Theoretical and Applied Climatology
https://doi.org/10.1007/s00704-020-03367-1

ORIGINAL PAPER

Agricultural zoning as tool for expansion of cassava in climate change scenarios

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Received: 20 March 2020 / Accepted: 25 August 2020

Abstract

Improvement of planting season and crop growth time, considering climatic and soil needs of plants, is important to increase cassava (*Manihot esculenta*) production in Midwestern Brazil. Thus, we sought to develop an agricultural zoning for cassava cultivation in the Midwest of Brazil in different climate change scenarios. Mean air temperature and precipitation data from localities of the Midwest of Brazil were obtained from the Brazilian National Institute of Meteorology (INMET). Clay (%) data from localities of the Midwest of Brazil were obtained from SoilGrids. Regions where the air temperature was within the range from 20 to 27 °C were considered climatically favorable for commercial exploitation of cassava, in addition to precipitation between 1000 and 1500 mm year^{-1}, and clay content was less than ≤ 35%. Moreover, regions with air temperature below 16 °C and above 38 °C, precipitation below 1000 mm and above 1500 mm year^{-1}, and clay content > 35% were considered unsuitable for cassava cultivation. Raster or matrix images, corresponding to mean annual air temperature, annual precipitation, and clay (soil), were superimposed to create cassava suitability classes, according to crop requirements. The climate change scenarios were established by changing the air temperature (°C) and rainfall (mm). The air temperature was increased by 1.5, 3.0, 4.5, and 6.0 °C as adopted by Pirttioja et al. (Clim Res 65:87–105, 2015). We changed in precipitation − 30, − 15, + 15, and 30% according to the future projections simulated by the IPCC (2014). Maps were made using geographic information systems. In the states of Mato Grosso do Sul, Mato Grosso, and Goiás, mean precipitation was around 1200 to 4000 mm year^{-1}. Northern Mato Grosso showed the highest annual precipitation, with values above 3500 mm. A large extension of the Midwest region of Brazil is climatically and soil favorable for cassava. The Midwest is a region with high rainfall, so we recommend planting in well-drained soils to avoid phytosanitary problems. Producers taking this care can plant cassava in 86.6% of the territory. The climate change scenarios demonstrated different Agriculture zonings for cassava in the Midwest of Brazil. With the increase in air temperature, greater marginal classes occurred, but cassava is resistant to this condition. But, this increase in temperature can reduce the cycle and consequently reduce production.

1 Introduction

Studies on climate influence on agricultural production have been essential to support crop adaptation to climate variability effects and subsidize rural planning (de Oliveira Aparecido et al. 2020). Besides influencing crop growth, development, and yield, climate affects relationships between plants with microorganisms, insects, fungi, and bacteria, favoring or not

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Published online: 01 September 2020

pests and diseases, which require suitable control measures (Sentelhas and Monteiro 2009).

Thus, the climate is an important factor of agricultural yield, characterized mainly by the hydro and thermal meteorological elements (Quaye et al. 2018). Therefore, the effects of climate change will have significant impacts on the yield and management of agricultural crops (Chatzopoulos and Lippert 2015; Arshad et al. 2017). The Intergovernmental Panel on Climate Change (IPCC 2018) declares with high confidence that global warming is expected to reach 1.5 °C between 2030 and 2052, mainly attributed to the increase in greenhouse gas emissions (Adefisan 2018).

Some cultures are more tolerant than others to certain types of stress and, at each phenological stage, different types of stress affect each crop species in different ways (Hernandez-Espinoza and Barrios-Masias 2020). The cassava is an important food security crop in many parts of the developing world (de Oliveira et al. 2020), bearing in mind that approximately 800 million people in the world eat cassava (Rocha et al. 2020).

Cassava root is the third-largest source of carbohydrate for human consumption worldwide (Ramcharan et al. 2017). It is considered important for food security, as its harvest occurs throughout the year, growing well with a minimal water supply and being easily propagated (Atwijukire et al. 2019). Regarding the economic production, table cassava is harvested, preferably, with one cycle (10 to 12 months), while industrial cassava is harvested with one or two cycles (18 to 24 months) (Silva et al. 2012).

