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Köppen-Geiger and Camargo climate classifications for the Midwest of Brasil

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Abstract

There is a wide variety of climates on the planet's surface, and climate classifications are tools for delimiting and describing prevailing climate types. Köppen classification relates types of climate to types of vegetation, while Camargo classification seeks to map climatic types based on thermal and water factors. In Brazil, the Midwest region is a major agricultural producer but still lacks detailed climate information. In this sense, we aimed to compare Köppen and Geiger (1928) with Camargo (1991) methods for climate classification in the Midwest of Brazil. For this purpose, we used data on daily global solar radiation; mean, maximum, and minimum air temperature; relative humidity; wind speed; and precipitation from 2160 weather stations, which were obtained from the NASA/POWER platform. Components of normal climatological water balance were calculated using the Thornthwaite and Mather (1955) method, with an available water capacity of 100 mm. Köppen and Geiger (1928) system uses data on mean annual temperature, annual precipitation, coldest month mean temperature, warmest month mean temperature, and driest month precipitation. The method of Camargo (1991), modified by Maluf (2000), uses the following meteorological elements: mean annual temperature, coldest month mean temperature, annual water surplus and deficit, and water deficit months. The similarity between classification methods was verified by agglomerative hierarchical clustering and Tukey's test at 95% reliability. The most predominant climate class according to Camargo (1991) was TR-UMi (humid tropical climate), representing 33.63% of the entire territory of the Midwest of Brazil. According to Köppen and Geiger (1928), six climate types were observed in the Midwest region, with a predominance of class Aw (tropical climate with dry winter), representing 58.50% of the entire region. While Köppen and Geiger (1928) showed a macroscale scope, Camargo (1991) classification had a mesoscale approach. The latter was more suitable for agricultural purposes, mainly because it provided information on prevailing water conditions in the region.

1 Introduction

Climate variability directly influences agricultural activities (Sá Junior et al. 2012), increasing or reducing crop productive potential (Aparecido et al. 2020). Climate comprises average atmospheric conditions within a minimum period of 30 years in order to characterize a particular location (Jo et al. 2019). It is defined by classification systems, which are efficient methods for determining climate classes (Aparecido et al. 2016; He et al. 2019).

Climate classification systems are designed to obtain and define geographical limits of prevailing climate types in a given area (Wang et al. 2019; Engelbrecht and Engelbrecht 2016) to facilitate dissemination of information and analysis for various purposes (Matos et al. 2018, Beck et al. 2018). Climate classification systems synthesize statistics of seasonal climate variability, thus simplifying, clarifying, and understanding intricate climate patterns (Terassi and Silveira 2013; Every et al. 2020).

Several climate classification systems have been used worldwide, such as Thornthwaite (1948), Holdridge (1967), Miller (1931), Strahler (2005) (Nóbrega 2010), Camargo (1991) (Maluf 2000), and Köppen and Geiger (1928). However, the most widely used climate classification system worldwide is that developed by Köppen and Geiger (1928) (Kuinchtner and Buriol 2016; Jo et al. 2019).

Köppen-Geiger climate classification is the most comprehensive (Köppen and Geiger 1928), analyzing natural vegetation as an expression of climate in a

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region (Rolim et al. 2007) based on mean annual and monthly air temperature and precipitation values (Gallardo et al. 2013). Köppen classification (Köppen and Geiger 1928) has been used for more than 80 years and has a didactic character, which allows it to be adapted to different levels while being simple and full of details. The most significant adaptation of this system was proposed by Trewartha (1954), which in general simplifies the Köppen system (Köppen and Geiger 1928), making it more adaptable for use in computerized systems (Rolim et al. 2007).

Climate classifications, such as that of Köppen (Köppen and Geiger 1928), bring information more adapted to geographic and climatological studies (Jo et al. 2019), as they need few parameters, simplifying complex situations of the relationship between climate and crop productivity (Rolim et al. 2007). For this reason, other classifications, such as Camargo (1991), have been gaining ground, mainly because they use water parameters and provide agricultural activities with more accurate information.

Camargo (1991) climate classification method is widely used in applications of agroclimatic zoning. It was developed to combine Köppen method simplicity with Thornthwaite (1948) rationality. Camargo climate classification system modified by Maluf (2000) uses the following climatic elements: mean annual air temperature, coldest month mean temperature, water deficit, and annual surplus, in addition to identifying months with the highest water deficit (Aparecido et al. 2016).

Studies on climate classifications have been developed worldwide. Izzo et al. (2010) classified climate in the Dominican Republic using the Thornthwaite system (1948). Rolim and Aparecido (2015) determined climate classes in São Paulo State (Brazil), using the Camargo (1991) method. Mohamed & Mohamed (2017) used the Thornthwaite (1948) system to determine climate in Sudan by comparing different aridity indices. Müller et al. (2018) carried out a climate classification for West Africa using the methods of Köppen and Geiger (1928) to improve land use and agricultural activities. However, none of them determined the

