AN ALTERNATIVE APPROACH TO THE ACTUAL BRAZILIAN MAIZE CROP ZONING

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ABSTRACT - Maize cropping under rainfed conditions are highly affected by the annual and intra-seasonal climate variability, especially dry spells, that affect yield. One of the simplest strategies with low cost to mitigate this problem is the determination of a sowing window. The study aimed to: a) use the maize yield simulated with a process-based model to establish sowing windows and, b) compare our results with the current Agricultural Crop Zoning of Climate Risk (ZRC) methodology employed by the Brazilian Ministry of Agriculture, Livestock and Supply (MAPA). The CSM-CERES-Maize model was used to simulate scenarios of weekly sowing dates, under rainfed conditions, for selected counties of Minas Gerais State, Brazil. For each sowing date it was determined the yield break by comparing the average yield of the current sowing date with the highest average yield obtained from all sowing dates. The use of a process-based model to simulate crop yield allows for the integration of several factors not considered in the ZRC-MAPA approach. The proposed methodology has advantages over the ZRC-MAPA approach in that it includes the possibility of determining the expected average yield and its amplitude.

Key words: *Zea mays* L., climate risk; sowing window; modeling; DSSAT.

UMA METODOLOGIA ALTERNATIVA PARA O ZONEAMENTO DE RISCO CLIMÁTICO DA CULTURA DO MILHO

RESUMO - O cultivo de milho em regime de sequeiro é afetado pelas variabilidades climáticas anual e interanual, especialmente os veranicos, que reduzem a produtividade. Uma das estratégias mais simples e de baixo custo para mitigar esse problema é a determinação de uma janela de semeadura. O estudo objetivou: a) usar a produtividade de milho simulada com um modelo baseado em processos para estabelecer períodos de semeadura; e b) comparar os resultados obtidos com a atual metodologia do Zoneamento Agrícola de Risco Climático (ZRC) empregada pelo Ministério da Agricultura, Pecuária e Abastecimento (Mapa). Utilizou-se o modelo CSM-Ceres-Maize para simular cenários de épocas de semeadura semanais, sob condições de sequeiro, para municípios selecionados do estado de Minas Gerais. Para cada época de semeadura, determinou-se a quebra de rendimento, comparando o rendimento médio da época de semeadura atual com o maior rendimento médio obtido a partir de todas as datas de semeadura. O uso de um modelo baseado em processos para simular o rendimento das culturas permite a integração de muitos fatores não considerados na atual metodologia do ZRC-Mapa. A abordagem proposta tem vantagens sobre a metodologia do ZRC-Mapa, entre as quais a possibilidade de determinar o rendimento médio esperado e a sua amplitude.

Palavras-chave: *Zea mays* L., risco climático; janela de semeadura; modelagem; DSSAT.

Grown in almost every continent, maize economic importance is characterized by the various forms of its use, from grazing to biofuels. Worldwide, Brazil is the third largest maize grower, with the state of Minas Gerais ranking third in production within the country (Agrianual, 2013). The average maize yield in Brazil is low with high variation within a region. In Minas Gerais, the average maize yield ranges from 6299 kg ha^{-1} in the Triângulo Mineiro region to 1898 kg ha^{-1} in the north region (IBGE, 2010). Possible causes of this low yield are related to the low level of technology employed by farmers, including sowing at inadequate time, water stress due to dry spells, and the use of cultivars with low adaptation to the region (Cruz et al., 2009; Forsthofer, 2004).

Minas Gerais agriculture is mainly rainfed. The rainfall in the state, ranging from 650 mm in the north region to 2100 mm in the south/southwest regions, is related to topography and geography (Santana, 2004; Guimarães et al., 2010). It is expected, therefore, that the main factor affecting maize yield in the state is water. Among all climatic factors, rainfall, temperature and solar radiation, are the most important as they directly affect the production of dry matter and grain (Sans & Guimarães, 2006; Brachtvogel et al., 2009). Water availability and temperature are the most important factors to be considered to characterize the best growing seasons within a region (Wagner et al., 2013).

One strategy to minimize the risk of yield losses due to climatic conditions is sowing at the right time. The success of such approach is tightly related to the planning capability of the farmer as it is highly dependent on several factors associated to weather conditions (Sans & Guimarães,

2006). The Brazilian Ministry of Agriculture, Livestock and Supply (MAPA) provides farmers with an Agricultural Crop Zoning of Climate Risk (ZRC) tool, which is also used by policy makers and risk management agencies. The ZRC-MAPA is prepared annually with the objective of minimizing the risks associated to weather and to allow producers to identify the best sowing window for various crops with varied cropping season and growing on different soil types (Brasil, 2013).

The ZRC-MAPA approach is based only on a soil-water balance approach. Process-based simulation models that simulate growth, development, and yield of crops based on weather, soil, cultivar-specific coefficients, and management practices, are better tools to assist in the determination of sowing windows. These dynamic crop models describe daily changes in the inputs used to simulate the main crop physiological processes (Dallacort et al., 2006). Dynamic crop simulation models are useful tools when the effects on crops depend on complex interactions with soil, weather and with other factors related to the management of agro-ecosystems (Jones et al., 2006). The CERES (Crop Environment Resource Synthesis) consists of group of models developed by the Grassland Soil and Water Research Laboratory (Jones & Kiniry, 1986). Among the CERES models, CERES-Maize was developed for the maize crop and allows simulations of the growth and development of maize, water balance, N levels and also enables economic evaluations based on four input variables: soil, climate, crop management and genotypes (Soler, 2000). The cropping season of maize in the CERES-Maize is divided into various phases (germination, emergence, end of juvenile phase, floral induction, silking, beginning of

grain filling, and harvest maturity), while development is influenced by the thermal sum or thermal time, expressed in degree-days (DD), which is calculated based on the minimum and maximum daily temperatures. The thermal time required to progress from one stage of development to another is a user input and can be defined as: P1 - Thermal time from seedling emergence to the end of the juvenile phase (expressed in DD above a base temperature of 8 °C), during which the plant is not responsive to changes in photoperiod; P2 - Extent to which development (expressed in days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 hours); P5 - Thermal time from silking to physiological maturity (expressed in DD above a base temperature of 8 °C); G2 - Maximum possible number of kernels per plant; G3 - Kernel filling rate during the linear grain filling stage and under optimum conditions (mg day^{-1}); PHINT - Phylochron interval, the interval in DD between successive leaf tip appearances (Ritchie et al., 1998; Jones et al., 2003). The CSM-CERES-Maize is part of the Decision Support System for Agrotechnology Transfer, DSSAT (Jones et al., 2003; Hoogenboom et al., 2013), a software that includes models for 28 different crops. The cropping system simulation model (CSM) included in DSSAT v4.5 simulates growth and development of maize at a daily time step, from planting to maturity. Several studies have demonstrated the applicability of DSSAT as a tool to help making management decisions. For example, a study conducted by Singh & Srinivas (2007) in India aimed at determining best planting dates for irrigated and rainfed maize in a succession system with chickpeas. Soler et al. (2007)

assessed the effect of different sowing dates for maize cultivars of different cycles growing on irrigated and rainfed fields for conditions in Manduri and Piracicaba counties, state of São Paulo, Brazil.