Brazil is the world's fourth-largest cassava producer (Moreto et al. 2018; Rocha et al. 2020), with a production of 18.88 million tons in 1.32 million hectares of planted area. The lowest cassava production is found in the Midwest region, with 1.19 million tons cultivated in an area of 65,229 ha

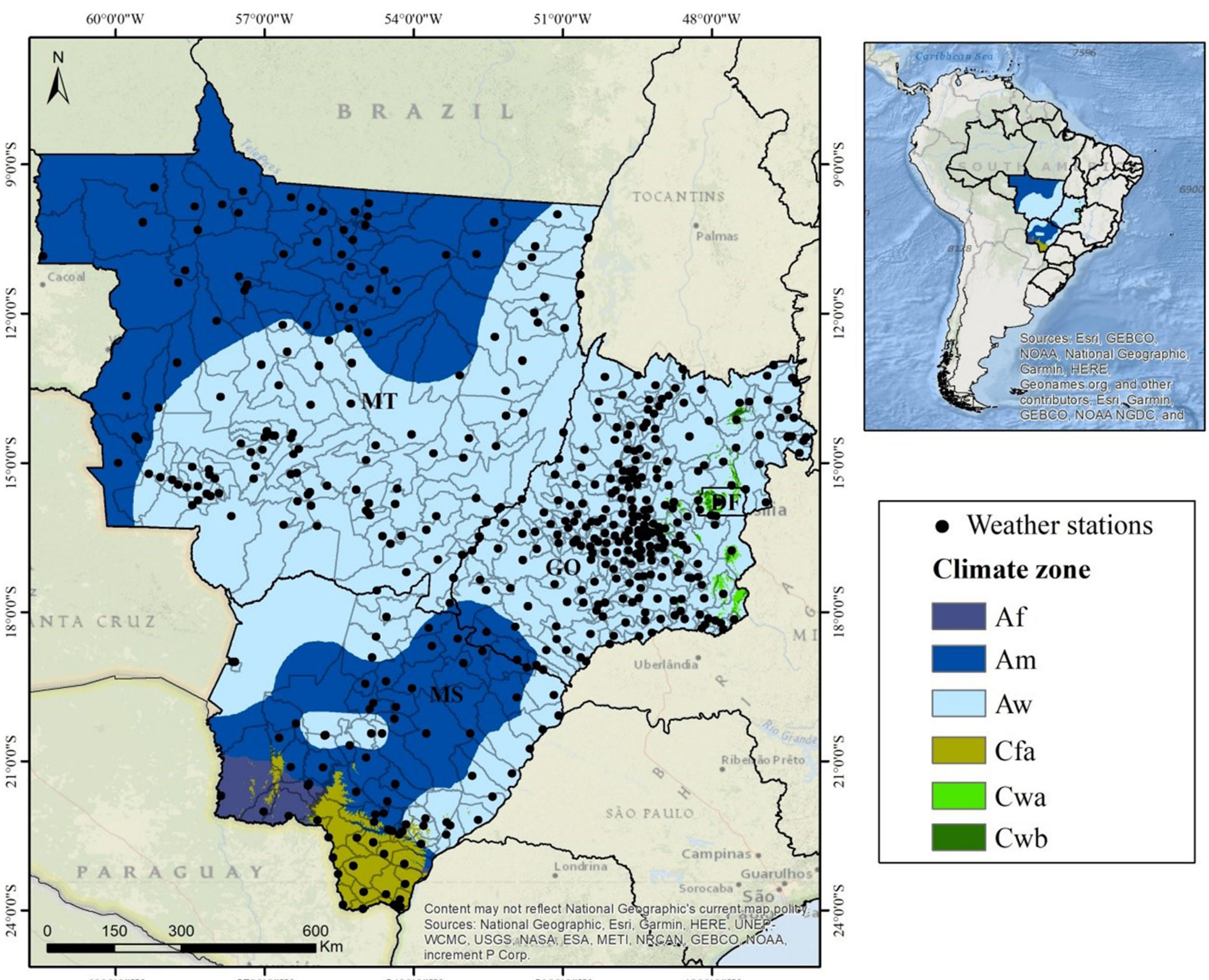

Fig. 1 Spatial distribution of weather stations in Midwestern regions Brazil. DF is Distrito federal, GO is Goias, MS is Mato Grosso do sul, and MT is Mato Grosso

(IBGE 2018), while the North region is the largest producer, with 7.21 million tons.