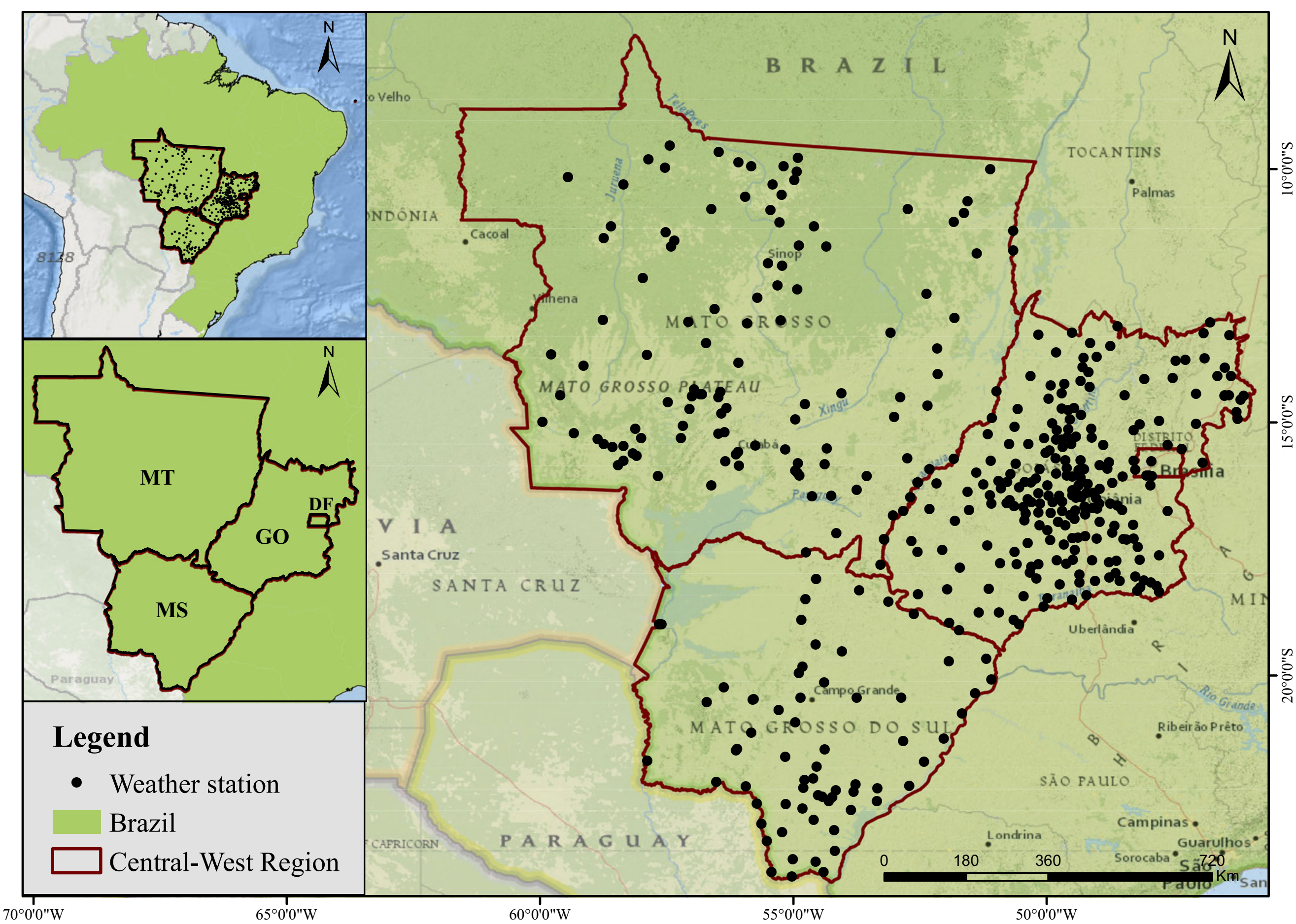

Fig. 1 Location of weather stations in the Midwest region of Brazil

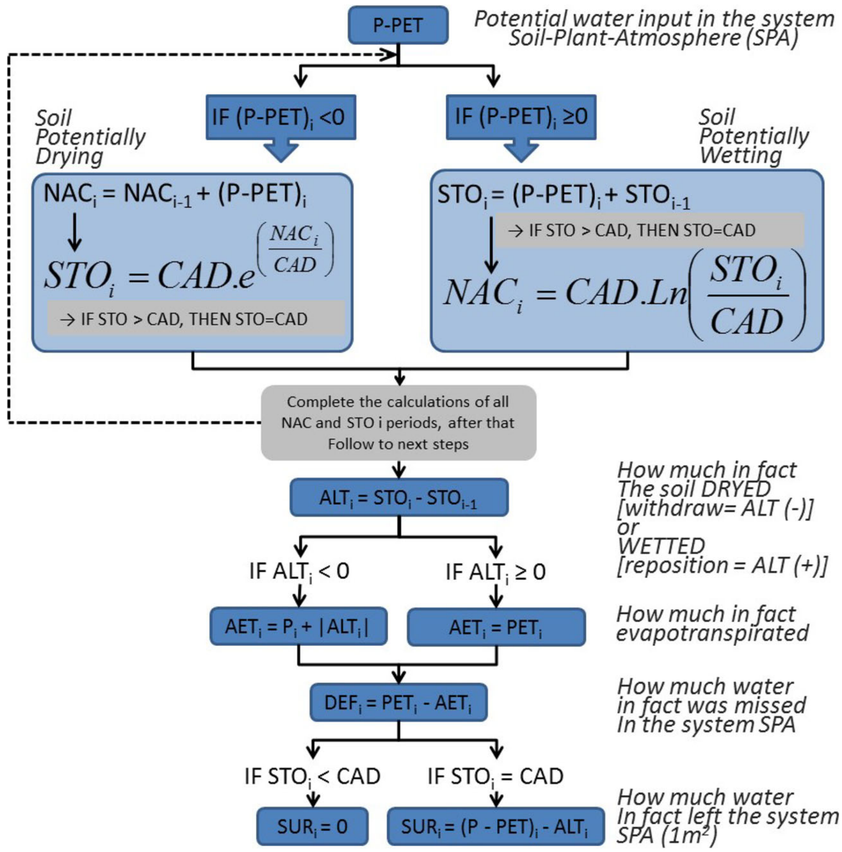

Fig. 2 Flowchart of the water balance model modified from Thornthwaite and Mather (1955). Legend: P is precipitation (mm), PET is evapotranspiration, AET is the real evapotranspiration (mm), STO is the soil water storage (mm), CAD is the soil water capacity (mm), NAC is the negative accumulated (mm), meaning the potential drying of the soil, ALT is the alteration of STO, SUR is the water surplus in the soil-plant-atmosphere system (mm), DEF is the water deficit of the soil-plant-atmosphere system (mm), and i a given period, $i-1$ previous period. Adapted by Rolim et al. (2020)

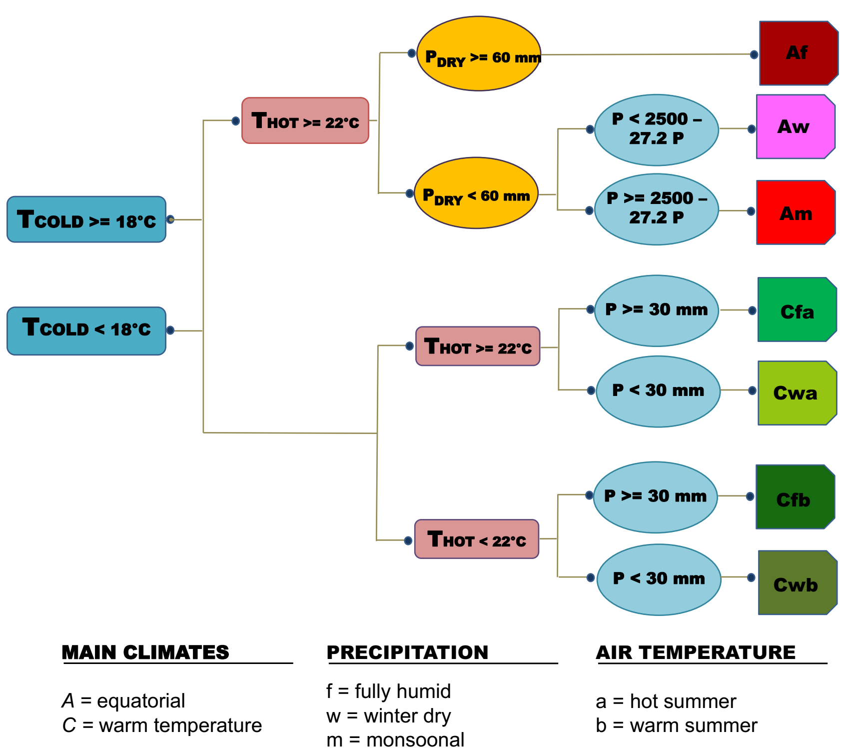

Fig. 3 Dendrogram for climate classification according to the Köppen and Geiger (1928) system. Legend: Cwb, humid subtropical climate with dry winter and temperate summer; Cfb, humid subtropical with an oceanic climate, with no dry season and temperate summer; Cwa, humid subtropical climate with dry winter and hot summer; Cfa, humid subtropical with an oceanic climate, with no dry season and hot summer; Am, tropical monsoon climate; Aw, tropical climate with dry winter; Af, tropical climate with no dry season

