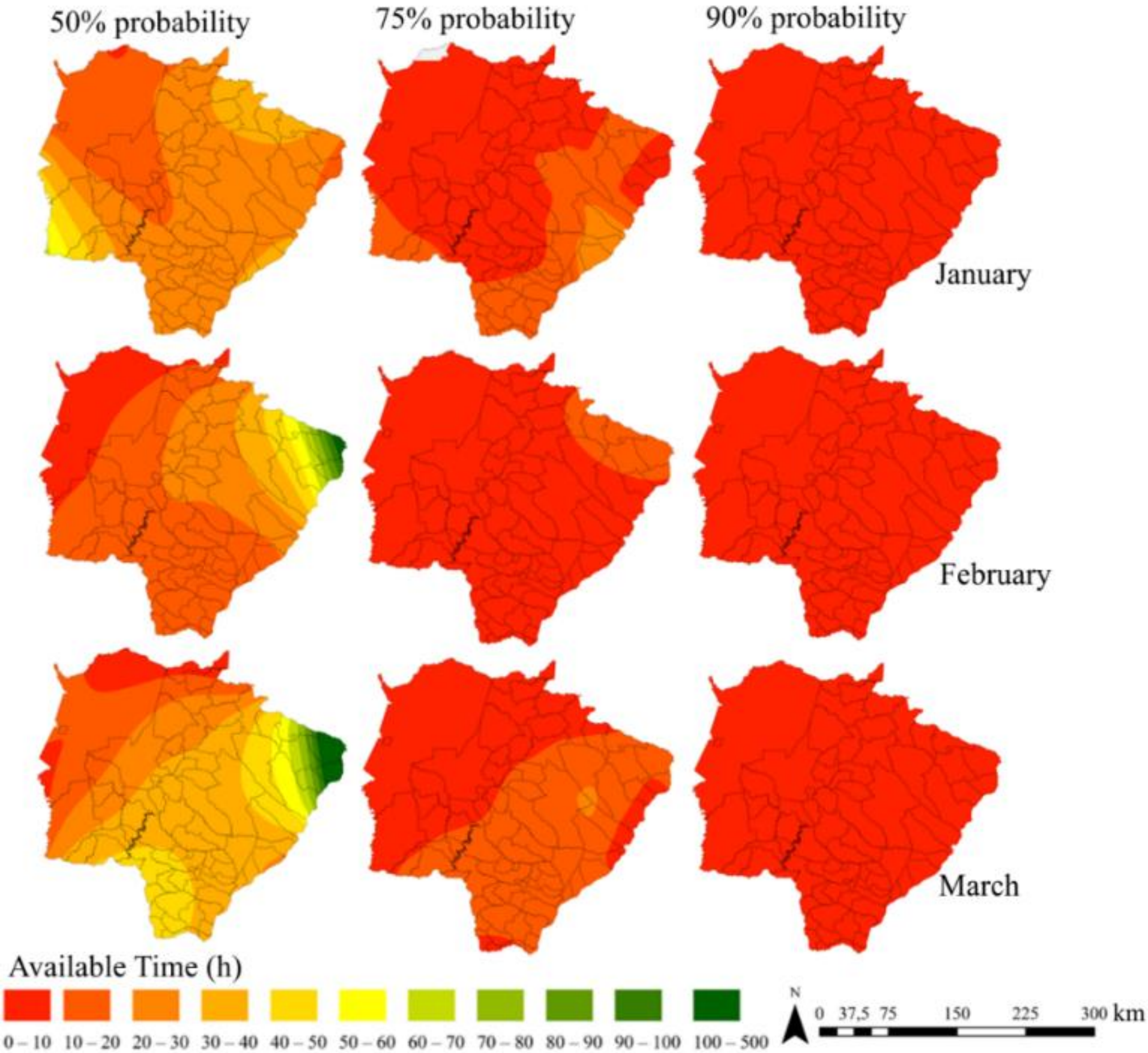

Figure 9. Available Time (h) for mechanized spraying according to the probability of occurrence being equaled or exceeded during the summer season for a ten-year historical series.

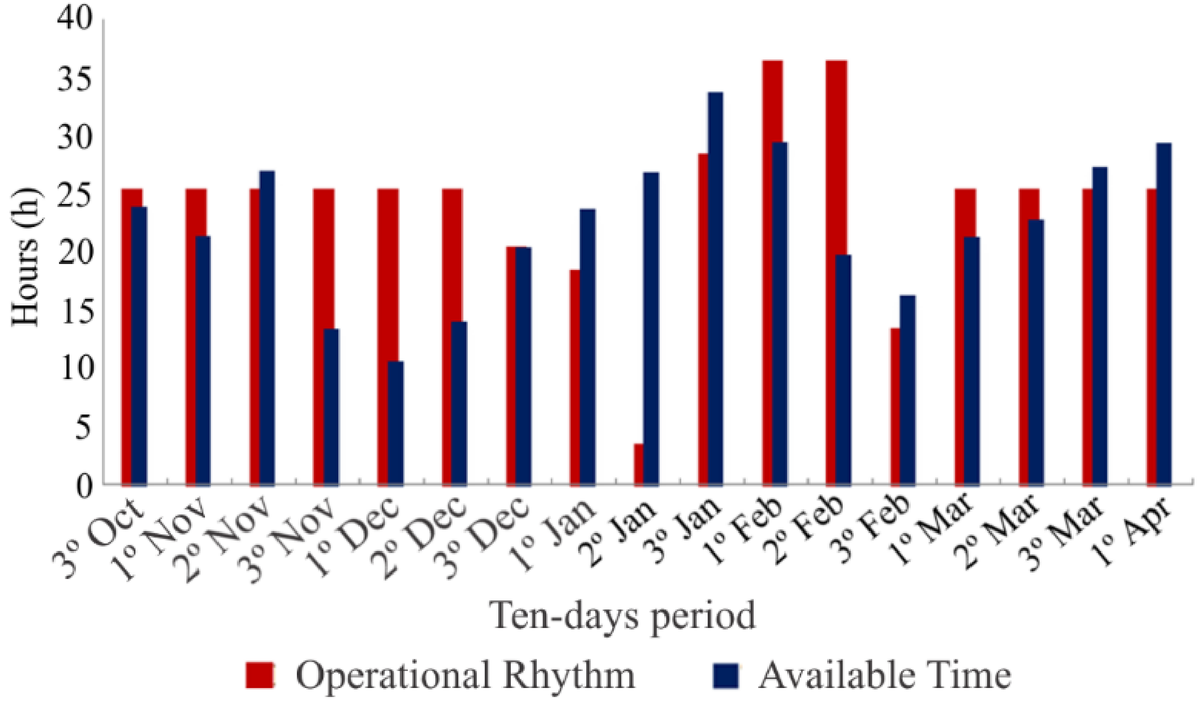

Figure 10. Available time for field spraying and operational rhythm required by the farm condition during the crop season.

Conclusions

The algorithm was programmed and installed in a web server to simulate the time required for agricultural field spraying in the state of Mato Grosso do Sul, Brazil.

During the cropping period in the state, there were climatic restrictions on agricultural spraying activities and relative humidity had the most significant impact. Soil moisture conditions also restricted the time available for agricultural spraying more than other variables such as wind speed, relative air humidity, and ambient temperature.

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