The objectives of this study were to use a simulation approach to determine best sowing windows for maize production and to compare those results with the current methodology employed by the ZRC-MAPA.

Material and Methods

The CSM-CERES-Maize model of DSSAT, version 4.5.1.013 (Hoogenboom et al., 2013) was used to simulate maize yield under rainfed conditions. The simulations were set weekly, from August 01 to July 24 for conditions in 49 of 853 counties of the State of Minas Gerais, Brazil (Figure 1). The counties were selected based on the availability of climate series data. Daily data were obtained from the National Institute of Meteorology (INMET) database for the period 1961 to 2010, totaling 49 years. Weatherman, a DSSAT tool to facilitate the manipulation of weather data, was used to analyze the consistency of the data, to fill up short periods (< 7 days) of gaps on air temperature and rainfall in the series and to estimate solar radiation from sunlight records.

The genetic coefficients of the single-cross hybrid BRS1030 were previously determined from observed data obtained from maize field trials conducted under optimum conditions of growth and development (Santana et al., 2010). The adjusted coefficients were 263.8 for P1; 0.5 for P2; 1034 for P5; 648 for G2; 5.14 for G3; 44.22 for PHINT. Because of the lack of specific soil information in the areas of interest (selected counties), the same

approach used by the current ZRC-MAPA was used (Sans et al., 2001). The ZRC-MAPA criteria consists of a maize crop with a root system 0.50 m deep and three generic soil types with low (20 mm), medium (40 mm) and high (60 mm) water retention capacity. The values of the lower and upper limits of available water of each layer of existing DSSAT´s soil profiles data were adjusted to become similar, in terms of water retention, to the three soil types used in the ZRC-MAPA (Table 1).

The management conditions used in the simulations was obtained from the Embrapa Maize and Sorghum online recommendations for maize production (Cruz, 2009). The model was set for 0.90 m row spacing and a plant population of 68,000 plants ha^{-1}. Fertilization consisted of 500 kg ha^{-1} of 8-28-16 + Zn applied at sowing and 200 kg ha^{-1} of nitrogen as urea + 70 kg ha^{-1} of K$_2$O in, as potassium chloride, side-dressed at 40 days after sowing (DAS).
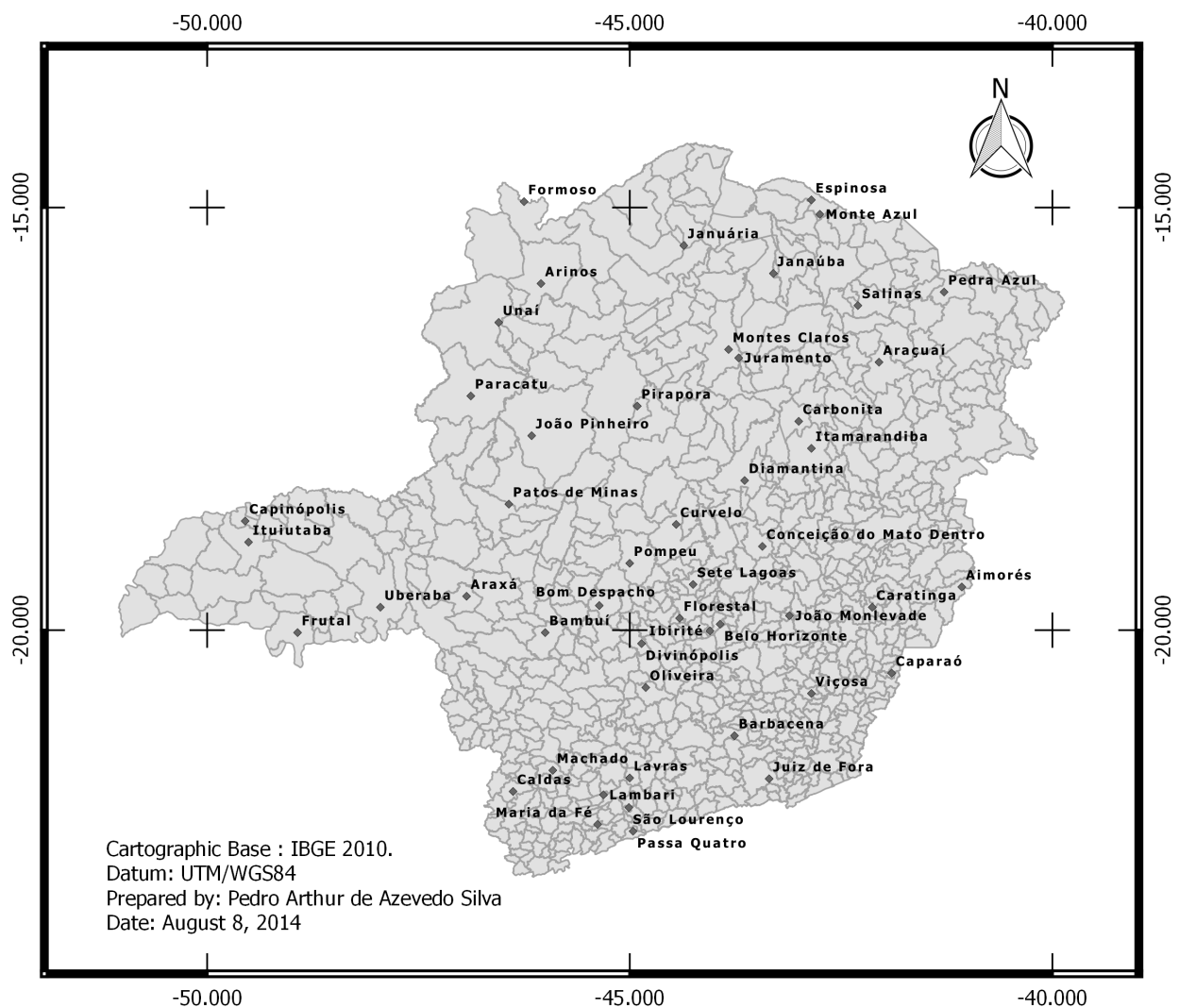

FIGURE 1. Location of weather stations of the state of Minas Gerais, Brazil, used in the study.