Table 1 Temperature ranges of climate classes from Camargo (1991) climate classification system modified by Maluf (2000)

Mean annual air temperature (T_M, °C)	Coldest month mean temperature (T_{cold}, °C)	Climate class	Symbol
$T_M > 25$		Equatorial	EQ
$22 < T_M \leq 25$	Or $20 < T_{cold}$	Tropical	TR
$18 < T_M \leq 22$	And $13 < T_{cold} \leq 20$	Subtropical	ST
$18 < T_M \leq 22$	And $T_{cold} \leq 13$	Sub-temperate	STE
$12 < T_M \leq 18$	Or $T_{cold} \leq 13$	Temperate	TE
$7 < T_M \leq 12$		Cold	CO
$T_M \leq 3$		Glacial	GL

similarity between different classification systems, such as Köppen and Geiger (1928) and Camargo (1991).

We aimed to compare Köppen and Geiger (1928) and Camargo (1991) climate classification methods in the Midwest region of Brazil.

2 Materials and methods

2.1 Study region and data

This study was carried out in the Midwest region of Brazil (Fig. 1). This is the second largest region countrywide and has a share of around 30% in gross domestic product. It is also the largest grain exporter region in the country (Silva and Marujo 2012), producing mainly corn and soybean.

2.2 Climate data

The climatic elements global solar radiation (Qg, MJ m^{-2} d^{-1}); mean (Tm, °C), maximum (Tmax, °C), and minimum air temperatures (Tmin, °C); relative humidity (RH, %); wind speed (U_2, m s^{-1}); and precipitation (P, mm) were used on a daily scale from 1983 to 2019. Data were obtained from the National Aeronautics and Space Administration/Prediction of Worldwide Energy Resources (NASA/POWER) platform (Sparks 2018). This data platform was developed to provide meteorological information derived in grids with a spatial resolution of one degree (latitude-longitude). A total of 2160 NASA/POWER weather stations were used to cover the entire Midwest region of Brazil.

Table 2 Annual water deficit and surplus for Camargo (1991) climate classification system

	Water loss (mm)		Class	
Surplus (SUR)		Deficit (DEF)	Climate description	Symbol
SUR > 1000	and	DEF = 0	Extremely humid	SU
200 < SUR ≤ 1000	and	DEF = 0	Very humid	PU
SUR > 200	and	0 < DEF ≤ 150	Humid	UM
0 < SUR ≤ 200	and	0 < DEF ≤ 150	Sub-humid	SB
SUR > 200	and	DEF > 150	Monsoon	MO
0 < SUR ≤ 200	and	DEF > 150	Dry	SE
SUR = 0	and	150 < DEF ≤ 800	Arid	AR
SUR = 0	and	DEF > 800	Desert	DE

2.2.1 Calculation of potential evapotranspiration

Potential evapotranspiration (PET) was calculated from climate data using the Penman-Monteith (PM) method (Allen et al. 1998). This method is written as follows:

$$PET = \frac{0.408 \times s \times (Rn - G) + \frac{\gamma \times 900 \times U_2 \times (es - ea)}{T + 273}}{s + \gamma \times (1 + 0.34 \times U_2)}. \quad (1)$$

The Rn, s, e_s, and e_a values (Allen et al. 1998) were estimated using the following equations:

a) e_s – mean daily vapor saturation pressure (kPa):

$$es = (esTmax + esTmin)/2 \quad (2)$$

Table 3 Symbols for dry season defined by Camargo (1991)

Season	Symbol
Spring	p
Summer	v
Autumn	o
Winter	i

Table 4 Convention for the seasonal period

Season	Period
Summer	$^1/_3$ Dec. + Jan. + Feb. + $^2/_3$ Mar.
Autumn	$^1/_3$ Mar. + Apr. + May + $^1/_3$ June
Winter	$^2/_3$ June + July + Aug. + $^2/_3$ Sept.
Spring	$^1/_3$ Sept. + Oct. + Nov. + $^2/_3$ Dec.

$^1/_3$: first 10-day period; $^2/_3$: second 10-day period

Wherein:

$$esTmax = 0.6108 \times e[(17.27 \times Tmax)/(237.3 + Tmax)] \quad (3)$$

$$esTmin = 0.6108 \times e\,[(17.27 \times Tmin)/(237.3 + Tmin)] \quad (4)$$

b) e_a – partial vapor pressure (kPa):

$$ea = (RHmean \times es)/100 \quad (5)$$

c) s – slope of the vapor saturation curve (kPa °C^{-1}):

$$s = 4098 \times es/(T + 273)^2 \quad (6)$$

d) Rn – net radiation (MJ m^{-2} day^{-1}):

$$Rn = BOC - BOL \quad (7)$$

Wherein:

$$BOC = (1-\alpha) \times Qg \quad (8)$$

$$BOL = -\left[4.903 \times 10^{-9}\,x\;\; Tmean^4\,x\,\left[0.56\text{–}0.25\,x\,ea^{0.5}\right]x\,\left[0.1 + 0.9\,x\left(\frac{n}{N}\right)\right]\right] \quad (9)$$

Wherein PET is the potential evapotranspiration (mm day^{-1}), s is the slope of the vapor saturation curve (kPa °C^{-1}), U_2 is the mean daily wind speed at 10 m

