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Agrometeorological and Soil Criteria for Defining Workable Days for Rational Mechanized Sugarcane Harvest in Southern Brazil

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Abstract

The number workable days (NWD) for agricultural field operations is of great importance for sizing agricultural machinery fleets. This is especially pivotal for sugarcane harvest, which extends from 8 to 10 months/year. In light of this, the current study aimed at defining criteria for obtaining the NWD for rational sugarcane harvest at different sites in the state of São Paulo, southern Brazil, taking into account both a general and a specific criteria. For this purpose, data from harvest interruption of 30 sugar mills in southern Brazil throughout periods ranging from two to five years were used. The following variables were tested as criteria for defining harvest interruption: minimum precipitation (PREC); soil water holding capacity (SWHC); and the limit of the ratio between actual soil moisture (SM) and SWHC. Based on such a specific criterion ascribed to each site along with a general criterion, NWD maps were prepared for the state of São Paulo, Brazil. The results showed that there were variations from the definition criteria of NWD at the different sites in the state. However, the use of a general criterion for harvest interruption, based on PREC ≥ 3 mm, SWHC = 40 mm and SM/SWHC ≥ 90%, provided accurate results. During the validation of these criteria, the NWD maps generated from the individual criterion proposed for each site resulted in an average error of 24.9 days/year, whereas the map generated from the general criterion culminated in an average error of 4.4 days/year.

Keywords

1. Introduction

The study of workable days for the completion of field operations with agricultural machinery and implements turns out to be of extreme importance to minimize possible impacts of machinery traffic on soils whenever they contain high moisture contents in order to prevent soil compaction [1] [2].

The climatic study dealing with the frequency of suitable days to diverse works with agricultural machinery has been done on the basis of meteorological historical data and soil information, providing technical support to planning, selection and rationalization of mechanized field operations, although such a strategy is not always taken into account at the stage of fleets' sizing [3].

In the sugar-energy industry sector, fleets' sizing has been done based on economic and logistic criteria without, however, taking into consideration how many effective days are suitable for field activities. Thus, in order to size the number of agricultural fleets necessary for a given activity or available effective time for such machinery to perform a specific operation, it is pivotal to scrutinize soil water content and also its influence on such a field operation. This defines the actual magnitude of how many effective workable days are to be considered in the crop growing season for such an operation.

Under the current high-intensity agriculture model, it is indispensable that the growers acquire some knowledge of actual time availability for the performance of field operations throughout crop growing seasons [4] [5]. This is the first step to obtaining the greatest efficiency in the execution of these operations, which are subjected to variations in local meteorological conditions, mainly rainfall regimes. Rainfall and its influence on soil water status at a given site directly impinged upon the number of available days for work with agricultural machinery [6] [7].

According to [8], a simple empirical analysis of dry days within a long-term precipitation series already provides useful information for plenty of agricultural applications. Duration of dry periods is an important input variable to define management strategies of agricultural practices, such as soil preparation, sowing and harvest planning, fertilizer application and phytosanitary control. Nevertheless, information regarding soil water availability is also crucial, since the main problem caused by indiscriminate traffic of machinery in the fields is soil compaction, which in turn depends directly on soil moisture conditions [1].

The criteria for determining workable days for field operations at Central Nigeria, Africa, were proposed by [9]. These authors found a good agreement between observed and estimated workable days by assessing a 30-cm soil layer in conjunction with soil water storage less than 95% of available water capacity plus daily rainfall below 5 mm. Similarly, the number of days potentially useful for work with forest machinery as a function of soil water balance at Guanhães, MG, Brazil, was determined by [10].

The criteria for the determination of the number of workable days vary in ac-

cordance with the field operation to be carried out. The following criteria were used by [11] for assessing workable days for soil preparation and management: precipitation of the day lower than 5 mm along with a limit of the ratio between actual soil moisture (SM) and soil water holding capacity (SWHC) between 40 and 90%. According to these authors, the number of workable days varied from place to place and also from season to season, with a predominance of 11 to 20 workable days per month at Piracicaba, SP, Passo Fundo, RS, and Dourados, MS, whereas at Londrina, PR, a lower number of workable days of up to 10 days per month throughout the year prevailed. Similar criteria to those employed by [11] were utilized by [6] for determination of the probability of workable days for rice cultivation in Southern Brazil. On the other hand, [12] just used the ratio between SM and SWHC of 80% in a computational system to predict workable days for several field operations in Sudan.

Several studies report methodologies for determining the number of workable days, with the majority of them reported by [2]; however, in most cases such methodologies are solely regionally applicable and were not always validated by means of observed data obtained from production fields. Also, São Paulo State, Brazil, does not possess a full analysis of the determination of the number of workable days for mechanized harvest of sugarcane. This emphasizes the importance of a scientific study in order to assist mechanized harvest planning to be adopted by many sugarcane-mills that are installed all over the state.

Thus, the hypothesis of the current research was to verify whether it is possible to develop site-specific and/or general criteria for the definition of workable days to carry out the mechanized harvest of sugarcane in Southern Brazil by means of local meteorological data in conjunction with information on soil type and water balance. The aim of the current study, therefore, was to propose agrometeorological criteria, both site-specific and general ones, for the estimation of the number of workable days (NWD) for the mechanized harvest of sugarcane, as well as to validate such criteria by comparing estimated NWD with independent observed values obtained from sugarcane mills at different sites in the State of São Paulo, Brazil. Based on the criteria defined in this study, mapping of the mean NWD for mechanized harvest of the crop was also elaborated in order to assist the scaling of harvesters.

2. Material and Methods

For the definition of agrometeorological criteria aimed at determining the NWD for the mechanized harvest of sugarcane in the State of São Paulo, Brazil, data on grinding interruption hours due to rainfall from 30 sugarcane mills allotted within the State (Figure 1) was collected. Grinding interruption hours due to rainfall are highlighted by the industry; however, this type of stoppage only occurs whenever there is interruption of harvest in the field. Therefore, it was assumed that grinding interruption at the cane mills depicting a suspension of harvest in the field was a plausible assumption, as well as the resumption of

grinding representing the recovery of these activities.

As it deals with several cane mills belonging to different companies/economic groups, data regarding stoppage hours corresponded to series varying from two to five years, between 2012 and 2016, depending on what was made available by the company.