TABLE 1. Attributes of the three generic soil profiles.

Layer base depth (m)	Lower limit ($m^3\,m^{-3}$)	Upper limit ($m^3\,m^{-3}$)	Saturation ($m^3\,m^{-3}$)	Root growth factor	Saturated hydraulic conductivity ($m\,h^{-1}$)	Bulk density ($kg\,m^{-3}$)	Organic carbon (%)	Clay (%)	Silt (%)	pH in Water
					Soil type one					
0.05	0.050	0.075	0.438	1.0	0.682	1460	0.35	10	1	5.5
0.10	0.050	0.075	0.438	1.0	0.682	1460	0.35	10	1	5.5
0.20	0.060	0.085	0.416	1.0	0.601	1540	0.21	9	1	5.5
0.40	0.067	0.095	0.429	0.8	0.625	1480	0.15	11	1	5.5
0.60	0.067	0.110	0.439	0.5	0.327	1470	0.13	13	3	5.5
0.80	0.067	0.114	0.450	0.2	0.451	1430	0.16	15	1	5.5
1.00	0.067	0.125	0.441	0.0	0.436	1460	0.12	16	0	5.5
1.20	0.067	0.125	0.441	0.0	0.436	1460	0.12	16	0	5.5
1.50	0.067	0.125	0.441	0.0	0.436	1460	0.12	16	0	5.5
					Soil type two					
0.05	0.290	0.340	0.568	1.0	0.0523	1050	2.18	63	19	5.7
0.10	0.280	0.340	0.577	1.0	0.0977	1020	2.10	63	22	5.8
0.20	0.280	0.350	0.569	1.0	0.0881	1040	2.00	66	21	5.8
0.40	0.280	0.340	0.580	0.8	0.0715	1010	1.79	70	17	5.5
0.60	0.270	0.335	0.605	0.5	0.1474	904	1.65	72	13	5.1
0.80	0.258	0.340	0.619	0.2	0.3011	910	1.53	72	14	5.0
1.00	0.252	0.335	0.629	0.0	0.3725	880	1.43	72	14	5.0
1.20	0.252	0.335	0.629	0.0	0.3725	880	1.43	72	14	5.0
1.50	0.252	0.335	0.629	0.0	0.3725	880	1.43	72	14	5.0
					Soil type three					
0.05	0.265	0.370	0.465	1.0	0.790	1310	2.03	26	36	6.4
0.10	0.275	0.380	0.452	1.0	0.790	1350	2.03	26	36	6.4
0.20	0.285	0.385	0.445	1.0	0.790	1370	2.03	27	37	6.4
0.40	0.280	0.370	0.455	0.8	0.790	1340	2.03	27	37	6.4
0.60	0.275	0.360	0.451	0.5	0.790	1350	0.44	27	37	6.7
0.80	0.260	0.360	0.458	0.2	0.790	1330	0.44	29	36	6.7
1.00	0.260	0.360	0.446	0.0	0.790	1360	0.29	25	32	7.3
1.20	0.260	0.350	0.410	0.0	0.790	1470	0.15	20	28	7.9
1.50	0.260	0.350	0.403	0.0	0.790	1490	0.15	18	31	7.9

The seasonal analysis tool of DSSAT, which simulates yield for each sowing week and each year, was used. Additionally, the water and nutrient balance routine from the model was turned off to allow the simulation of maize potential yield, in which the crop is grown without any biotic or abiotic stresses. The model was set to perform weekly sowings, beginning on August 01 and extending for 52 weeks to July 24, generating 49 simulation scenarios at each county.

The highest average simulated yield was identified among all sowing dates and a yield break was calculated for each county according to (Amaral et al., 2009):

$$Y_b = [1 - (Y_w / Y_{max})] \times 100$$

where Y_b is the yield break in percentage; Y_w is the average yield of week "w" in kg ha^{-1}; and Y_{max} is the maximum average yield among all weeks in kg ha^{-1}.

An analysis of the yield break curve was performed to determine the sowing windows for different levels of risk that the decision maker would be willing to take. We arbitrarily assumed a risk level of 10%; i.e., the decision maker would tolerate a yield reduction of up to 10%. In the example showed in Figure 2, the sowing windows would be from October 24 to December 19, October 17 to December 26 and from October 10 to December 26, for soil type 1, type 2 and type 3, respectively.

The criteria used to determine whether a county was suitable or not for maize production was based on the relationship:

$$Y_{pr} = [1 - (Y_{str} / Y_{pot})] \times 100$$

where Y_{pr} is the yield break relative to the potential yield in percentage; Y_{str} is the average rainfed yield, for the sowing window, in kg ha^{-1} and Y_{pot} is the average potential yield, for the same sowing window, in kg ha^{-1}. A county was considered suitable for maize production when Ypr was 60% or less. This procedure was performed for the three soil types in all counties.

The simulated yields from the 49 counties and for the three different soils were then interpolated by using a kriging procedure. The software gvSIG 1.11 (gvSIG, 2013) and Quantum GIS 1.9 (Quantum, 2013) were used to create the yield maps.

The yield break curve approach allowed determining the suitability for maize production and the establishment of a sowing window for each selected county as demonstrated for Uberaba, Minas Gerais, Brazil (Figure 2). Our results were compared with the suitability and sowing windows established by the ZRC-MAPA. Additionally, the average expected maize yield was determined for each soil type and county. Results for soil type 2, the most common in Brazil, were compared to the average estimated yield provided by the Brazilian Institute of Geography and Statistics (IBGE), for the period 2003 to 2011.

Results and Discussion

Our results showed large maize yield variation as a consequence of the climatic diversity in the state of Minas Gerais, characterized by humid climate in the south to semi-arid climate in the north and northeastern regions (Figure 3).