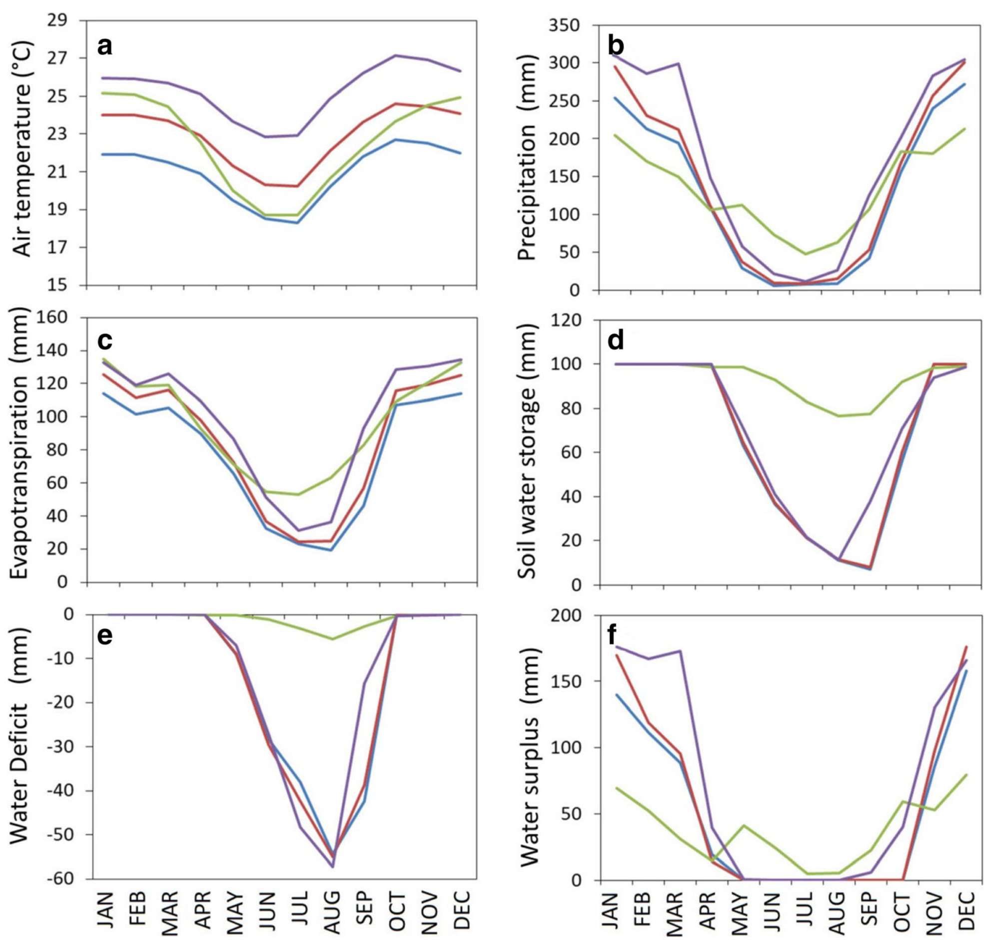

Fig. 4 Seasonal variation of air temperature and precipitation for the Midwest of Brazil. Legend: GO is state of Goiás (red); MS is state of Mato Grosso do Sul (green); MT is state of Mato Grosso (purple) and DF is Federal District (blue)

high (m s^{-1}), Rn is the net radiation (MJ m^{-2} day^{-1}), G is the heat flow density (MJ m^{-2} day^{-1}), T is the mean daily air temperature (°C), γ is the psychrometric constant (0.063 kPa °C^{-1}), e_a is the partial vapor pressure (kPa), e_s is the mean daily vapor saturation pressure (kPa), α is albedo, n = insolation (hours) = N photoperiod (hours).

2.2.2 Climatological water balance

The climatological water balance was generated for all studied locations according to the method of Thornthwaite and Mather (1955). Available water capacity (CAD) was 100 mm, as it is used for regional climate characterization (Fig. 2).

2.3 Köppen and Geiger (1928) climate classification

Köppen and Geiger (1928) climate classification system uses mean annual temperature, annual precipitation, coldest month mean air temperature, warmest month mean temperature, and driest month precipitation (Fig. 3).

2.4 Camargo climate classification

Mean annual temperature (Tm), coldest month mean temperature (Tc) (Table 1), annual water surplus, annual water deficit (Table 2), and water deficit months were the meteorological elements used for the method of Camargo (1991) modified by Maluf (2000) (Table 3).

Camargo (1991) classification system requires defining the driest periods (Table 3); therefore, months were

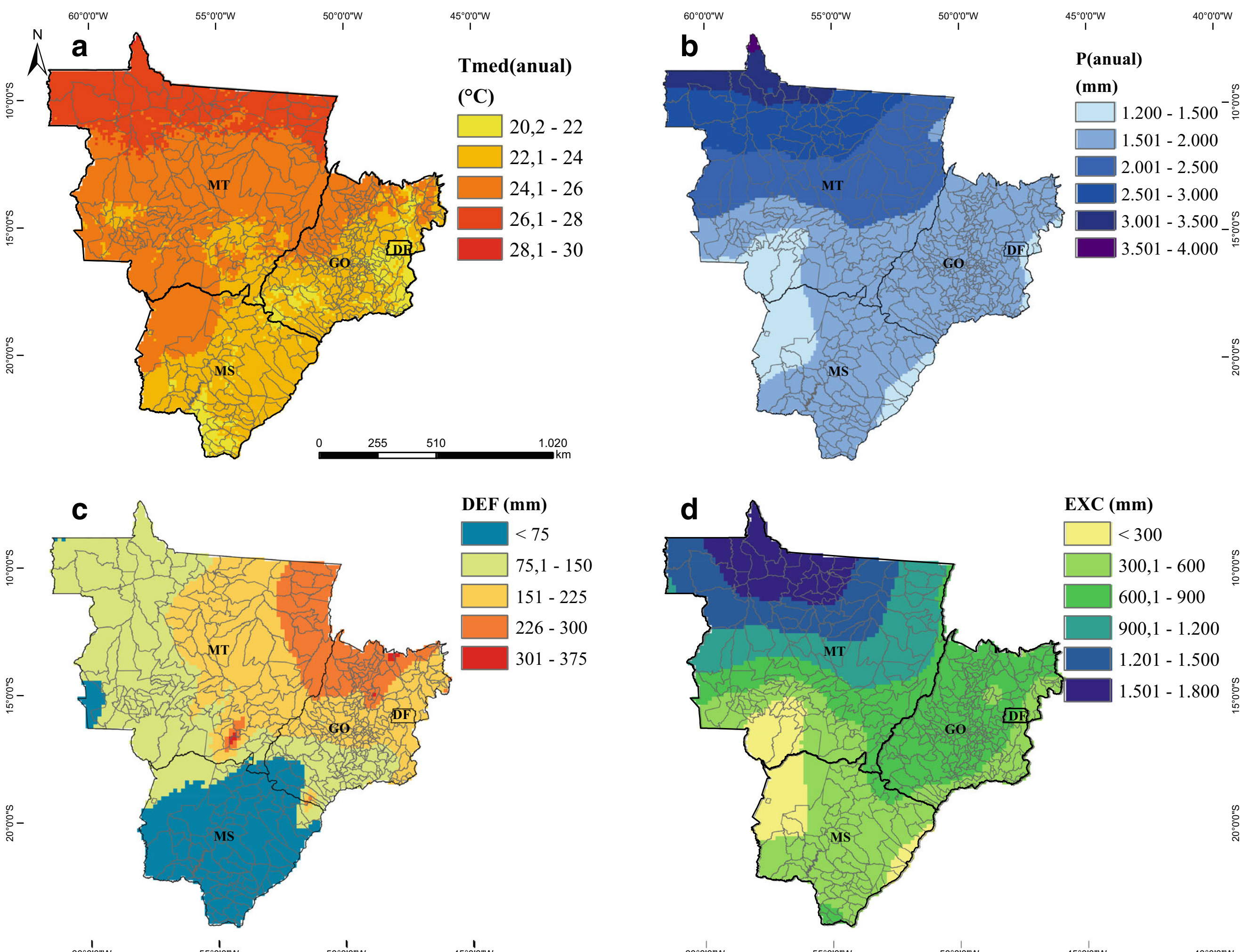

Fig. 5 Spatial variation of annual air temperature (**a**, °C), annual precipitation (**b**, mm), annual water deficit (**c**, mm), and annual water surplus (**d**, mm) for the Midwest region of Brazil

divided into seasons to reach the most accurate classification of climate groups. These seasons were established according to Table 4.