Figure 1 shows the distribution of sugarcane mills which provided data on grinding interruption due to rainfall. It was observed that there is an excellent distribution of these mills, representing the great majority of sugarcane-producing areas in the State of São Paulo. Further in Figure 1, 23 sites are presented where cane mills are located, which indicates that there were locations that hosted more than one single cane mill. Daily data of stoppage hours due to rainfall were grouped into monthly hours. After the summation of total monthly hours with stoppage, the total was divided by 24 hours in order to determine throughout the month how many equivalent days were not taken as workable due to the occurrence of rainfall along with high soil moisture conditions. The determination of the number of workable days throughout the month was obtained by means of subtraction of the overall days computed during the crop growing season for each month in relation to stoppage days. Such data were referred to as the observed
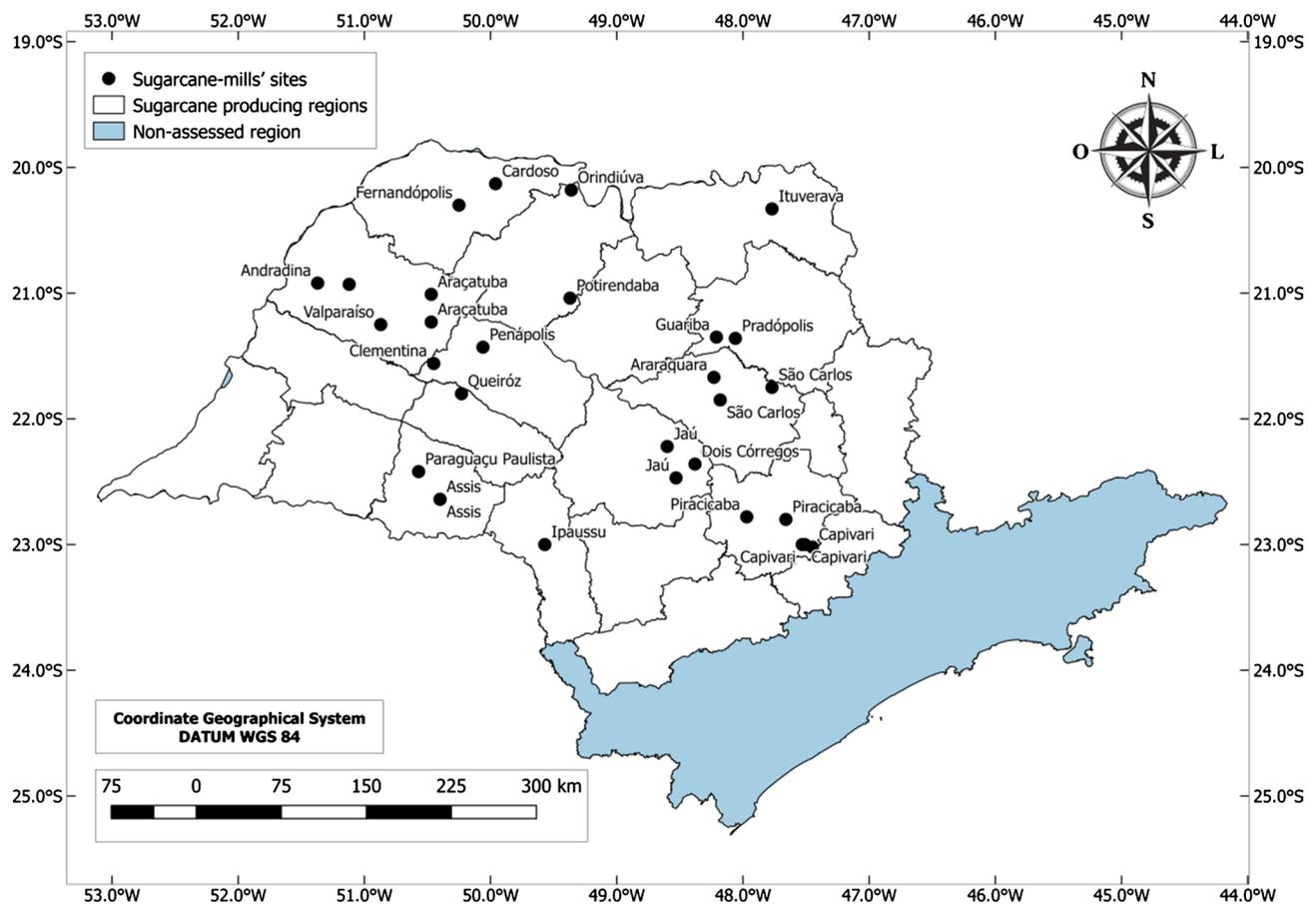
Figure 1. Distribution of sugarcane mills which provided data of grinding interruption due to rainfall in the State of São Paulo, Brazil.

data (OBS).

To determine effective soil water status, a sequential climatological water balance (WBSeq) approach was applied in accordance with the method proposed by [13], similarly to what was done by [4]. Firstly, WBSeq on a daily basis scale was elaborated for all the sites under scrutiny (**Figure 1**) for the period between 2012 to 2016 when the harvest stoppage hours due to rainfall were recorded. The WBSeq was also run for the historical series (1983 to 2014) of each location to be used later for determining the annual average NDW. For each site, rainfall data collected from the Department of Water and Electrical Power of the State of São Paulo (DAEE-SP) was obtained from the website http:/www.hidrologia.daee.sp.gov.br [14]. For the series featuring gaps, data supplied by other weather stations located at the same site or from the closest one were used [14] [15] [16] [17].

Further meteorological variables taken as input for the elaboration of WBSeq, such as maximum, minimum and mean air temperature, mean wind speed, mean relative humidity and solar radiation, were obtained from the database system provided by the NASA Prediction of Worldwide Energy Resource (NASA/POWER) available at https://power.larc.nasa.gov/cgi-bin/agro.cgi?na [18] [19]. According to [7] and [20], meteorological information generated by gridded climate data set was satisfactory to represent the water balance and the trafficability conditions for field operations.

In order to come up with the best criterion for determining the NWD for the mechanized harvest of sugarcane, 27 combinations were taken into account by employing: three precipitation thresholds (PREC); three thresholds of the relationship between actual soil moisture and soil water holding capacity (SM/SWHC); and three levels of SWHC (**Table 1**). This kind of analysis was only made for the sugarcane harvest periods when stoppage hours due to rainfall were reported by the sugar mills.

Variations of SWHC aimed to simulate the combination of different soil types or root depths under compaction effects. Thus, a SWHC = 40 mm was adopted as the representative of a sandy loam soil or shallow depth, a SWHC = 80 mm for an intermediate soil texture or medium depth, and a SWHC = 120 mm for a clay loam soil or deep soil. The definition of thresholds for PREC and SM/SWHC for a given day to be considered as a workable day was made on the basis of the contributions published by [6] [11] [21].

On the basis of the criteria illustrated in **Table 1**, a set of the combination of

Table 1. Soil water holding capacity (SWHC) levels and thresholds for precipitation (PREP) and ratio between actual soil moisture and SWHC (SM/SWHC) for the determination of workable days for mechanized harvest of sugarcane.

SWHC (mm)	PREC (mm)	SM/SWHC (%)
40	≤3	≤70
80	≤5	≤80
120	≤7	≤90

three factors with three levels, totaling 27 combinations, was tested with the purpose of determining NWD for the mechanized harvest of sugarcane. Such combinations of criteria were defined with the aim of identifying which one of them performed best at each site in the State, as well as to propose a general criterion (a state-wide one) for obtaining NWD at the State of São Paulo, Brazil.

To define the best criterion for determining NWD a comparative analysis between monthly values observed at sugarcane mills (NWD Obs) and estimated from the criteria presented in Table 1 (NWD Est) was made. The performance of NWD estimates was assessed by means of the following statistical parameters: mean error (ME); mean absolute error (MAE); Willmott agreement index (d) revealing exactness of the estimates; coefficients of determination (R^2) and Pearson correlation (r) which indicate precision or accuracy of the estimates; and performance index (C) proposed by [22].

Statistical analyses were made with the software R, whereas elaboration of graphs was performed by making use of the software *Statistica* 11.0. From the results obtained, the best three models associated with the lowest MAE for each site were classified. In case of a MAE tie, we took into consideration the C index to make a decision, which in turn is calculated by the product between d, proposed by [23], and r.

After evaluation of the three best models by means of statistical analyses, a creation function of Box Plot with the software *Statistica* 11.0 was utilized in the search for a sole model that could be applied all over the State of São Paulo, by assessing individually each single variable. In this particular case, the SWHC, PREC and SM/SWHC criteria were evaluated using all datasets available for the study, regardless of the site or region under scrutiny and considering the MAE values of each criterion. Therefore, the SWHC, PREP and SM/SWHC that possessed the lowest MAE when all data was analyzed with no regional discrimination, comprised the general model proposed to determine the number of workable days.

As the study aimed to propose agrometeorological criteria for the assessment of NWD for the mechanized harvest of sugarcane, shortly after the determination of individual criteria for each site, such criteria were interpolated and spatialized by means of the Voronoi method [24], making used of the *Open Source Quantum GIS* (QGIS).