The Midwest of Brazil is an example of an agricultural frontier region, consolidated as a modern agro-industrial production area with a robust economic dynamism (Guimarães and Leme 2002). Its high production potential is related to favorable climatic conditions (Helfand et al. 2015). The share of agricultural activities in the Midwest region in the Brazilian gross domestic product grew from 7.4% in 1970 to 19.5% in 2009 (Castro 2014). Midwest of Brazil is a region where cassava can be strongly expanded and planted.

Adjusting planting date and crop growth time based on climatic requirements of plants has a direct relationship with crop production increases. Cassava requires a warm climate and well-drained soils to enhance its root development and yield (El-Sharkawy 2007). Although it is considered a drought-tolerant species, its growth and productivity are reduced by prolonged periods of drought (Alves 2006). Plants respond to water stress at morphological, physiological, cellular, and metabolic levels. Such responses depend on stress duration and severity, plant genotype, development stage, and type of cell or organ in question (Bray 1994).

Since climate elements widely vary in space, an agroclimatic zoning becomes important for agricultural planning, mainly for precipitation and air temperature (de Aparecido et al. 2019). This tool consists of determining suitable locations for cultivation of a species of interest, considering its agroclimatic requirements and macroclimatic information (Pereira et al. 2002). In areas where agroclimatic zoning is done, there is a greater likelihood of success in terms of crop yield (Nabati et al. 2020).

Some agroclimatic zoning studies have been found in the literature such as for irrigated rice in the state of Rio Grande do Sul (Klering et al. 2008), rubber cultivation in the Southeast and Midwest of Brazil (Pilau et al. 2007), and sugarcane in the state of Minas Gerais (Almeida et al. 2013). The effects of climate change are environmental, economic, and social for the country and therefore need to be studied. Given the lack of studies on cassava agriculture zoning in Brazil, especially with climate change, our study aimed to develop agriculture zoning for cassava cultivation in different climate change scenarios.

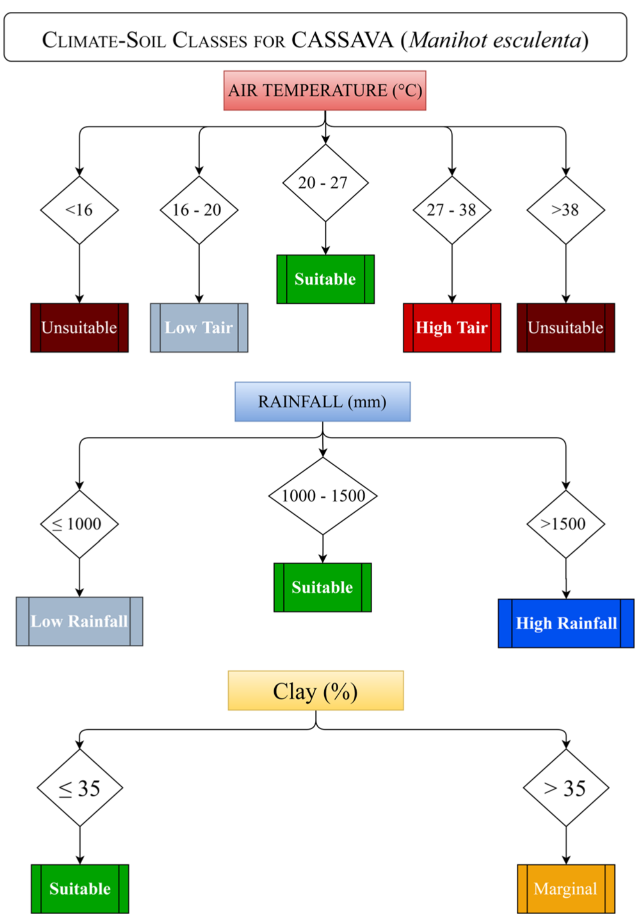

Fig. 2 Climatic soil classification key used in cassava zoning. *Tair* is mean annual air temperature