2.5 Geostatistical analysis

Geographic information system allowed spatial interpolation of all climatic elements for all locations, using a kriging method (Krige 1951) with a spherical model, a neighbor, and a spatial resolution of 0.25°. Climate maps for the Köppen and Geiger (1928) and Camargo classifications were obtained from the overlay of maps.

Similarities between both classification systems were evaluated with the climate classes of each system. Water components of different climate classes of each classification were compared using the Tukey's test at 95% reliability. The degree of similarity between classification methods was obtained by agglomerative hierarchical clustering, using the Ward (1963) optimization method, according to all monthly climatic elements together (P, PET, AET, DEF, and SUR).

3 Results and discussion

3.1 Mean temporal variability in the Midwest

The Midwest had a mean air temperature of 24 °C, mean precipitation of 128 mm month^{-1}, and DEF reaching − 56 mm in August. The Federal District and the states of

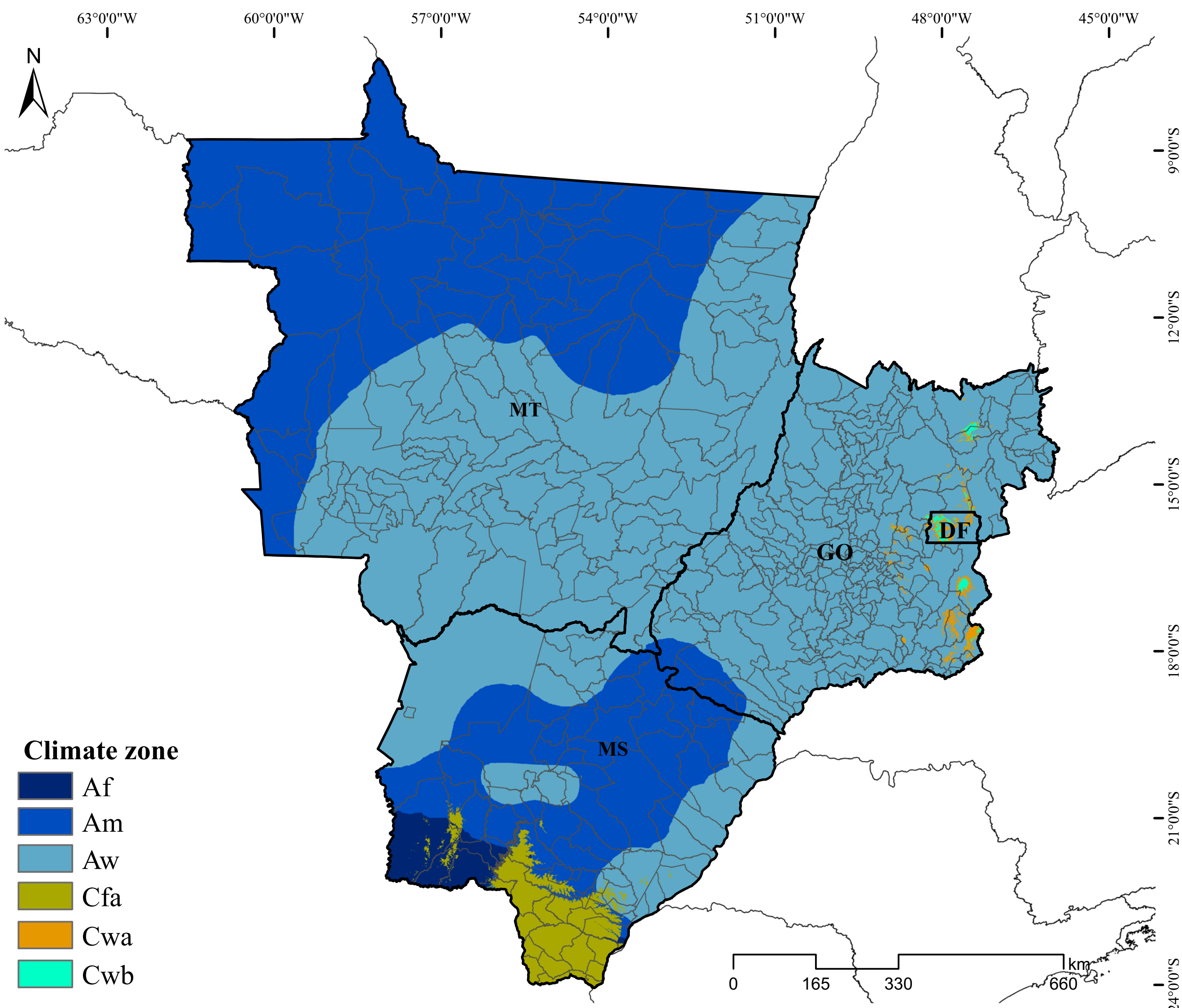

Fig. 6 Köppen and Geiger (1928) climate classification for the Midwest region of Brazil

Goiás and Mato Grosso had a more similar temporal variability. The state of Mato Grosso do Sul showed the lowest T_{AIR}, most constant P in the year, highest PET in the winter, highest mean STO in the year, and lowest DEF (Fig. 4).

The lowest T_{AIR}, P, PET, STO, DEF, and SUR values were observed in the winter in all states. The lowest T_{AIR} values in Mato Grosso and Federal District were close to 23 and 18 °C, respectively, thus presenting an difference of 4 °C between states in the same region. DEF and STO were different between states. Mato Grosso do Sul showed a maximum water deficit close to − 10 mm, while Mato Grosso, Goiás, and Federal District had values lower than − 50 mm. Precipitation showed different total values among the states of the Midwest region, with values of about 50 mm in Mato Grosso do Sul and mean total values of 0 mm in the other states (Fig. 4).

In the Midwest region, the annual T_{AIR} varied spatially from 20.2 (south of Mato Grosso do Sul) to 30 °C (north of Mato Grosso), with predominant values ranging from 24.1 to 26 °C, which correspond to the central region of Mato Grosso and northwest of Mato Grosso do Sul, encompassing the municipalities of Cáceres and Corumbá, respectively. However, the other regions of Mato Grosso do Sul showed T_{AIR} below 24 °C (Fig. 5a). The highest water deficits were observed in the east and northeast regions of Mato Grosso and northwest and west regions of Goiás, with values between 226 and 300 mm. These results are evidenced mainly by higher mean temperatures and lower total precipitations in these regions.

The Midwest showed higher P volumes in the extreme north of Mato Grosso, mainly in the municipalities of Alta Floresta and Nova Monte Verde. In Mato Grosso do Sul, high levels of precipitations were restricted to regions close to the state of Paraná, more precisely in Iguatemi. The lowest P volumes in the Midwest were recorded in the northwest and southwest of Mato Grosso do Sul (Fig. 5b). Mato Grosso presented the highest values of T_{AIR}, P, and SUR. These results reinforce the importance of municipalities, such as Primavera do Leste, Sorriso, and Lucas do Rio Verde, located in Mato Grosso, as the largest grain producers in Brazil (Silva and Marujo 2012).