Once developed, validation of both individual and general criteria by means of the comparison of NWD estimates with observed independent data was made. Such a validation procedure employed the same statistical parameters previously described. For that, 16 sites (sugarcane mills) from which observed data of grinding interruption hours for the 2015-2016 growing season along with its corresponding meteorological information were chosen. The set of data used for validation of both criteria was a result of the performance analysis of the NWD on a monthly basis, as it was also done for the NWD estimation with individual and general criteria. Rather than merely making statistical analyses taking into

account annual NWD, the monthly data of NWD was assumed in order to make the number of observations under scrutiny larger and the outcomes more consistent.

To make maps of annual average NWD for the State of São Paulo, the values of such a variable obtained by either site-specific or general criteria were determined for the historical series (1983-2014) and correlated to geographical coordinates (latitude—ϕ, longitude—λ, and altitude—ξ) by means of a multiple linear regression analysis, as well as with an integration of these inputs along with their values raised to the power of two ($\phi^*\lambda$, $\phi^*\xi$, $\lambda^*\xi$, ϕ^2, $\lambda^2 e \xi^2$):

$$\text{NWD} = a + b\phi + c\lambda + d\xi + e\phi\lambda + f\phi\xi + g\lambda\xi + h\phi^2 + i\lambda^2 + j\xi^2 + \varepsilon \qquad (1)$$

where *a* corresponds to the linear coefficient and *b*, *c*, *d*, *e*, *f*, *g*, *h*, *i* and *j* are the angular coefficients of the multiple regression equation; and ε is the error associated with the estimates.

The multiple linear regression model generated to provide information on annual average NWD both from a site-specific and general criterion was processed under the ArcGis software, version 10.3. This kind of procedure is an accurate method for interpolating climate-related variables [25].

Firstly, images from the *Shuttle Radar Topography Mission* (SRTM) under the GEOTIFF format (16 bits) referring to a Digital Elevation Model of the terrain surfaces of the entire State of São Paulo were obtained from [26].

From the SRTM images, a composite image to represent the whole State of São Paulo was obtained by means of the ArcGis 10.3 Mosaic option, which is accessed shortly after activating the following shifts: *ArcToolBox, Data Management Tools, Raster, and Mosaic*. The resulting image had a spatial resolution (grid) of 90 m and has been geo-referenced originally on the DATUM WGS 84 projection system.

Since the SRTM *Raster* images are related to the mean altitude of the terrain in each pixel, in order to generate the layers of latitude and longitude it was necessary to extract central points of each pixel making use of *AddXYCoordinates* tool. Assuming that São Paulo State possesses a total area of 248,221.996 km^2 (IBGE, 2017) and that each pixel possesses a square area of 90 × 90 m, corresponding to 0.0081 km^2, 30,644.691 points were generated.

After the completion of the determination procedure of the latitude, longitude and altitude layers for each pixel, it was possible to start the NWD spatialization process. Latitude and longitude maps in conjunction with altitude were employed in the making of NWD maps for the mechanized harvest of sugarcane determined by both site-specific and general criteria, by means of the algebra of maps, as preconized by [25]. For such, *Spatial Analyst—Options* and *Spatial Analyst—Raster Calculator* tools were employed in the ArcGis, version 10.3, together with the NWD multiple linear regression models, having latitude, longitude and altitude as independent variables.

Mean annual NWD maps built for the mechanized harvest of sugarcane, tak-

ing into consideration both criteria under scrutiny, were validated by comparing mean annual NWD obtained from maps with those ones calculated for 16 sites allotted in the State of São Paulo, which in turn were not used in the making of the multiple linear regression models referring, therefore, to a completely independent dataset (Table 2). For such analysis, the same statistical parameters previously described (ME, MAE, d, R^2, r, C), along with the root mean square error (RMSE) [22] [23], were employed to give support and consistency to the outcomes obtained in the current study.

Table 2. Sites taken into consideration for the validation of NWD maps for mechanized harvest of sugarcane in the State of São Paulo, Brazil.

ID	Site	Latitude South	Longitude West	Altitude (m)
1	Jales	20˚18'00"	50˚33'00"	450
2	Pirapozinho	22˚16'00"	51˚30'00"	470
3	Garça	22˚12'00"	49˚39'00"	680
4	Salto	23˚11'48"	47˚17'23"	500
5	Araras	22˚15'17"	47˚22'34"	677
6	Matão	21˚36'00"	48˚21'00"	560
7	Batatais	20˚53'00"	47˚37'00"	860
8	Olímpia	20˚36'32"	48˚57'32"	530
9	Adamantina	21˚41'16"	51˚02'31"	440
10	Pederneiras	22˚18'44"	48˚53'26"	565
11	Itabera	24˚03'00"	49˚05'00"	680
12	Vargem Grande do Sul	21˚50'00"	46˚54'00"	750
13	Ourinhos	22˚59'00"	49˚50'00"	460
14	São José do Rio Preto	20˚48'28"	49˚22'27"	484
15	Getulina	21˚45'00"	50˚07'00"	430
16	Santa Albertina	20˚02'00"	50˚44'00"	410

3. Results and Discussion

3.1. Definition of Criteria for Determining the Number of Workable Days for the Mechanized Harvest of Sugarcane

Simulations with the 27 criteria combinations taking into account three levels of PREC, SWHC and SM/SWHC for each of the 30 cane mills allowed us to propose the best models for NWD estimation for the mechanized harvest of sugarcane. Table 3 shows the relation of the three best combinations for each one of the sites from which MAE and C were calculated. For cases from which there was more than one single observed data for a given site, the outcomes chosen were those that resulted in the lowest MAE on average for the month or in case of a tie, the highest C was taken into consideration for decision-making. On the

Table 3. Classification of the three criteria combinations for determining the number of workable days for the mechanized harvest of sugarcane along with its respective values of mean absolute error (MAE) and performance index (C) for each site. For the "Criteria" column the first number refers to SWHC, the second to precipitation limit for the day to be considered as workable, and the third to ratio limit SM/SMHC.

Site	Classification	Criteria	MAE (days month^{-1})	C
	1st	40-03-80	2.320	0.881
Andradina	2nd	40-05-80	2.400	0.876
	3rd	40-03-70	2.520	0.867
	1st	40-03-70	2.440	0.865
Araçatuba	2nd	40-03-80	2.520	0.869
	3rd	40-05-70	2.720	0.851
	1st	80-03-90	3.720	0.692
Araraquara	2nd	40-03-80	3.720	0.691
	3rd	40-05-80	3.760	0.689
	1st	40-03-70	3.654	0.794
Assis	2nd	80-03-80	3.769	0.769
	3rd	40-05-70	3.846	0.771
	1st	40-03-80	2.087	0.895
Capivari	2nd	80-03-90	2.522	0.868
	3rd	40-03-70	2.565	0.871
	1st	40-07-90	1.267	0.967
Cardoso	2nd	40-03-90	1.333	0.951
	3rd	40-05-90	1.433	0.948
	1st	40-05-90	1.224	0.956
Clementina	2nd	40-07-90	1.265	0.955
	3rd	40-03-90	1.449	0.953
	1st	40-03-80	3.640	0.723
Dois Córregos	2nd	40-03-70	3.680	0.707
	3rd	40-03-90	3.720	0.711
	1st	40-05-90	1.333	0.958
Fernandópolis	2nd	40-03-90	1.400	0.950
	3rd	40-07-90	1.533	0.948
	1st	40-03-80	3.240	0.671
Guariba	2nd	40-05-80	3.360	0.655
	3rd	40-03-70	3.440	0.674
	1st	40-03-70	3.370	0.806
Ipaussu	2nd	40-05-70	3.556	0.787
	3rd	40-07-70	3.556	0.787