The average yield of maize, for the sowing window, ranged from 750 kg ha^{-1}, in Espinosa, to 10,523 kg ha^{-1}, in Maria da Fé. Regardless of the soil-water retention capacity, the regions North,

Jequitinhonha and Vale do Rio Doce, which are drier and warmer, presented the lowest yield, while the south region, which is wetter and has milder temperatures, showed the highest. Yields below 1,000 kg ha^{-1} were considerably larger in the regions North, Jequitinhonha, Vale do Mucuri and Vale do Rio Doce, especially in soils with poor water holding capacity (soil type 1). For soils with medium or high water holding capacity (soils type 2 and type 3), the amplitude of the simulated yield was higher due to better crop response to nitrogen fertilization in years with more favorable climatic conditions (Figure 3). This yield variability observed in our results is the consequence of the interactions between crop, soil and climatic conditions, especially water. Crop productivity is the result of the interaction of various factors, especially those

related to soil attributes. However, Bergamaschi et al. (2004), indicate that water is the main factor that affects maize yield worldwide.

There is a close relationship between the average simulated maize yield and elevation and latitude of the sites (Figure 4). The higher the latitude and altitude, the greater the simulated maize yields. This is because for conditions in Minas Gerais, rainfall and air temperature are related to both, elevation and latitude (Guimarães et al., 2010; Santana, 2004).

When comparing the average simulated yield of the sowing window, for soil type two, with the average maize yield estimated by IBGE, for the 2003 to 2011 period and for the same counties, considerable differences can be observed (Figure 5). These gaps indicate that the average maize
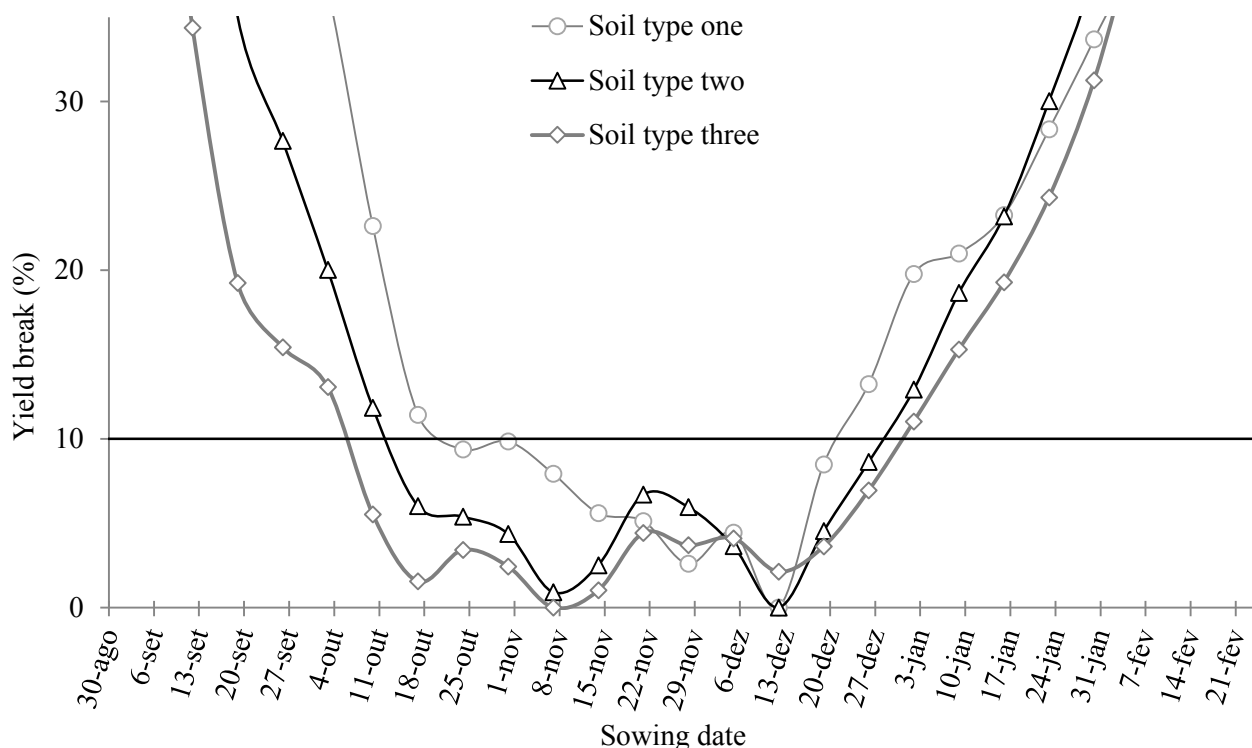

FIGURE 2. Maize yield break for different sowing dates in a rainfed production system for conditions in Uberaba, Minas Gerais, Brazil.

yield is considerably lower than the potential yield in many counties. The largest yield gaps are in the southern counties, such as Maria da Fé, which has climatic conditions for high maize yields but rugged topography that is not suited for maize production.

On the other hand, in some counties, such as Uberaba, Unai and Frutal, the average simulated yields are lower than the average yield estimated by IBGE, indicating that in these counties the farmers are utilizing more technology, including cultivars better than the BRS1030 and, irrigation. Maize yield from Unai county is an unusual case because the IBGE data reflects the yield of farms located on the plateau, 300 meters above the location where the weather station is installed.

This difference in elevation has a considerable effect on maize yield mainly due to changes in the amount and distribution of rainfall and in temperature. According to a study conducted in the region by Landau et al. (2011) during the 2010 growing season, large increase in maize production were observed in the south/southwest and western (Campos das Vertentes) regions, eastern of Triângulo Mineiro, and west of the northwest region, which was in agreement with our results (Figure 3).

There is a large variation in the start and in the length of the sowing window (Table 2), as a consequence of the interactions between the crop and the weather conditions of the counties, captured by the simulation model. The shortest