3.2 Köppen and Geiger (1928) climate classification

The high density of spatial points provided good accuracy in determining climatic types. The Midwest region presented six climate classes, according to Köppen and Geiger (1928) climate classification system: Af, Am, Aw, Cfa, Cwa, and Cwb (Fig. 6). However, the types Aw, which has as characteristics the dry winter and maximum summer precipitations, besides being found in several areas of Brazil (Alvares et al. 2014), and Am, which has a small dry season and under the influence of monsoons (Fig. 7) (Remedio et al. 2019; Jo et al. 2019).

The climate class Aw showed the highest predominance (Fig. 7), reaching 58.50% of the entire region. Cardoso et al. (2014) identified the class Aw from the Köppen classification in the state of Goiás and Federal District. The class Cfa predominated in only three records in the Midwest region, which occurred in the municipalities of Amambai, Iguatemi, and Naviraí in Mato Grosso do Sul (Fig. 6). This climatic class has few dry seasons in the year and hot summer, with a mean air temperature of around 22 °C (Chen et al. 2017; Rubel et al. 2017).

3.3 Camargo climate classification

Camargo (1991) climate classification for the Midwest showed 14 different classes (Fig. 8). The most prevalent

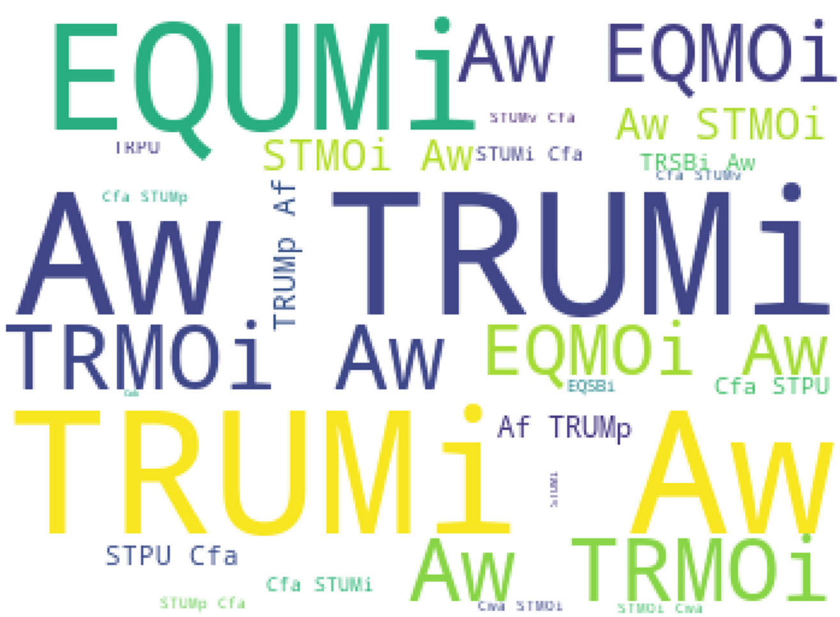

Fig. 7 Frequency diagram for climatic types of the Midwest in the Köppen and Geiger (1928) and Camargo (1991) climate classification systems

climate class was TR-UMi, representing 33.63% of the entire territorial extension. TR-UMi is characterized by being a humid tropical climate with a water deficit in the winter (Rolim and Aparecido 2015).

Among the states in the Midwest region, the climate class EQ-MOi (equatorial monsoon climate) had the highest occurrence in Mato Grosso, encompassing the capital Cuiabá and a small strip of the west and north of Goiás. This climatic type is characterized by annual air temperatures higher than 25 °C, water surplus higher than 200 mm, and water deficiency higher than 150 mm in the region. The climate TR-MOi (tropical monsoon climate) had a high occurrence in Goiás, with small areas in Mato Grosso (Fig. 8). The mean annual air temperature above 18 °C, water surplus above 200 mm, and water deficit above 150 mm stand out among the main characteristics of this climatic type (Rolim and Aparecido 2015). The class TR-UMi predominates in Mato Grosso do Sul and is characterized by a temperature of the coldest month below 20 °C and water deficit below 150 mm, but with different classes in the south of the state (Naviraí, Juti, and Mundo Novo), such as ST-PU, ST-UMi, ST-UMp, ST-UMv, and ST-UMo.

3.4 Comparison between both climate classifications

The comparison between both methods showed that Köppen and Geiger (1928) classified the region into six types of climate, while Camargo (1991) method classified the Midwest into 14 distinct climatic types (Table 5). This higher number of climatic types in comparison to Köppen-Geiger shows that Camargo (1991) classification is very useful on mesoscale or topo-scale, whose effects of topography have a direct effect on climatic elements