Continued

	1st	40-03-70	3.520	0.739
Ituverava	2nd	40-05-70	3.600	0.735
	3rd	40-07-70	3.600	0.735
	1st	40-03-80	1.840	0.939
Jaú	2nd	80-03-90	1.960	0.915
	3rd	40-05-80	2.160	0.925
	1st	40-03-70	1.958	0.920
Mirandópolis	2nd	80-03-80	2.125	0.915
	3rd	40-03-80	2.208	0.913
	1st	40-07-90	5.033	0.716
Orindiúva	2nd	120-07-90	5.100	0.697
	3rd	40-05-90	5.533	0.680
	1st	40-03-80	1.654	0.943
Paraguaçu Paulista	2nd	80-03-90	1.769	0.940
	3rd	40-07-80	1.808	0.937
	1st	40-05-90	1.706	0.787
Penápolis	2nd	40-07-90	1.765	0.798
	3rd	40-03-90	2.000	0.777
	1st	80-03-90	2.043	0.860
Piracicaba	2nd	40-03-90	2.043	0.853
	3rd	40-03-80	2.130	0.843
	1st	80-03-90	1.944	0.725
Potirendaba	2nd	40-03-90	2.167	0.744
	3rd	40-03-80	2.222	0.697
	1st	40-03-90	0.962	0.958
Pradópolis	2nd	40-05-90	1.077	0.955
	3rd	40-07-90	1.192	0.944
	1st	40-07-90	1.750	0.919
Queiróz	2nd	40-05-90	2.000	0.903
	3rd	40-03-90	2.396	0.892
	1st	40-03-80	3.080	0.798
São Carlos	2nd	80-03-90	3.160	0.802
	3rd	40-03-90	3.240	0.789
	1st	40-03-90	1.240	0.952
Valparaíso	2nd	40-05-90	1.480	0.941
	3rd	40-07-90	1.640	0.933

column "Criteria" in Table 3, the first number refers to SWHC, the second to precipitation limit for the day considered to be workable, and the third to ratio limit SM/SWHC.

According to Table 3, in most of the sites scrutinized a SWHC corresponding to 40 mm prevailed and even when a SWHC of 80 mm was shown as the most appropriate, the second best criterion was the one of 40 mm associated with MAE and C values quite similar as noticed in Araraquara, Piracicaba and Potirendaba, SP, Brazil, where MAE of the first and second best criteria were equal, with a tiebreaker for decision-making being based on the C. These results evidence that for workable days' studies we should employ a lower SWHC, as the soil layer under the influence of machinery will usually be confined to a 30-cm depth as reported by [10] [21]. This was observed when a SWHC of 120 mm only took place in Orindiúva as the second-best criterion, which clearly demonstrates that for studies dealing with the number of workable days, the lowest SWHC values must be considered as they represent the superficial layer of the soil.

With regards to MAE values, Table 3 evidences that the majority of this statistical parameter fluctuated from 0.9 to 3.6 days per month. Only in Orindiúva the MAE remained above 5 days. The likely causes of such a result are as follows: errors in the notes related to stoppages owing to rainfall; inconsistencies in meteorological dataset; or soil type not fitting in the scrutinized SWHC ranges.

When a SWHC corresponding to 80 mm prevailed as the best criterion to be selected, which comprised Araraquara, Piracicaba and Potirendaba (Table 3), discrepancies of MAE between the best and second best with a SWHC equivalent to 40 mm were rather small—a fact that indicated that both criteria performed quite well when it came to estimating NWD. The outcomes revealing a predominance of a SWHC of 80 mm indicated that a SWHC of 100 mm recommended by [11] was suitable for determining NWD either for operations involving only traffic of machinery, such as harvest, or soil tillage practices under which SWHC must be higher than what it is reported in the literature. This situation is mainly applied to locations where soil texture varies from intermediate to loam clay as in the particular case of Piracicaba.

Table 4 just presents the best model for each site under scrutiny. A huge variation in criteria combinations can be noticed; however, there is a conspicuous predominance ascribed to SWHC and precipitation thresholds. Based on results illustrated in Table 4, it is possible to verify that a SWHC of 40 mm shows up as the pivotal value for determining NWD in 87% of the sites, whereas for PREP a 3 mm value was found to be the most frequent (74%). For the criterion related to SM/SWHC, such predominance is not as evident as it is for the other criteria. The most frequent occurrence for SM/SWHC was attributed to a threshold of 90%, having been considered as the most suitable one in 48% of the sites followed by a threshold of 80% occurring in 30% of the sites.

In order to assure a better understanding of the impact of each one of the criteria proposed in the current study for determining NWD, MAE related to each

Table 4. Best criteria combination for determining the number of workable days for the mechanized harvest of sugarcane at different sites in the State of São Paulo, Brazil.

ID	Site	Criteria
1	Andradina	40-03-80
2	Araçatuba	40-03-70
3	Araraquara	80-03-90
4	Assis	40-03-70
5	Capivari	40-03-80
6	Cardoso	40-07-90
7	Clementina	40-05-90
8	Dois Córregos	40-03-80
9	Fernandópolis	40-05-90
10	Guariba	40-03-80
11	Ipaussu	40-03-70
12	Ituverava	40-03-70
13	Jaú	40-03-80
14	Mirandópolis	40-03-70
15	Orindiúva	40-07-90
16	Paraguaçu Paulista	40-03-80
17	Penápolis	40-05-90
18	Piracicaba	80-03-90
19	Potirendaba	80-03-90
20	Pradópolis	40-03-90
21	Queiróz	40-07-90
22	São Carlos	40-03-80
23	Valparaíso	40-03-90

of them was evaluated for each selected site. Those criteria that resulted in the lowest MAE values were a SWHC of 40 mm, PREC of 3 mm and SM/SWHC of 90%, corroborating the outcomes presented in Table 5. Thus, we suggest for broader investigations encompassing macro-regions or states that the number of workable days be determined by the combination of criteria given by an SWHC = 40 mm, PREC ≤ 3 mm and SM/SWHC ≤ 90%, *i.e.*, the 40-03-90 combination. Such a result turns out to be similar to that obtained by [21] who in turn made use of a threshold of PREC of 5 mm and SM/SWHC of 90%. Similar thresholds for PREC and SM/SWHC were also adopted by [11] to define the interruption of soil preparation operations with agricultural machinery. In this case, the afore-mentioned authors assumed that under PREC > 5 mm and SM/SWHC > 90%

Table 5. Occurrence frequency of the best criteria related to available water capacity (SWHC), rainfall (PREC) and relative soil moisture (SM/SWHC) for determining the number of workable days for the mechanized harvest of sugarcane in the State of São Paulo, Brazil.

Criteria		Number of occurrences	Relative Frequency (%)
SWHC	40 mm	20	87
	80 mm	3	13
	120 mm	0	0
PREC	3 mm	17	74
	5 mm	3	13
	7 mm	3	13
SM/SWHC	70%	5	22
	80%	7	30
	90%	11	48

non-favorable conditions for soil management were established as also assumed by [21], since risks associated with compaction of soil layers right underneath tillage depth were eminent. Nevertheless, the threshold of 90% for SM/SWHC is higher than the one adopted by [12] in rainfed areas of Sudan, which was 80%, the second most frequent threshold in our study.

Spatial distribution of site-specific criteria for the mechanized harvest of sugarcane at each producing site in the State of São Paulo obtained from interpolation proposed by the Voronoi approach can be seen in Figure 2.