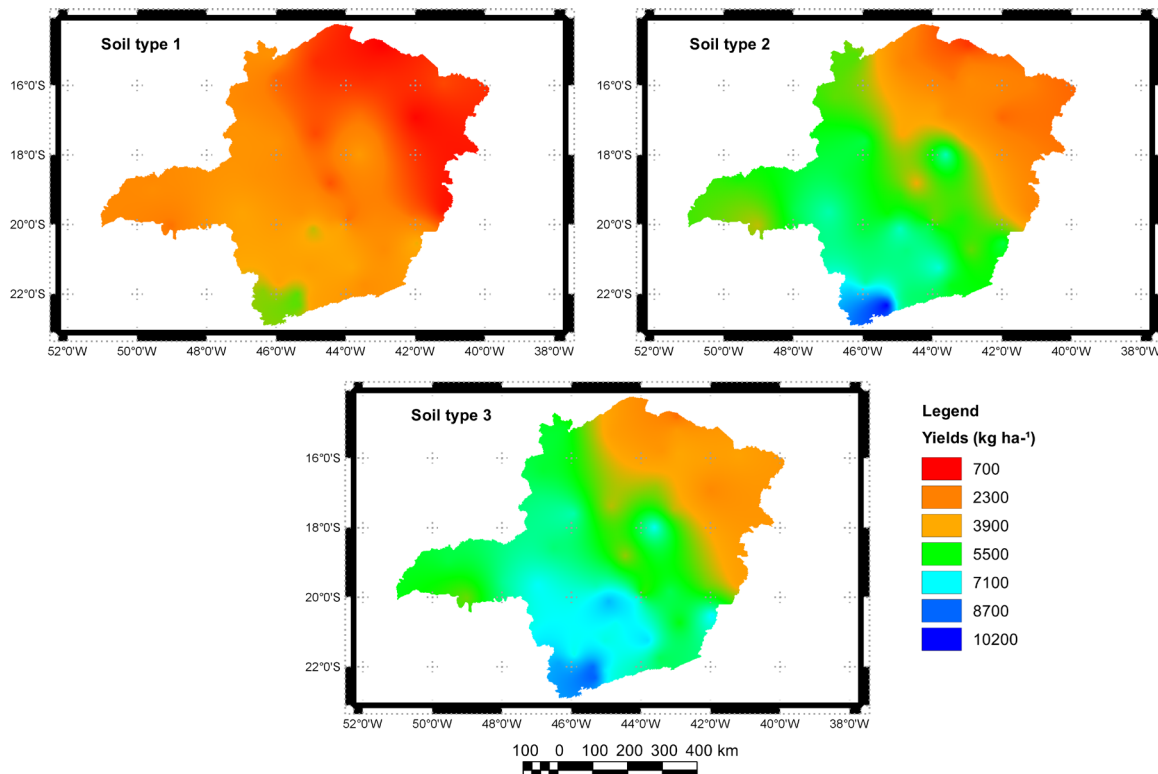

FIGURE 3. Distribution of the average simulated maize yield for the state of Minas Gerais, Brazil, considering soils with different water holding capacity.
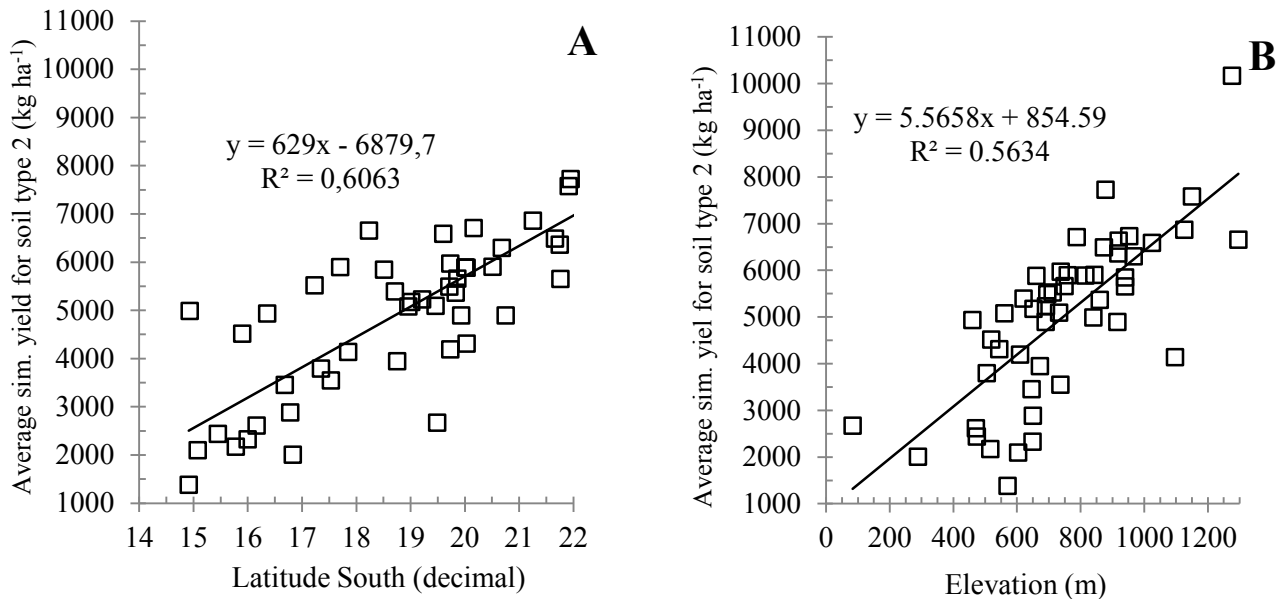
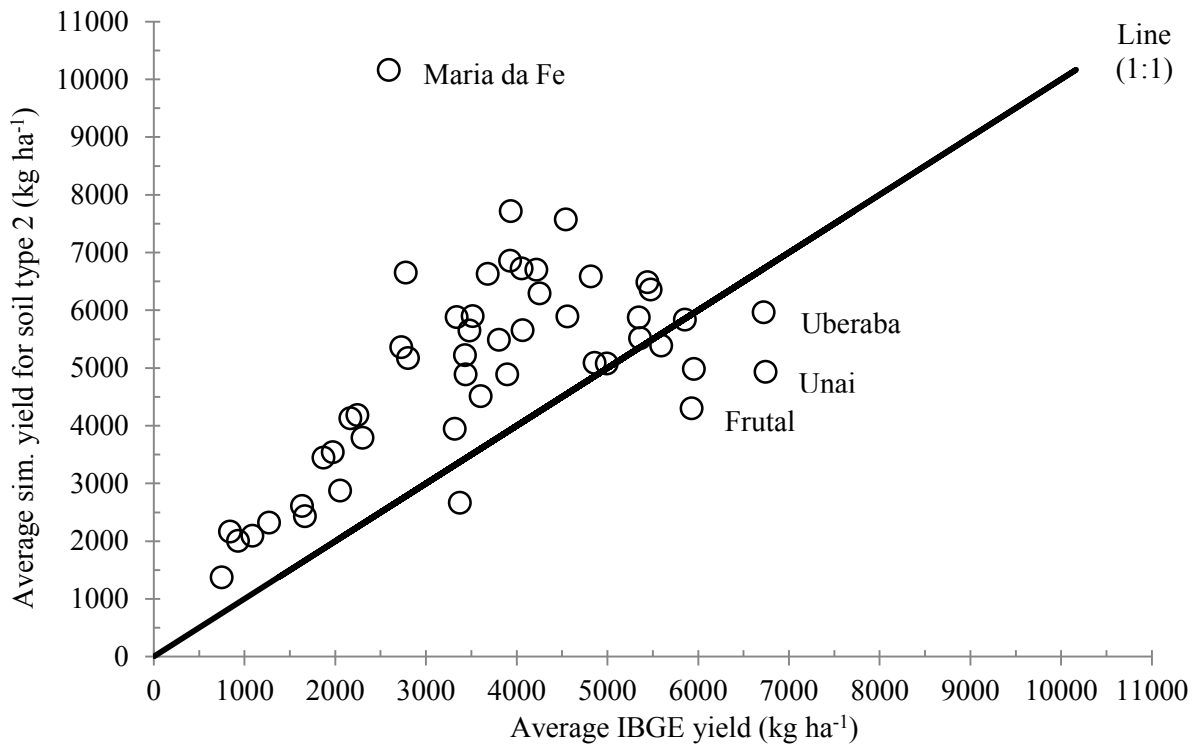**FIGURE 4.** Maize yield in relation to latitude south (A) and to elevation (B), for soil type two.