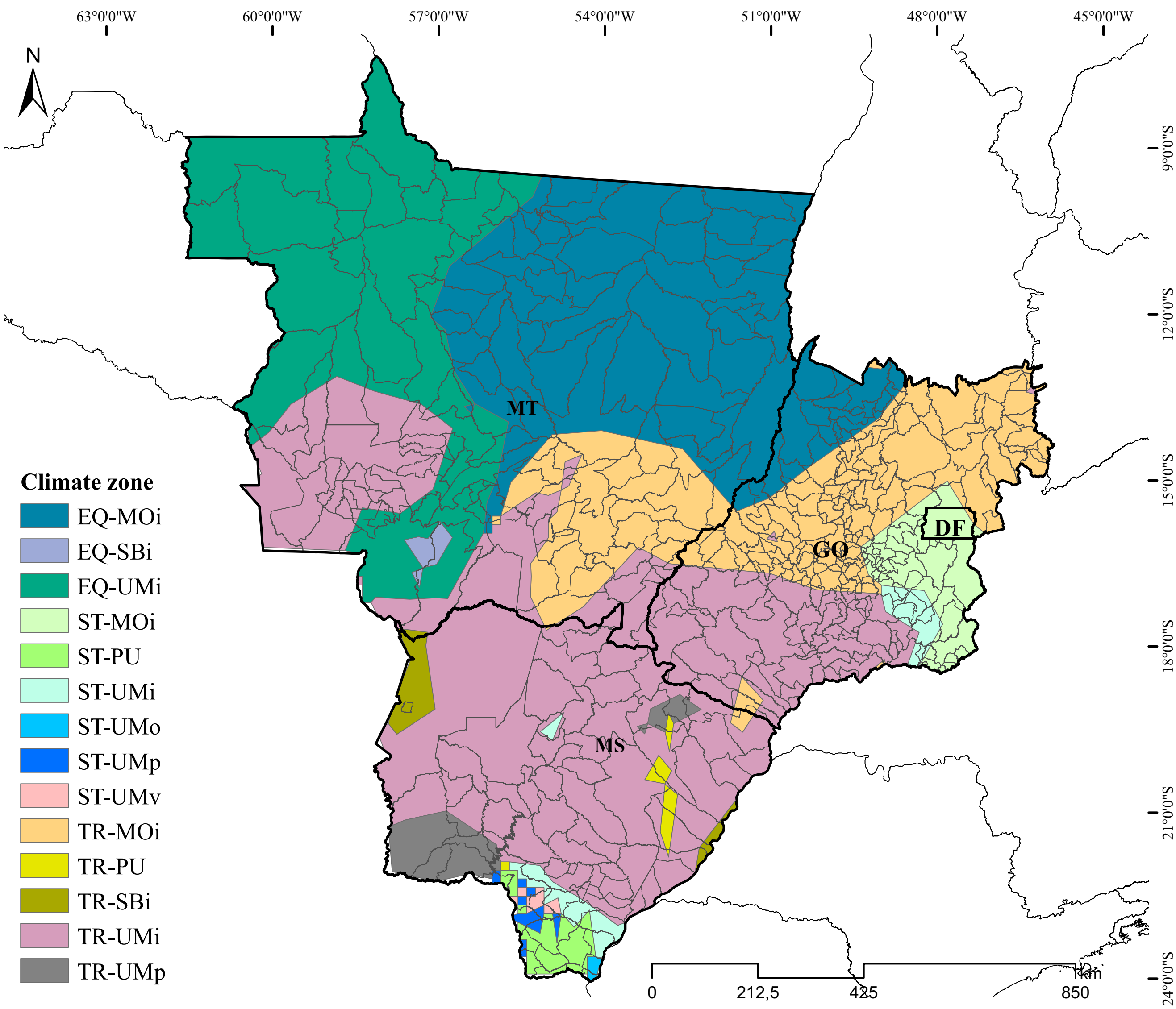

Fig. 8 Camargo (1991) climate classification for the Midwest region of Brazil

Table 5 Correspondence between Köppen and Geiger (1928) and Camargo (1991) climate classes for the Midwest region of Brazil

Köppen and Geiger (1928) climate classes	Camargo (1991) climate classes
Af [1.25%]	TR-UMi [0.14%]
	TR-UMp [1.11%]
Am [37.42%]	EQ-MOi [10.05%]
	EQ-UMi [14.4%]
	ST-UMi [0.09%]
	TR-MOi [0.05%]
	TR-PU [0.28%]
	TR-UMi [12.32%]
	TR-UMp [0.23%]
Aw [58.50%]	EQ-MOi [13.43%]
	EQ-SBi [0.32%]
	EQ-UMi [4.96%]
	ST-MOi [2.55%]
	ST-UMi [0.56%]
	TR-MO [15.01%]
	TR-PU [0.14%]
	TR-SBi [0.74%]
	TR-UMi [20.8%]
Cfa [2.36%]	ST-PU [0.88%]
	ST-UMi [0.46%]
	ST-UMo [0.05%]
	ST-UMp [0.28%]
	ST-UMv [0.23%]
	TR-UMi [0.37%]
	TR-UMp [0.09%]
Cwa [0.38%]	ST-MOi [0.23%]
	TR-MOi [0.14%]
Cwb [0.09%]	ST-MOi [0.09%]

Values within brackets represent the percentage of the predominance of each climate class

and, therefore, on the regional agricultural activity. For example, while Köppen describes most of the climate of the Midwest as Aw (58.50% representativeness), Camargo (1991) method divides it into nine different types of climate: EQ-MOi, EQ-SBi, EQ-UMi, ST-MOi, ST-UMi, TR-MO, TR-PU, TR-SBi, and TR-UMi (Fig. 9).

Therefore, it proves that Köppen and Geiger (1928) climate classification method has a macro-scale approach and may not be useful for agricultural purposes because it generalizes the variability of climate conditions and uses no soil water information. This result has also been found by other authors, such as Rolim et al. (2007), Aparecido et al. (2016), and Rolim and Aparecido (2015). The economy of the Midwest region is focused on agricultural production (Silva and Marujo 2012), showing the importance of farmers to use Camargo (1991) climate classification for agricultural planning.

3.5 Water balance by Köppen and Geiger (1928) and Camargo (1991)

For more details, we compared the water balance between climate classes within both climate classification

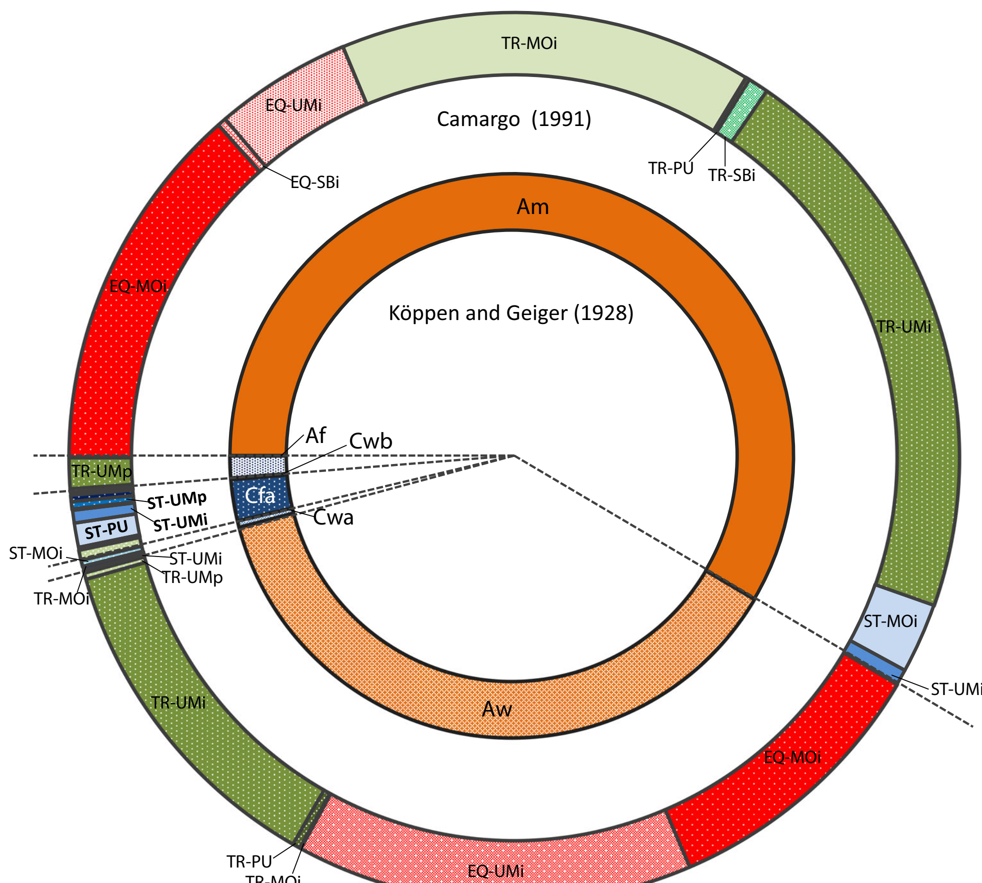

Fig. 9 Correspondence between Camargo (1991) and Köppen and Geiger (1928) climate classification systems for the Midwest region of Brazil

systems. Camargo (1991) method showed that the climatic types EQ-UMi and EQ-MOi had the highest water surplus rates, while TR-SBi and EQ-SBi showed the lowest water surplus. The similarity between these classes was also observed in the dendrogram (Fig. 11b). The climate EQ-SBi showed high levels of water deficit and low water surplus, which characterized it as a potentially dry class (Fig. 10A). Köppen and Geiger (1928) method showed that the class Am has high water surplus rates, with annual values of around 1120 mm y^{-1}, and water deficiency close to − 100 mm y^{-1}. Climate classes with the lowest water deficits were Cfa and Af. The other climate classes showed similar deficits (Fig. 10B). Water deficit is an important variable for agriculture, which is related to the yield and quality of several crops (Martins et al. 2015; Moreto et al. 2015; Moreto et al. 2017) (Fig. 11).