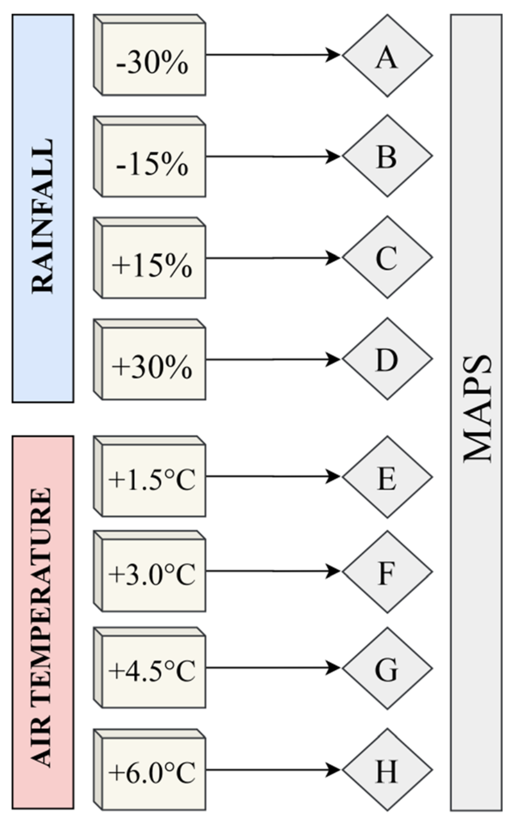

Fig. 3 Scenarios of climatic changes simulated to establish zoning cassava

2 Material and methods

2.1 Characterization of the study area

We considered the Midwest region of Brazil composed by the states of Mato Grosso, Mato Grosso do Sul, and Goiás, plus the Federal District, for agroclimatic zoning of cassava (Fig. 1). In this region, cassava cultivation is of high interest for starch agroindustry and as alternative source of income for family farmers. There, the most prevalent climatic class is Aw, according to Köppen's classification, with annual means of precipitation of 1534.5 ± 336.5 mm and air temperature of 22.1 ± 2.97 °C.

2.2 Climatic data

Monthly air temperature and precipitation data were obtained from 406 weather stations and database from the Brazilian National Institute of Meteorology (INMET), National Department of Construction Works Against Drought (DNOCS), and Food and Agriculture Organization of the United Nations (FAO/UN) (FAO 2001). These data were used to characterize agroclimatic conditions of cassava cultivation in the region (Fig. 1). For that, we selected the climatic variables that most influence cassava production (Doorenbos and Pruitt 1977; Ayoade 1983).

Air temperature data is crucial for linear estimation models based on correlations between altitude and geographic coordinates (latitude and longitude), obtaining the matrix image of the mean temperature for the Midwest region through multiple linear regression (Eq. 1). Precipitation data allowed spatial interpolation by ordinary kriging method, with statistical fit to spherical semivariogram model, with a smaller error between estimations. The input raster of annual mean precipitation zoning in the region was created from the semivariogram model.

$$T = \beta + \beta 1 \times \gamma 1 + \beta 2 \times \gamma 2 + \beta 3 \times Z \quad (1)$$

wherein T is the mean temperature (°C), β is the intercept, $\beta 1$ is a coefficient, γ is the latitude (decimal degrees), $\beta 2$ is a coefficient, $\gamma 2$ is the longitude, $\beta 3$ is a coefficient, and Z is the altitude (m).

Table 1 Statistical parameters for multiple linear regression to estimate mean air temperature (°C) in the Midwest region of Brazil

Parameter	Coefficient	*t* statistic	*P* value
Intercept (β)	29.1811	67.78	4.475×10^{-222}
Longitude ($\gamma 2$)	− 0.0323	− 4.34	1.838×10^{-05}
Latitude (γ)	0.3254	54.37	2.193×10^{-187}
Altitude (Z)	− 0.0039	− 36.55	7.464×10^{-130}

Altitude data, characterized as digital elevation model (DEM), were obtained from the Topodata project (de Morisson and de Fátima 2012), which provides refined SRTM (shuttle radar topography mission) data by kriging for the entire Brazilian territory, with a spatial resolution of 30 m.

2.3 Soil data

We used the soil profile information generated by the SoilGrids system on a 250-m scale to map the clay content (Hengl et al. 2017). This system provides global predictions for numerical properties of soil pattern such as organic carbon, bulk density, cation exchange capacity (CTC), pH, soil texture fractions, and coarse fragments at seven standard depths (0, 5, 15, 30, 60, 100, and 200 cm).