FIGURE 5. Average simulated yield for soil type 2 in relation to average yield estimated by IBGE, for the period of 2003-2011.

TABLE 2. Sowing window and average simulated maize yield for counties of Minas Gerais state, Brazil. Dashes indicate county unsuitable for maize production.

Regions	Counties	Soil type one				Soil type two				Soil type three			
		Sowing window		N° of days	Yield (kg ha⁻¹)	Sowing window		N° of days	Yield (kg ha⁻¹)	Sowing window		N° of days	Yield (kg ha⁻¹)
Triângulo Mineiro/Alto Paranaíba	Capinópolis	-	-	-	2613	Nov-14	Dec-19	36	5391	Oct-17	Dec-12	57	5859
	Frutal	-	-	-	2134	Nov-21	Dec-26	36	4307	Nov-7	Dec-26	50	4801
	Uberaba	Oct-24	Dec-19	57	3083	Oct-17	Dec-26	71	5968	Oct-10	Dec-26	78	6363
	Ituiutaba	-	-	-	2803	Nov-7	Dec-26	50	5080	Oct-24	Dec-26	64	5836
	Araxá	Oct-10	Nov-21	43	3648	Oct-17	Dec-5	50	6588	Oct-10	Nov-28	50	7006
	Patos de Minas	-	-	-	2947	Oct-17	Dec-19	64	5842	Oct-10	Dec-19	71	6181
Norte (north)	Monte Azul	-	-	-	961	-	-	-	2096	Oct-24	Nov-14	22	3266
	Juramento	-	-	-	2113	-	-	-	2881	Oct-17	Oct-24	8	4517
	Espinosa	-	-	-	709	-	-	-	1379	-	-	-	2088
	Janaúba	-	-	-	1228	-	-	-	2171	-	-	-	3087
	Januaria	-	-	-	1237	-	-	-	2435	Oct-24	Oct-31	8	3450
	Montes Claros	-	-	-	1867	-	-	-	3454	Oct-17	Oct-31	15	4174
	Pirapora	-	-	-	1619	Oct-24	Nov-7	15	3793	Oct-17	Nov-14	29	4304
	Salinas	-	-	-	1245	-	-	-	2613	Oct-17	Oct-31	15	3504
Noroeste (northwest)	João Pinheiro	-	-	-	2942	Oct-31	Nov-21	22	5896	Oct-24	Nov-21	29	6522
	Formoso	-	-	-	3000	Nov-21	Dec-12	22	4989	Oct-24	Dec-19	57	5671
	Arinos	-	-	-	1992	Oct-24	Nov-21	29	4515	Oct-17	Nov-14	29	5485
	Paracatu	-	-	-	2997	Oct-24	Nov-28	36	5521	Oct-17	Nov-21	36	6221
	Unaí	-	-	-	2501	Oct-17	Nov-21	36	4936	Oct-17	Nov-14	29	5758
Jequitinhonha	Carbonita	-	-	-	2247	Oct-24	Oct-31	8	3548	Oct-10	Oct-31	22	4286
	Pedra Azul	-	-	-	1601	-	-	-	2326	-	-	-	3587
	Araçuaí	-	-	-	780	-	-	-	2007	Oct-17	Nov-7	22	2587
	Diamantina	-	-	-	3314	Oct-17	Nov-14	29	6655	Oct-10	Nov-14	36	6966
	Itamarandiba	-	-	-	2163	Oct-10	Nov-14	36	4136	Oct-10	Nov-14	36	4846
	Caratinga	-	-	-	2038	Oct-10	Nov-21	43	4191	Oct-3	Nov-14	43	4858
	Aimorés	-	-	-	949	Oct-24	Nov14	22	2668	Oct-17	Nov-7	22	3564