According to the map shown in Figure 2, no particular predominance of a given criteria combination in the state was detected, however, it was possible to delimitate coverage areas for each one of the combinations. The observed variation is a result of differences in soil characteristics such as soil texture and structure, as well as soil hydric physical attributes, relief/topography, and weather conditions. As to the weather influences at hotter areas, there is a proclivity for the soil to start to dry off earlier, favoring, therefore, anticipation of the resumption of activities related to machinery traffic [5] [27].

It is important to emphasize that many areas belonging to the state lack scientific information leading to the application of the interpolation method proposed by Voronoi to define criteria by area without access to observed actual data. A quintessential example of this particular case encompasses Andradina passing through Portal do Paranapanema and reaching the region of Paraguaçu Paulista. On the other side, in Southern São Paulo, two analyzed sites (Assis and Ipaussu) culminated in the same criterion for determining NWD, a fact that drew us to the conclusion that there might be a clear continuity of these criteria. At other sites in the State of São Paulo it is also possible to identify neighboring municipalities under the same criterion, as observed in Cardoso and Orindiúva,
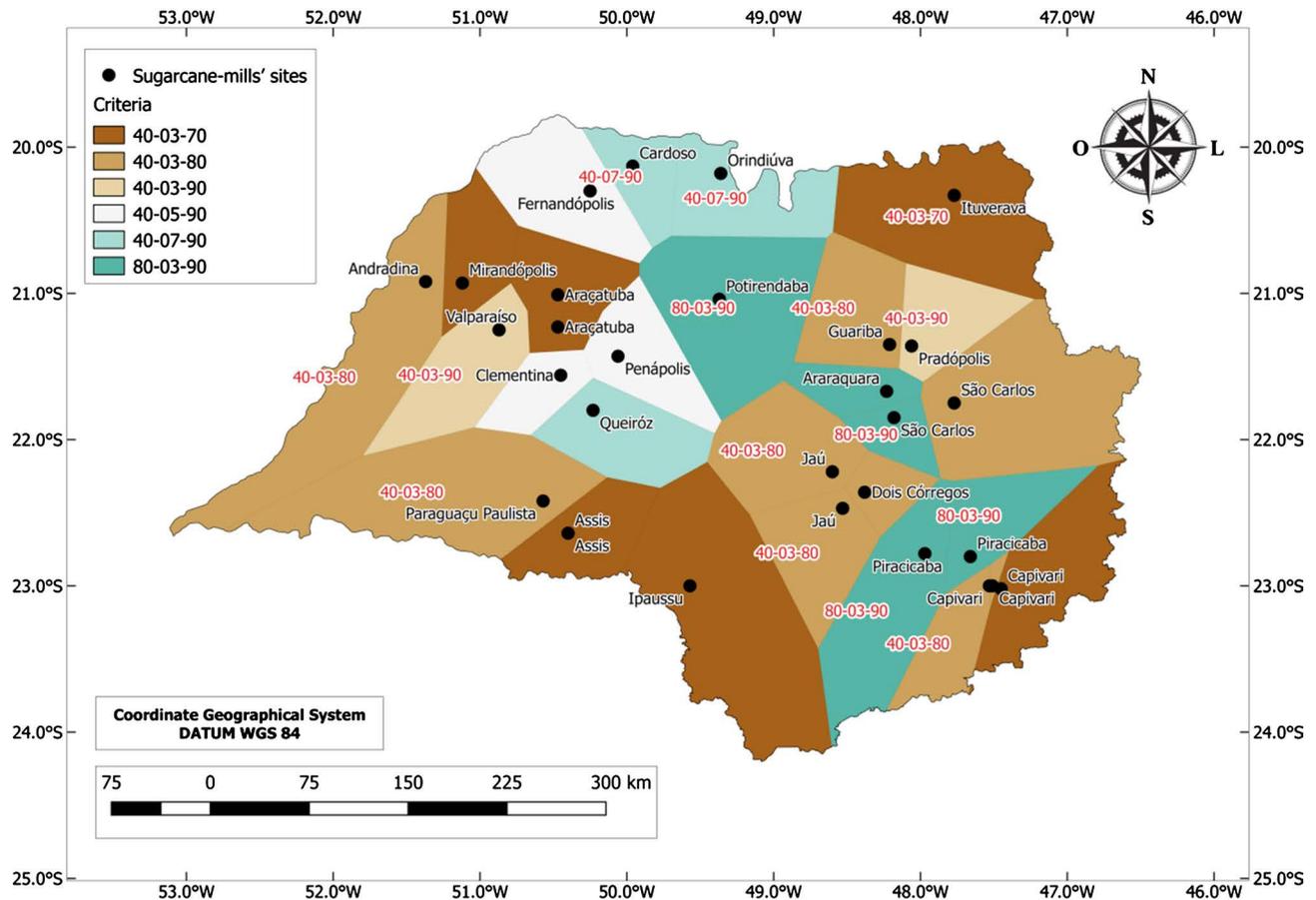
Figure 2. Spatialization of the criteria for determining the number of workable days for the mechanized harvest of sugarcane in the State of São Paulo, Brazil, taking into consideration the site-specific SWHC-PREC-SM/SWHC combination.

Araraquara and São Carlos, Jáu and Dois Córregos, as well as in Araçatuba and Mirandópolis. Conversely, in Capivari a significant difference among the SM/SWHC criterion for two producing areas located within the same municipality was detected (Figure 2).

On the basis of what was previously presented, it is conspicuous that the determination of NWD for the mechanized harvest of sugarcane in the State of São Paulo might be established by means of two distinct procedures: one based on specific criteria for determining NWD for each site (Figure 2), and another one that takes into account a general approach (coming from a mean information depicting the whole state, *i.e.*, considering the SWHC of 40 mm, PREC of 3 mm and SM/SWHC of 90% combination (40-03-90)).

A model for field operations of machinery that requires a simulation technique for discrete events in order to evaluate the performance of machines on the basis of daily status of soil workability throughout a series of years was developed by [28]. The results of this model were compared with those obtained from a simpler method based on mean values of the probability of workable days available for agricultural operations at different growing seasons and the authors reached the conclusion that such a simpler method, due to its simplicity, gener-

ated unsatisfactory outcomes as opposed to the procedure of a daily determination of workability conditions. In the current study, the proposed procedure might be considered to be of an intermediate complexity compared to the two different approaches studied by [28].

3.2. Validation of the Criteria Employed for Determining the Number of Workable Days for the Mechanized Harvest of Sugarcane

One way to assure utilization feasibility of the proposed criteria (specific and general) is by means of their validation by comparing NWD estimates with data observed in the cane-mills. Table 6 presents statistical analyses concerning the validation of both proposed criteria, from which calculated and observed (independent data) NWD values for 15 sites located in the State of São Paulo in 2015-2016 growing season were used. The magnitude of the errors inherent in both procedures is quite similar; as is also the performance of the models in terms of precision and accuracy. Despite this, as it was expected *a priori*, the specific criteria generated MAE slightly lower (3.8 days) than that obtained from general criteria (4.4 days). In general, both specific and general criteria were able to explain between 78 and 79% of the NWD variation among different sites in the state, which evidences a satisfactory performance of such criteria. This might also be confirmed by the values of d and C indices, with the latter classified as "Good" for the two procedures in accordance with the classification proposed by [22].

By analyzing Table 6, it is possible to observe that the determination of NWD obtained by specific criteria for each single site tends to underestimate NWD

Table 6. Mean error (ME), mean absolute error (MAE), agreement index (d), coefficient of determination (R^2), coefficient of correlation (r), performance index (C), and root mean square root (RMSE) of the estimates of the number of workable days for mechanized harvest of sugarcane in the State of São Paulo (NWD), considering site-specific and general criteria (40-03-90) during the validation period from a set of independent data.