2.4 Agroclimatic soil zoning

Raster or matrix images, corresponding to mean annual temperature, annual precipitation, and clay (soil), were superimposed to create cassava suitability classes, according to crop requirements (Fig. 2). The final zoning map was then analyzed considering climatically and clay content favorable regions for cassava. We consider favorable when air temperature required for commercial exploitation of the crop ranges from 20 to 27 °C, precipitation from 1000 to 1500 mm year^{-1}, and clay content less than ≤ 35%. Regions with air temperatures lower than 16 °C and higher than 38 °C, precipitation lower than 1000 mm and higher than 1500 mm, and clay content > 35% were considered unsuitable for cassava cultivation (Peixoto 2009).

Cassava phenology and planting season were adapted for the Midwest region based on studies carried out in the region, such as Alves (2006).

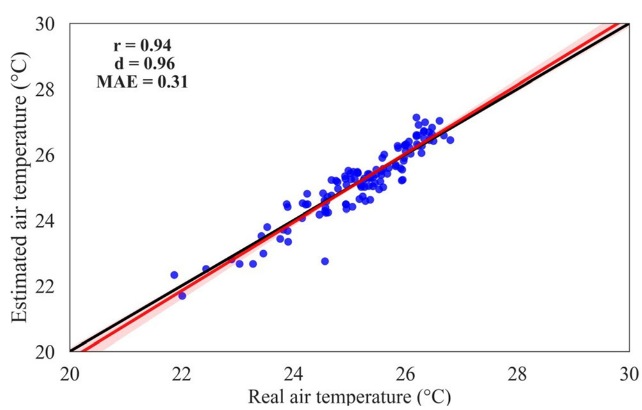

Fig. 4 Statistical determination to estimate the mean air temperature (°C) in the Midwest region of Brazil. *r* is correlation coefficients, *d* is Willmott agreement, MAE is mean absolute error

Table 2 Mean monthly air temperature and precipitation in the Midwest region of Brazil

State	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
Air temperature (°C)													
DF	21.90	21.90	21.50	20.90	19.50	18.50	18.30	20.20	21.80	22.70	22.50	22.00	20.98
GO	24.02	24.02	23.69	22.94	21.33	20.32	20.23	22.12	23.65	24.61	24.47	24.10	22.96
MS	25.17	25.10	24.46	22.60	20.02	18.70	18.72	20.64	22.23	23.68	24.53	24.94	22.57
MT	25.95	25.92	25.70	25.13	23.67	22.84	22.91	24.88	26.21	27.14	26.90	26.33	25.30
Precipitation (mm)													
DF	254.00	213.00	194.00	109.00	29.00	6.00	8.00	9.00	42.00	156.00	240.00	272.00	1532.00
GO	294.82	230.78	211.97	111.42	37.77	9.22	8.67	15.30	53.56	168.09	257.12	301.17	1699.91
MS	204.33	170.40	149.69	105.93	112.36	72.82	47.72	62.35	106.19	183.07	180.42	213.00	1608.29
MT	309.29	286.12	299.11	148.42	58.42	21.44	11.58	26.36	125.38	201.51	283.43	304.86	2075.92

DF Distrito Federal, *GO* Goias, *MS* Mato Grosso do Sul, *MT* Mato Grosso

2.5 Climate change scenarios

The climate change scenarios were established by changing the air temperature (°C) and rainfall (mm). The air temperature was increased by 1.5, 3.0, 4.5, and 6.0 °C as adopted by Pirttioja et al. (2015). We changed in precipitation −30, −15, +15, and 30% according to the future projections simulated by the IPCC