Region	Location												
Oeste (west)	Bambuí	Oct-31	Dec-5	36	3366	Oct-10	Nov-28	50	5882	Oct-10	Nov-28	50	6914
	Oliveira	Oct-10	Out-31	22	3733	Oct-10	Nov-21	43	6295	Oct-3	Nov-21	50	6968
	Divinópolis	Oct-17	Nov-7	22	4283	Oct-17	Nov-21	36	6709	Oct-17	Nov-14	29	7702
Sul / Sudoeste (south / southwest)	Passa Quatro	Sep-19	Dec-26	99	3690	Oct-10	Dec-5	57	6633	Sep-26	Dec-12	78	7051
	Maria da Fé	-	-	-	4879	Sep-19	Nov-28	71	10166	Sep-26	Nov-28	64	8646
	Machado	Oct-17	Dec-19	64	3593	Oct-17	Dec-19	64	6490	Oct-17	Dec-19	64	6913
	Lambari	Oct-10	Nov-28	50	4922	Oct-17	Dec-5	50	7723	Oct-10	Dec-5	57	8547
	Caldas	Nov-14	Dec-26	43	4628	Nov-7	Dec-26	50	7579	Oct-17	Jan-2	78	7941
	Lavras	Oct-17	Dec-19	64	3464	Oct-10	Dec-12	64	6362	Oct-10	Dec-5	57	6878
	São Lourenço	Oct-3	Dec-19	78	3780	Oct-10	Dec-19	71	6731	Oct-10	Dec-19	71	7190
Zona da Mata	Caparaó	Oct-10	Dec-5	57	4022	Oct-3	Nov-28	57	5903	Oct-3	Nov-7	36	7137
	Juiz de Fora	Oct-3	Dec-12	71	2871	Oct-3	Jan-9	100	5651	Oct-3	Jan-16	107	6013
	Viçosa	-	-	-	2789	Oct-10	Nov-28	50	4894	Oct-3	Nov-28	57	5542
Central	Bom Despacho	-	-	-	2982	Oct-24	Nov-14	22	5491	Oct-10	Nov-7	29	6573
	Pompéu	-	-	-	2729	Oct-24	Nov-14	22	5229	Oct-10	Nov-14	36	1245
	Curvelo	-	-	-	1755	Oct-17	Nov-21	36	3948	Oct-17	Nov-21	36	4540
Metropolitana de Belo Horizonte	Florestal	-	-	-	3082	Oct-17	Nov-28	43	5659	Oct-31	Dec-26	57	6866
	Belo Horizonte	-	-	-	2127	Oct-17	Dec-5	50	4895	Oct-10	Dec-5	57	5203
	Conceição do Mato Dentro	-	-	-	2460	Oct-10	Nov-28	50	5177	Oct-10	Nov-21	43	5623
	Sete Lagoas	-	-	-	2426	Oct-10	Nov-21	43	5091	Oct-3	Nov-21	50	5626
	Ibirité	Oct-17	Oct-31	15	3576	Oct-10	Nov-28	50	5889	Oct-10	Nov-7	29	6779
	João Monlevade	-	-	-	2644	Oct-24	Nov-14	22	5367	Oct-10	Nov-14	36	5954
Campos das Vertentes	Barbacena	Sep-26	Dec-12	78	3787	Oct-3	Dec-5	64	6864	Oct-3	Dec-5	64	7294

sowing windows, of eight days, were simulated for counties in the North and Jequitinhonha regions, which are the driest and have the highest temperatures. The longest windows were simulated for the south/southwest and Zona da Mata regions (Table 2). The soil water retention capacity had an important role in defining the start and length of the sowing window, especially in cities with low rainfall.

Shorter sowing windows were also associated with lower yields (Figure 3 and Table 2). It is possible that the sowing date used by farmers is not the most appropriate for each site, contributing to lower than expected yields indicated by the estimates made by IBGE (Figure 5). Sowing out of the appropriate period is the major cause of low maize yield in Brazil (Forsthofer, 2004).

The methodology used to define the suitability of a certain county for dryland maize production proved consistent (Table 2). Most of the counties that were considered unsuitable for maize production are located in the North and Jequitinhonha regions, which receive lower amounts of precipitation and, in some cases, are associated with high temperatures. Obviously, the smaller the water holding capacity of the soils, the greater the number of counties considered unsuitable for rainfed maize production.

When comparing the sowing window and the suitability of the county for maize production (Tables 2 and 3), it can be observed that the proposed methodology is more restrictive than the ZRC-MAPA approach. According to the proposed methodology, and regardless of soil type, the counties of Espinoza, Janauba and Pedra Azul are not suitable for rainfed maize production, while when using the ZRC-MAPA approach those same

counties are only suitable for maize production if the soil is of type three. If the soil has low water holding capacity (soil type 1), 34 counties are considered non suitable for rainfed maize production, against nine counties considered non suitable by the ZRC-MAPA approach. For soils with average water holding capacity (soil type 2), nine counties are considered non suitable by the proposed method while all counties are considered suitable by the ZRC-MAPA approach. For the ZRC-MAPA approach (Table 3), the beginning of the sowing window in all counties and for the three soil types, is October 01, while by the proposed methodology (Table 2), the starting of the sowing window ranged from September 19, in Passa Quatro and Maria da Fé, to November 21, in Formoso. Additionally, by the proposed methodology, the duration of the sowing window varied from eight days in Juramento, Januaria and Carbonita to 107 days, in Juiz de Fora.

For the ZRC-MAPA approach the expected duration of the sowing window is 31, 20, 20 and 92 days, respectively for Juramento, Januaria, Carbonita and Juiz de Fora. In general, in drier regions the proposed methodology was more restrictive than the ZRC-MAPA approach, establishing shorter sowing windows.

The discrepancy in the results obtained with the proposed methodology and the ZRC-MAPA is due to the use of different approaches to determine the sowing window and the suitability of the different counties for maize production. The ZRC-MAPA is based solely on crop water requirements satisfaction, determined through a simple soil water balance (Sans et al., 2001). The proposed methodology is based on a yield break curve, obtained from a process-based

model, which takes into consideration the crop response to several factors, including air temperature, radiation and water requirements. The CSM-CERES-Maize model, used in the present study, simulates growth, development and yield of crops deterministically resulting in accurate predictions of the variables of interest; i.e., without any probability distribution or random element associated. One of the advantages of the proposed methodology is the ability to estimate the expected average yield for each county, which is not provided by the ZRC-MAPA approach. On the other hand, the ZRC-MAPA approach only considers a land area as suitable for maize production if the crop water requirement satisfaction index is greater than 0.6, something that was not considered in the proposed methodology.

The shortest sowing windows and lowest yields were found to be in the North, Jequitinhonha and Vale do Rio Doce regions by both methodologies. These results properly reflect the low levels of economic and social development of those regions, which economies are primarily based in agriculture. The human development index for the North and Jequitinhonha regions are in the range of 0.568 to 0.707 as compared to 0.744 to 0.841 from of Triângulo and south regions (Santos & Pales, 2012).

Based on this study, it is evident that the current ZRC-MAPA can be improved through the use of process-based simulation models. However, calibration of model´s coefficient for new cultivars and characterization of soil and climate for other Brazilian counties is required. Through the use of the proposed methodology one could improve policies for technology transfer and for granting credit for maize production.

Conclusões

The use of process-based simulation model allowed the establishment of sowing windows as well as the determination of the expected average maize yield for various counties in the state of Minas Gerais, Brazil.

Our results indicate that there is a potential to increase rainfed maize yield for conditions in the state of Minas Gerais.

The proposed methodology turned out to be more restrictive than the approach currently used by the ZRC-MAPA.

The study highlights the needs for better monitoring of environmental conditions in the state of Minas Gerais, a necessary step to enable the widespread application of the proposed methodology.