Variables, errors and indices	Site-specific criteria	General criteria (40-03-90)
NWD Obs. (±SD) (days month^{-1})	19.3 (±8.6)	19.3 (±8.6)
NWD Est. (±SD) (days month^{-1})	19.0 (±7.8)	21.4 (±6.5)
n (locations × seasons)	133	133
ME (days month^{-1})	−0.4	2.0
MAE (days month^{-1})	3.8	4.4
d	0.88	0.84
R^2	0.63	0.61
r	0.79	0.78
C	0.70	0.66
RMSE (days month^{-1})	5.3	5.7

SD = Standard Deviation; Obs. = Observed; Est. = Estimated.

(ME = −0.4 days month^{-1}), whereas general criteria (40-03-90) lead to an overestimation of NWD (ME = 2.0 days month^{-1}). With regards to MAE, NWD determined either from site-specific or general criteria resulted in errors far closer to each other, respectively, corresponding to 3.8 and 4.4 days/month. The other statistical parameters/indices were also similar, a fact that permits the consideration that the use of either site-specific or general criteria was conducive to a good estimation of NWD at different sites located in the State of São Paulo, as well as in other sites in the world with similar climatic conditions.

Table 7 shows the mean number of workable days determined by specific and

Table 7. Mean number of workable days per year for the mechanized harvest of sugarcane in the State of São Paulo determined by site-specific (SE) and general (GE) criteria.

ID	Site	NWD SE (days year^{-1})	NWD GE (days year^{-1})	ID	Site	NWD SE (days year^{-1})	NWD GE (days year^{-1})
1	Araraquara	264	277	26	Colômbia	295	282
2	Jaú	250	274	27	S.J. Boa Vista	235	262
3	Araçatuba	249	289	28	Luis Antonio	279	279
4	Guariba	257	278	29	Dracena	260	281
5	Capivari	258	279	30	Jaguariúna	217	270
6	Clementina	291	284	31	Americana	225	274
7	Piracicaba	265	278	32	Itirapina	247	270
8	Dois Córregos	248	273	33	Campinas	221	272
9	Andradina	268	288	34	Botucatu	245	270
10	Cardoso	297	284	35	Agudos	253	277
11	Ipaussu	217	270	36	Marília	286	273
12	Ituverava	227	270	37	Pirajuí	296	286
13	Assis	233	279	38	Pres. Prudente	265	286
14	Mirandópolis	249	288	39	Teod. Sampaio	261	284
15	Fernandópolis	289	282	40	Itapetininga	257	278
16	Paraguaçu Pta	259	282	41	Taquarituba	213	269
17	Penápolis	294	287	42	Borborema	270	290
18	Pradópolis	273	273	43	V.Alegre do Alto	258	278
19	Queiróz	294	281	44	Orlândia	227	269
20	São Carlos	249	272	45	Altinópolis	266	266
21	Valparaíso	284	284	46	Avaré	203	262
22	Potirendaba	266	278	47	Auriflama	244	285
23	Orindiúva	298	284	48	Tanabi	292	279
24	Franca	214	260	49	Pres. Venceslau	265	286
25	Barretos	271	284	50	Itapeva	214	271

general criteria for the evaluated sites. The determination of NWD on the basis of general criteria for the majority of the sites tends to overestimate NWD when compared to estimated values obtained by site-specific approaches. By comparing both criteria for each particular site in absolute terms, that is, by bearing in mind NWD determined by both adopted criteria without therefore taking into consideration whether there is an overestimation or underestimation, a mean difference of 25 workable days might be observed. Also shown in Table 8, specific criteria culminated in a higher variation of NWD among different regions/sites (ranging from 203 to 298 days month^{-1}), whereas such a variation was lower whenever NWD was estimated by general criteria/approach (varying from 260 to 290 days month^{-1}).

For 50 scrutinized sites (Table 7), 10 of them (Clementina, Cardoso, Fernandópolis, Penápolis, Queiróz, Orindiúva, Colômbia, Marília, Pirajuí and Tanabi) had the lowest NWD as determined by the general criteria. Except for Marília, there is a clustering of such sites in the same region, as observed in Clementina,

Table 8. Mean number of workable days (NWD) per year for the mechanized harvest of sugarcane, taking into account site-specific (SE) and general (GE) criteria for its determination in different sites in the State of São Paulo to assure validation of the maps. NWDCalc refers to NWD calculated on the basis of meteorological inputs along with observed soil water storage, and NWDEst corresponds to NWD extracted (estimated) from the maps.

ID	Site	SE	GE	NWDCalc SE	NWDEst SE	NWDCal GE	NWTEst GE
				(days year^{-1})			
1	Jales	40-05-90		293	303	285	286
2	Pirapozinho	40-03-80		259	273	281	281
3	Garça	40-07-90		284	284	271	277
4	Salto	40-03-70		229	253	278	274
5	Araras	80-03-90		256	264	271	272
6	Matão	80-03-90		273	286	285	277
7	Batatais	40-03-70		221	273	265	269
8	Olímpia	40-07-90	40-03-90	296	296	283	279
9	Adamantina	40-03-90		286	293	286	286
10	Pederneiras	40-03-80		254	287	277	281
11	Itabera	40-03-70		186	202	255	259
12	Vargem Grande do Sul	40-03-80		244	254	270	268
13	Ourinhos	40-03-70		221	278	272	282
14	São José do Rio Preto	80-03-90		264	299	278	282
15	Getulina	40-07-90		298	298	285	284
16	Santa Albertina	40-07-90		301	298	288	287
	Average			260	278	277	277

Penápolis, Queiróz and Pirajuí in the Midwest plus Cardoso, Fernandópolis, Orindiúva, Colômbia and Tanabi in the North of the state. This indicates that in these two macro-regions the general criteria for determining NWD might be employed in planning surveys related to the mechanized harvest of sugarcane in order to increase security of agricultural operations, since the lowest NWD will cause the sizing to be done with a large amount of machinery for harvest. In Pradópolis, Luis Antonio, Altinópolis and Valparaíso sites, both criteria generated the same mean number of workable days (Table 7). Thus, at such sites located in the Northeast of the state, both criteria might be employed to scale the fleets of harvesters in sugarcane production fields.

Such variations according to the location and criterion used are expected. Using two models to examine the number of workable days suitable for harvest from long-term climatic records and soil characteristics at three distinct sites in the USA, [29] observed that in Illinois central region 113 workable days were obtained by the ASAE model, whereas 111 workable days were estimated by the simulation model proposed by these authors. In addition, for the State of Iowa such values were of 133 days by means of the ASAE approach and 127 days on the basis of the proposed method, whist for Southern Michigan NWD reached values of 72 and 84, respectively [29].

3.3. Spatialization of the Number of Workable Days for the Mechanized Harvest of Sugarcane in the State of São Paulo

Equation (2) displays the multiple linear regression analysis between mean annual NWD for the mechanized harvest of sugarcane in the State of São Paulo determined by the site-specific criteria and independent variables, such as latitude, longitude and altitude for the 50 evaluated sites:

$$
\begin{aligned}
\text{NWD} = &-23959.172 - 536.561 \times \text{lat} - 715.533 \times \text{long} + 2.773 \times \text{alt} \\
&- 5.8338 \times \text{lat} \times \text{long} + 0.0490 \times \text{lat} \times \text{alt} + 0.0309 \times \text{long} \times \text{alt} \qquad (2) \\
&- 5.346 \times \text{lat}^2 - 5.749 \times \text{long}^2 - 0.000185 \times \text{alt}^2 \quad r = 0.70
\end{aligned}
$$

This linear estimation model for determining mean annual NWD had a standard error of 20.5 days year^{-1}, which can be interpreted as small in view of the magnitude of the total mean NWD throughout the year (257 days). Although such an error turns out to be equivalent to almost a month of workable days, it is distributed throughout the year in such a way as to allow the monthly error to remain lower and in general concentrated into the summer when more abundant rain prevails and, therefore, promotes a great variation in NWD.