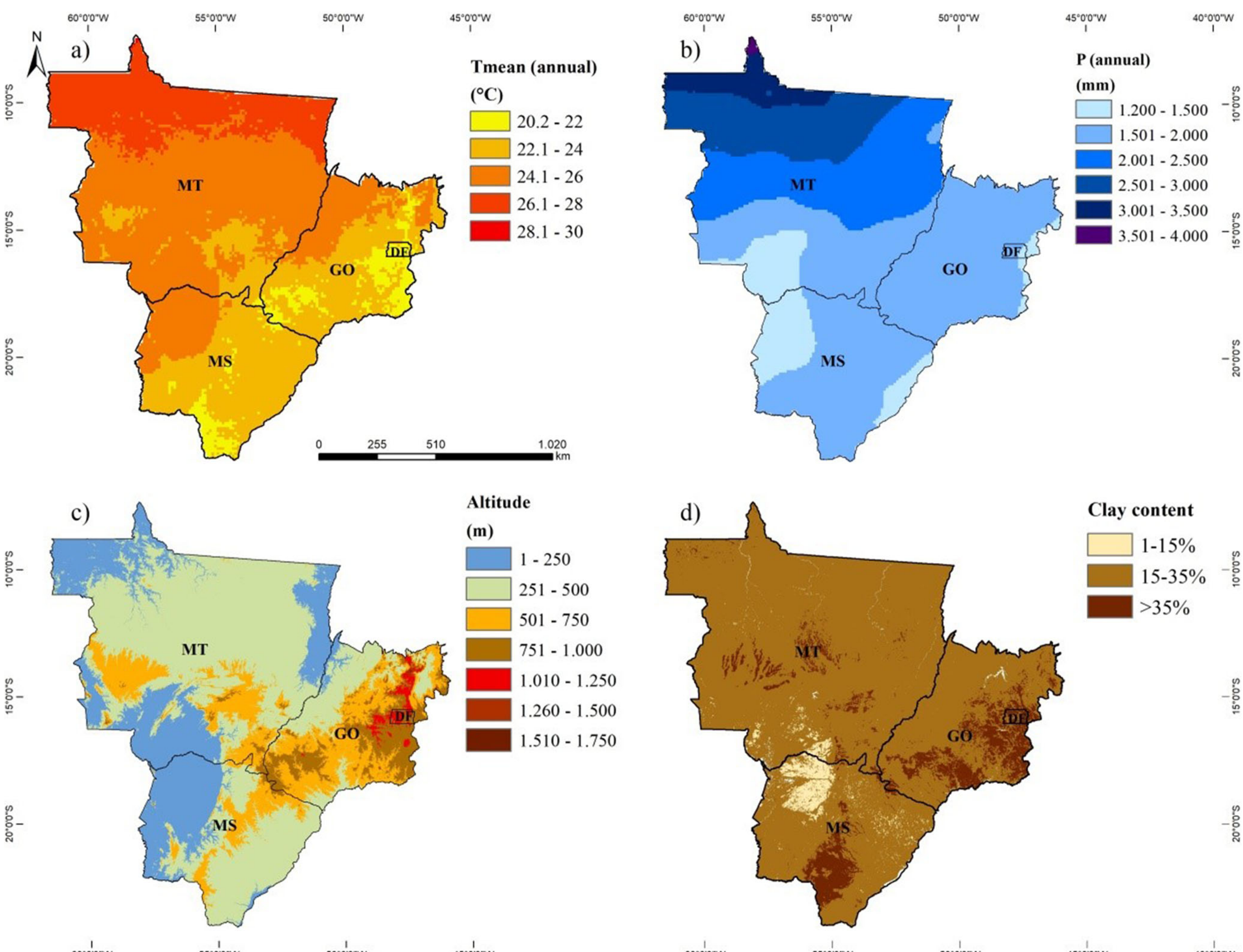

Fig. 5 Spatial variability of mean annual air temperature (a), annual precipitation (b), altitude (c), and clay (d) in the Midwest region of Brazil

(2014). We established the agricultural zoning of cassava for all these 8 scenarios (Fig. 3).

3 Results and discussion

Estimation model performance for mean air temperature in Midwestern Brazil was satisfactory, with correlation coefficients (*r*) of 0.94, Willmott agreement (*d*) of 0.96, and mean absolute error (MAE) of 0.31 (Fig. 4). Several authors in the crop modeling area have demonstrated that correlations above 0.80 are satisfactory (Moreto and Rolim 2015; de Oliveira Aparecido et al. 2018). The estimation model was significant at 1%, and its respective coefficients are shown in Table 1.

Mean annual air temperatures in the Midwest ranged from 20.2 to 30 °C (Fig. 5). July is the month with the lowest air temperature and rain in the Midwest (Table 2). Northern, northwestern, and northeastern Mato Grosso had the highest mean annual air temperatures, above 28 °C (Fig. 5(a)). Southern and eastern Mato Grosso presented milder air temperatures, ranging from 20.2 to 24 °C.

An increased air temperature directly interferes with soil temperature. Bud sprouting occurs at air temperatures preferably around 28–30 °C and growth stoppage occurs at soil temperatures above 37 °C and below 17 °C (El-Sharkawy 2007; Gabriel et al. 2014a).