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TABLE 3. Sowing window and number of days of the sowing window for different counties of Minas Gerais state, Brazil, as established by the ZRC-MAPA.

Regions	Counties	Soil type one			Soil type two			Soil type three		
		Sowing window		N° of days	Sowing window		N° of days	Sowing window		N° of days
Triângulo Mineiro/Alto Paranaiba	Capinópolis	Oct-1	Nov-30	61	Oct-1	Dec-31	92	Oct-1	Dec-31	92
	Frutal	Oct-1	Dec-31	92	Oct-1	Dec-31	92	Oct-1	Dec-31	92
	Uberaba	Oct-1	Dec-31	92	Oct-1	Dec-31	92	Oct-1	Dec-31	92
	Ituiutaba	Oct-1	Dec-31	92	Oct-1	Dec-31	92	Oct-1	Dec-31	92
	Araxá	Oct-1	Dec-31	92	Oct-1	Dec-31	92	Oct-1	Dec-31	92
	Patos de Minas	Oct-1	Nov-10	41	Oct-1	Dec-31	92	Oct-1	Dec-31	92
Norte (north)	Monte Azul	-	-	-	Oct-1	Oct-20	20	Oct-1	Oct-31	31
	Juramento	-	-	-	Oct-1	Oct-31	31	Oct-1	Nov-10	41
	Espinosa	-	-	-	Oct-1	Oct-20	20	Oct-1	Oct-20	20
	Janauba	-	-	-	Oct-1	Oct-31	31	Oct-1	Nov-10	41
	Januaria	Oct-1	Oct-20	20	Oct-1	Oct-31	31	Oct-1	Nov-10	41
	Montes Claros	Oct-1	Oct-20	20	Oct-1	Oct-31	31	Oct-1	Nov-10	41
	Pirapora	-	-	-	Oct-1	Oct-31	31	Oct-1	Nov-10	41
	Salinas	-	-	-	-	-	-	Oct-1	Oct-31	31
Noroeste (northwest)	João Pinheiro	Oct-11	Oct-20	10	Oct-1	Dec-31	92	Oct-1	Dec-31	92
	Formoso	Oct-1	Oct-20	20	Oct-1	Oct-31	31	Oct-1	Nov-20	51
	Arinos	Oct-1	Oct-20	20	Oct-1	Oct-31	31	Oct-1	Dec-20	81
	Paracatu	Oct-1	Nov-30	61	Oct-1	Dec-31	92	Oct-1	Dec-31	92
	Unai	Oct-1	Nov-10	41	Oct-1	Nov-30	61	Oct-1	Dec-10	71
Jequitinhonha	Carbonita	Oct-1	Oct-20	20	Oct-1	Nov-10	41	Oct-1	Nov-20	51
	Pedra Azul	-	-	-	Oct-1	Oct-20	20	Oct-1	Oct-31	31
	Araçuai	-	-	-	Oct-1	Oct-20	20	Oct-1	Oct-31	31
	Diamantina	Oct-1	Oct-31	31	Oct-1	Nov-20	51	Oct-1	Nov-30	61
	Itamarandiba	Oct-1	Oct-20	20	Oct-1	Nov-10	41	Oct-1	Nov-20	51
	Caratinga	Oct-1	Oct-20	20	Oct-1	Nov-10	41	Oct-1	Nov-20	51
	Aimorés	-	-	-	Oct-1	Oct-31	31	Oct-1	Oct-31	31

Oeste (west)	Bambuí	Oct-1	Nov-30	61	Oct-1	Dec-31	92	Oct-1	Dec-31	92
	Oliveira	Oct-1	Nov-30	61	Oct-1	Dec-31	92	Oct-1	Dec-31	92
	Divinópolis	Oct-1	Nov-10	41	Oct-1	Dec-31	92	Oct-1	Dec-31	92
Sul / Sudoeste (south / southwest)	Passa Quatro	Oct-1	Dec-31	92	Oct-1	Dec-31	92	Oct-1	Dec-31	92
	Maria da Fé	Oct-1	Dec-31	92	Oct-1	Dec-31	92	Oct-1	Dec-31	92
	Machado	Oct-1	Dec-20	81	Oct-1	Dec-31	92	Oct-1	Dec-31	92
	Lambari	Oct-1	Dec-20	81	Oct-1	Dec-31	92	Oct-1	Dec-31	92
	Caldas	Oct-1	Dec-31	92	Oct-1	Dec-31	92	Oct-1	Dec-31	92
	Lavras	Oct-1	Dec-20	81	Oct-1	Dec-31	92	Oct-1	Dec-31	92
	São Lourenço	Oct-1	Dec-20	81	Oct-1	Dec-31	92	Oct-1	Dec-31	92
Zona da Mata	Caparao	Oct-1	Oct-20	20	Oct-1	Nov-10	41	Oct-1	Nov-20	51
	Juiz de Fora	Oct-1	Nov-20	51	Oct-1	Nov-30	61	Oct-1	Dec-31	92
	Viçosa	Oct-1	Nov-10	41	Oct-1	Dec-31	92	Oct-1	Dec-31	92
Central	Bom Despacho	Oct-1	Oct-31	31	Oct-1	Nov-20	51	Oct-1	Dec-31	92
	Pompéu	Oct-1	Oct-31	31	Oct-1	Nov-20	51	Oct-1	Dec-31	92
	Curvelo	Oct-1	Oct-20	20	Oct-1	Nov-10	41	Oct-1	Nov-30	61
Metropolitana de Belo Horizonte	Florestal	Oct-1	Nov-20	51	Oct-1	Dec-31	92	Oct-1	Dec-31	92
	Belo Horizonte	Oct-1	Nov-20	51	Oct-1	Dec-31	92	Oct-1	Dec-31	92
	Conc. do Mato Dentro	Oct-1	Nov-10	41	Oct-1	Nov-30	61	Oct-1	Dec-31	92
	Sete Lagoas	Oct-1	Oct-31	31	Oct-1	Nov-20	51	Oct-1	Nov-30	61
	Ibirité	Oct-1	Nov-20	51	Oct-1	Dec-31	92	Oct-1	Dec-31	92
	João Monlevade	Oct-1	Oct-31	31	Oct-1	Nov-20	51	Oct-1	Nov-30	61
Campos das Vertentes	Barbacena	Oct-1	Nov-20	51	Oct-1	Dec-31	92	Oct-1	Dec-31	92

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