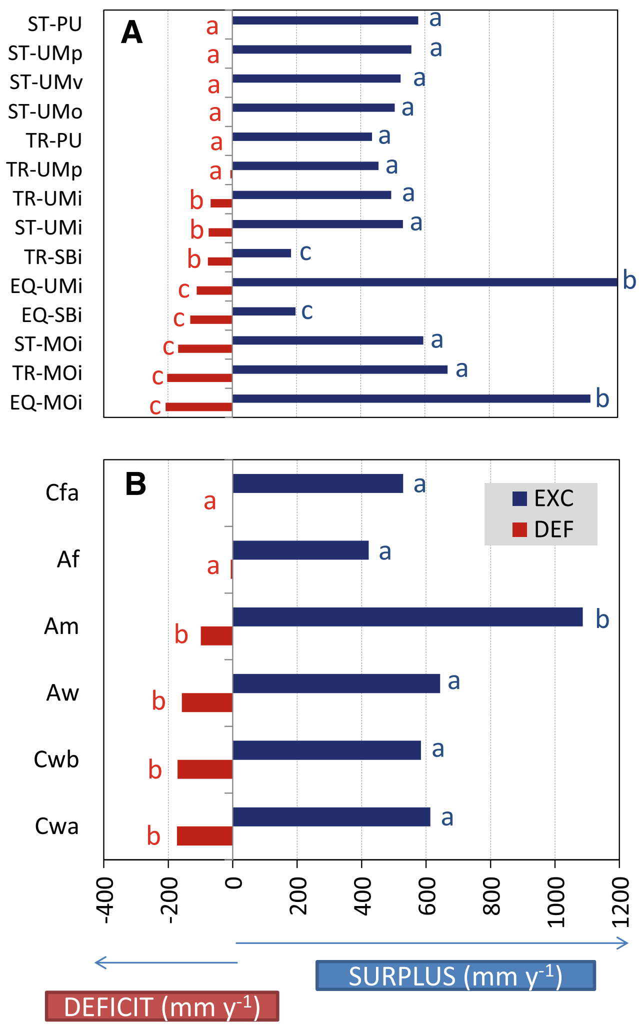

Fig. 10 Comparison of water components between Camargo (1991) (**A**) and Köppen and Geiger (1928) (**B**) climate classification systems for the Midwest region of Brazil

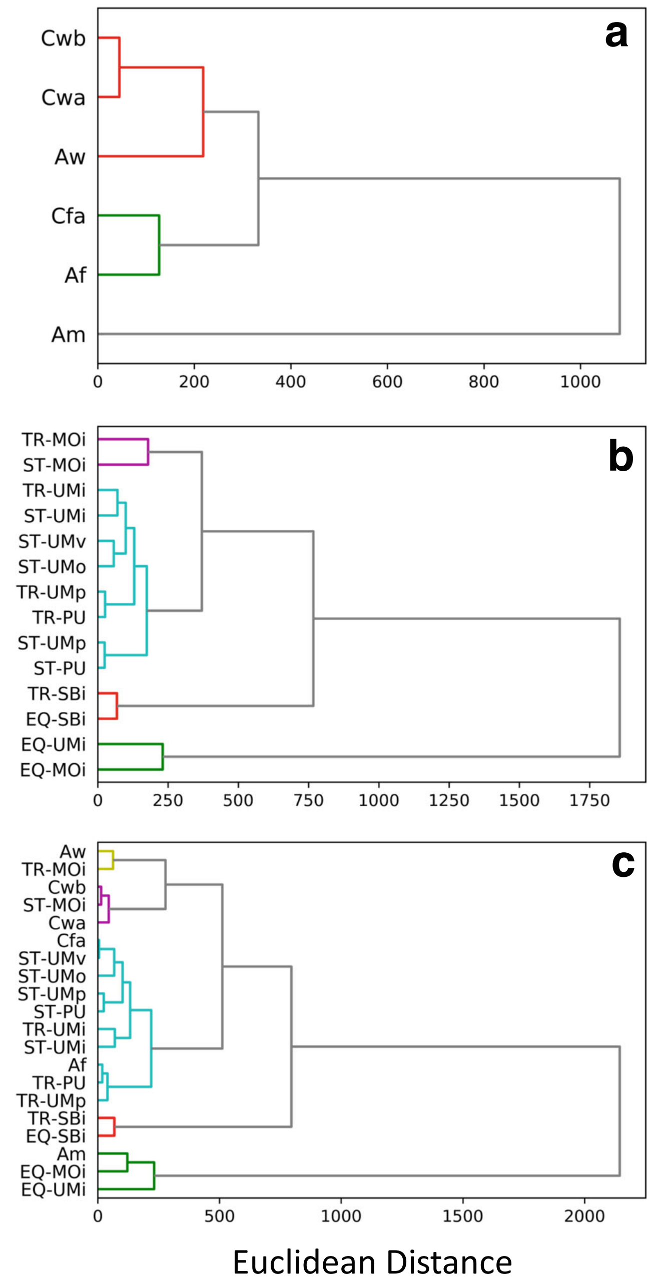

Fig. 11 Cluster analysis dendrogram from climate indicators (mean monthly air temperature, precipitation, and water surplus and deficit) based on the Ward (1963) optimization method for different types of climate. **a** Köppen and Geiger (1928) climate; **b** Camargo climate; **c** Comparison between Köppen and Geiger (1928) and Camargo

4 Conclusions

Climate classification of the Midwest region by Camargo (1991) showed the predominance of 14 different climatic types. The most prevalent climate class was TR-UMi (humid tropical climate), reaching 33.63% of the entire territorial extension of the Midwest region of Brazil. Köppen and Geiger (1928) climate classification method showed the presence of six climatic types in the Midwest region, with a higher dominance for the class Aw (tropical climate), representing 58.50% of the entire region. Aw is characterized by having a rainy season in the summer and drought in the winter.

Köppen and Geiger (1928) proved to be a macroscale classification, while Camargo (1991) has a mesoscale approach. Areas classified as Am by Köppen and Geiger (1928) presented seven climatic types when using Camargo (1991) method: EQ-MOi, EQ-UMi, ST-UMi, TR-MOi, TR-PU, TR-UMi, and TR-UMp. In the Midwest of Brazil, the most important activity is agriculture; therefore, Camargo (1991) method is more suitable for climate classification in the region since it provides information on local climatological water balance and greater detail in climate. Thus, it improves decision-making and crop planning.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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