By analogy, Equation (3) puts forward the results provided by a multiple regression analysis between NWD for the mechanized harvest of sugarcane determined by the general criteria for the State of São Paulo and independent variables:

$$
\begin{aligned}
\text{NWD} = &-5232.06 - 118.998 \times \text{lat} - 161.704 \times \text{long} + 0.779 \times \text{alt} \\
&- 1.663 \times \text{lat} \times \text{long} + 0.0118 \times \text{lat} \times \text{alt} + 0.0105 \times \text{long} \times \text{alt} \qquad (3) \\
&- 0.722 \times \text{lat}^2 - 1.199 \times \text{long}^2 - 0.0000345 \times \text{alt}^2 \quad r = 0.89
\end{aligned}
$$

For the aforementioned NWD linear model the standard error was of 3.8 days, which is considered to be low given the magnitude of the total mean NWD throughout the year (278 days), depicting less than 2% and evidencing therefore a better performance ascribed to the use of general criteria in comparison to site-specific criteria when NWD is to be associated with variations in geographical locations. This might be explained by the fact that general criteria for determining NWD basically vary as a function of climatic inputs, which demonstrates that there is a strong correlation between environmental variables and geographical space (r = 0.89). Further, for the NWD determined by the site-specific approach, besides climate fluctuations, SWHC also varies affecting the ratio SM/SWHC, which cannot be explained by the geographical coordinates.

Figure 3 and Figure 4 illustrate the maps of NWD for the mechanized harvest of sugarcane in the State of São Paulo, taking into consideration both site-specific and general criteria, respectively. These maps display a great spatial variation of NWD, both indicating an increase of such a variable from South to North and also from East to West of the state. This shows that integration of the results with geographical information systems is useful to create geo-referenced maps for ease of interpretation, as observed by [30] in a study dealing with the
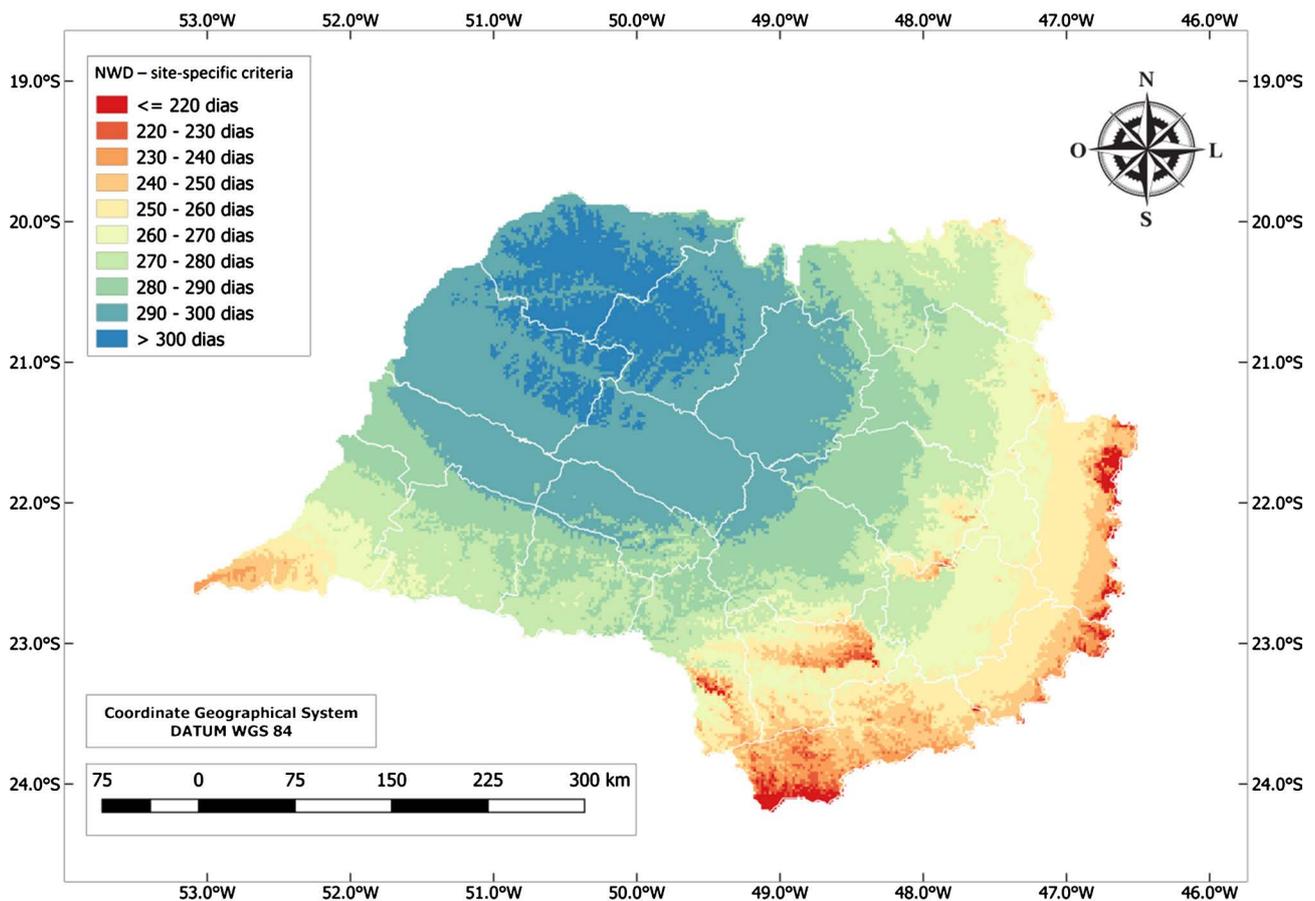
Figure 3. Mean number of workable days (NWD) for the mechanized harvest of sugarcane in the State of São Paulo determined on the basis of site-specific criteria and spatialized by the linear model as a function of geographical coordinates (Equation (2)).
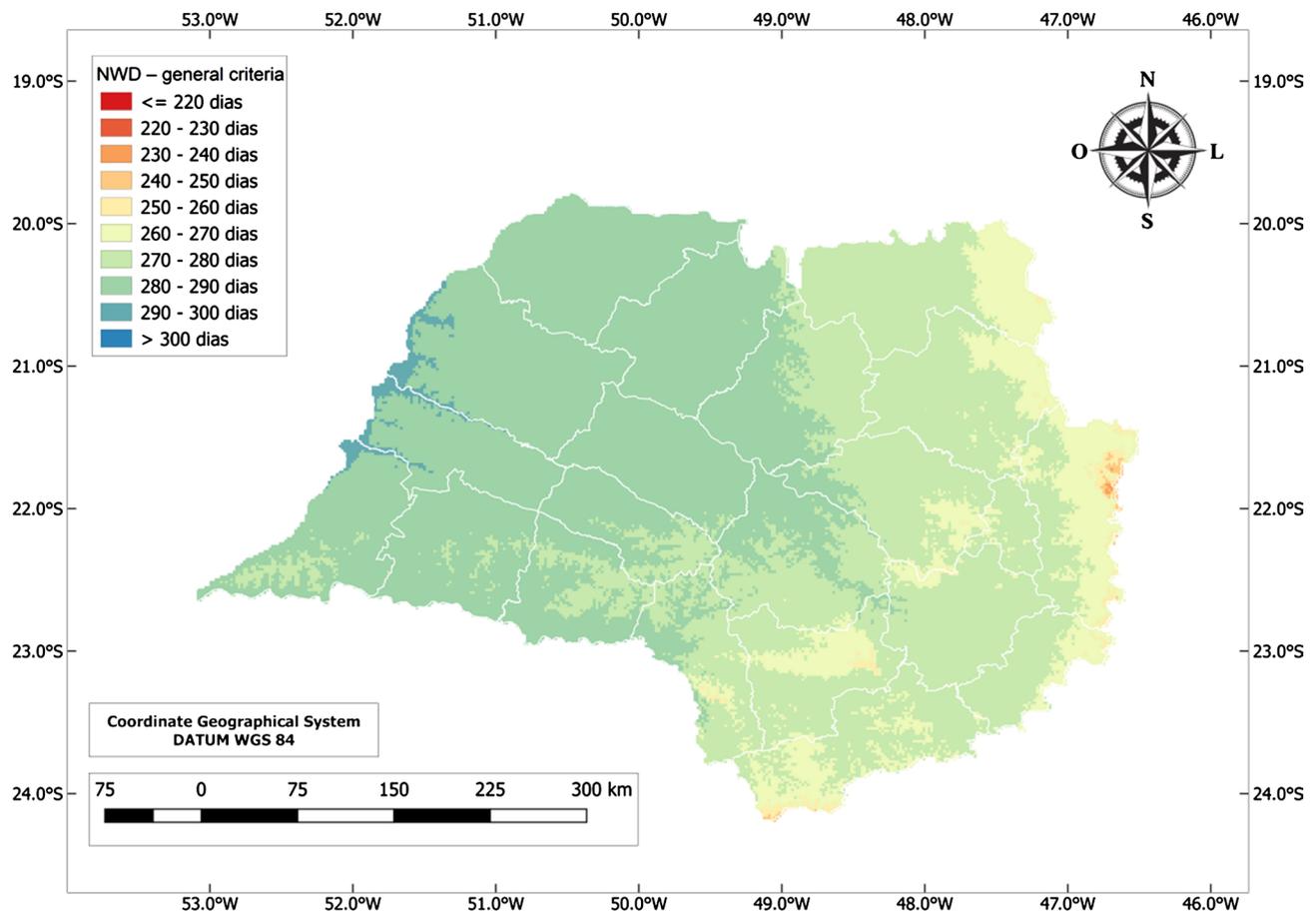
Figure 4. Mean number of workable days (NWD) for the mechanized harvest of sugarcane in the State of São Paulo determined on the basis of general criteria (40-03-90) and spatialized by the linear model as a function of geographical coordinates (Equation (3)).

effects of soil attributes and rainfall data on workability time of agricultural machinery. According to [7], maps of soil trafficability provide baseline data for further researches and risk assessment.

By comparing the maps of Figure 3 and Figure 4, expressive discrepancies might be noticed, for instance, in Southern São Paulo State in conjunction with Pontal do Paranapanema, which evidenced roughly 40 to 45 days less NWD for the map based on the site-specific criteria. In general, NWD obtained by the site-specific criteria tends to trigger a more pronounced variation in the outcomes, with NWD ranging from 220 to over 300 days (Figure 3). Conversely, the NWD map based on general criteria presents a variation of 255 to 295 days (Figure 4).

Examining the number of workable days for agricultural operations with machinery in planted forests as a function of meteorological variables, [10] obtained 170 days potentially useful in Guanhães, Minas Gerais State, Brazil. This reduced number of workable days is ascribed to the fact that agricultural operations with machinery were associated with soil tillage and not only with traffic, as considered in the current study. Similarly, [9] came up with 155 workable

days in sandy loam soils when working on the development of a simulation model to predict the number of workable days for harvest operations in Northern Central Nigeria. Under clay soil conditions, the aforementioned authors reported 115 days, which emphasizes the importance of taking into consideration soil specific characteristics at each given site for determining NWD along with information on SWHC of the soils under scrutiny.

To define which maps best depict NWD spatial variation for harvest of sugarcane a validation of such maps was performed taking into consideration an independent dataset. Mean values of NWD corresponding to the pixels at which 16 sites demonstrated in Table 3 are located, were extracted from the maps illustrated in Figure 3 and Figure 4. These data, defined as "NWD estimated", were compared to "NWD calculated" by both criteria (site-specific and general), making use of meteorological data along with sequential water balance corresponding to each studied site. Table 8 shows both NWD calculated and estimated values for the 16 sites employed on the validation of the maps of Figure 3 and Figure 4.

Table 9 presents a statistical analysis of the maps of NWD validation, when generated from both site-specific and general criteria. The outcomes obtained from the map generated from the general criteria resulted in lower errors (MAE = 3.4 days year^{-1}; RMSE = 4.4 days year^{-1}) as opposed to the map produced using site-specific criteria (MAE = 17.8 days year^{-1}; RMSE = 24.9 days year^{-1}). Moreover, ME of the map generated from site-specific criteria turned out to be of the same magnitude of MAE, which reveals systematic errors leading to a lower precision of the estimates with d = 0.81. On the other hand, for the map generated with general criteria, d index was 0.92. Finally, by assessing the values

Table 9. Mean error (ME), mean absolute error (MAE), agreement index (d), coefficient of determination (R^2), coefficient of correlation (r), performance index (d), and root mean square error (RMSE) of the estimates of the number of workable days (NWD) for mechanized harvest of sugarcane in the State of São Paulo, considering values extracted from the maps (NWDEst) in comparison to those calculated (NWDCalc) for both site-specific and general criteria (40-03-90).

Variables, errors and indices	Specific criteria	General criteria
NWDCalc average (±SD) (days year^{-1})	260 (±33.4)	277 (±9.1)
NWDEst average (±SD) (days year^{-1})	278 (±25.6)	278 (±7.8)
n (locations)	16	16
ME (days year^{-1})	−17.2	−0.9
MAE (days year^{-1})	17.8	3.4
d	0.81	0.92
R^2	0.70	0.76
r	0.84	0.87
C	0.68	0.80
RMSE (days year^{-1})	24.9	4.4

of C we found that the performance of NWD estimates obtained by means of the map based on the general criteria was considered to be very good (C = 0.80), according to the classification proposed by [22].

The best performance of the NWD linear model determined by general criteria might be possibly attributed to an alternation of criteria for determining NWD by means of site-specific criteria—a fact that does not always represent reality, since the macro-regions delimited by spatialization given by the Voronoi method are very large, involving different types of soil, which in turn affect SWHC and SM/SWHC thresholds to define NWD [1]. On the other hand, the NWD linear model based on the general criteria better represents the average NWD for the State of São Paulo, generating errors of a lower magnitude.

4. Conclusions

The results of the present study allowed concluding that:

1) To determine NWD, lower values of SWHC are to be considered by a recommendation of 40 mm;

2) It is possible to determine NWD by making use of site-specific and general criteria for the entire State of São Paulo;

3) Site-specific criteria for determining NWD, as expected, varied from site to site, noting however a prevailing condition of SWHC = 40 mm. For general criteria the best combination was the one that employed a SWHC of 40 mm along with thresholds for PREC and SM/SWHC of 3 mm and 90%, respectively;

4) NWD estimation based on agrometeorological and soil criteria was shown to be a useful tool with an intermediate complexity in such a way as to generate reliable results supported by performance index C;

5) The maps generated from a multiple linear regression analysis are a suitable tool for understanding spatial variability of NWD for the mechanized harvest of sugarcane in the State of São Paulo, particularly when general criteria were employed (SWHC = 40 mm, PREC ≤ 3 mm and SM/SWHC ≤ 90%);

6) Mean NWD varied in the State of São Paulo, increasing from South to North and from East to West, with values ranging from 203 to 298 by means of the map based on regional site-specific criteria, and from 260 to 290 in compliance with the map generated from general criteria, which was shown to be better during the validation process.

Acknowledgements

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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