In the states of Mato Grosso do Sul, Mato Grosso, and Goiás, mean precipitation ranged from 1200 to 4000 mm year^{-1} (Fig. 5(b)). Northern Mato Grosso had the highest annual precipitation, above 3500 mm. Western Mato Grosso do Sul and part of its eastern region had the lowest precipitation, between 1200 and 1500 mm year^{-1} (Fig. 5(b)). All states had precipitation levels suitable for cassava development, according to Jiang et al. (2018). Cassava is commonly grown in areas with precipitations below 800 mm year^{-1}, with a dry period from 4 to 6 months, which is important for flour storage (Pipatsitee et al. 2018).

The state of Goiás has the highest areas located mainly in the eastern region, with altitude values above 1260 m. On the other hand, the lowest altitudes occur in northwestern Mato Grosso and western Mato Grosso do Sul, with values lower than 250 m (Fig. 5(c)). In the Midwest, the greatest predominance of clay occurs from 15 to 35% (Fig. 5(d)).

Air temperature and precipitation variations in the Midwest also characterize its regional biome. In this sense, the Amazon biome predominates in areas with higher precipitations and air temperatures, while the Pantanal biome is observed in parts of Mato Grosso and Mato Grosso do Sul where lower water supply is predominant (Fig. 6). Nevertheless, the Cerrado biome extends over most of the Midwest region.

The results showed that phenology characteristics are different between Mato Grosso do Sul and the other states (Fig. 7). Thus, such differences were considered to distinguish planting seasons and duration of cassava phenological stages. In the states of Mato Grosso and Goiás, stages 1, 2, 3, and 4 were observed in October, while in Mato Grosso do Sul, it

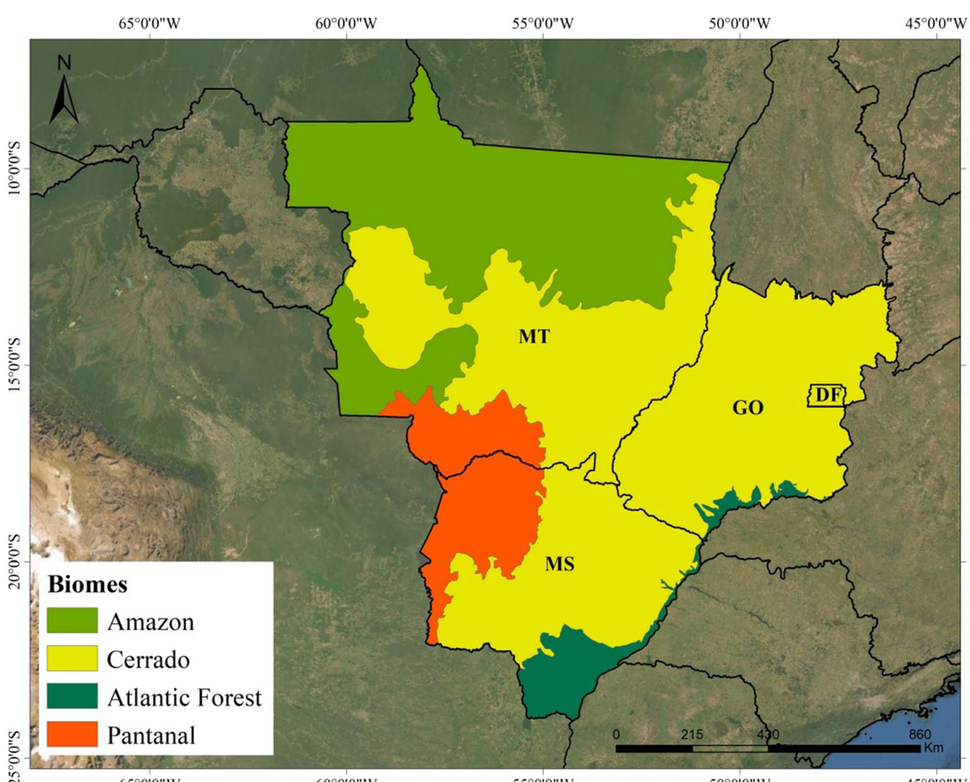

Fig. 6 Spatial variability of biomes in the Midwest region of Brazil

only occurred in April, mainly due to high air temperature needs for root development and beginning of emergence. Thus, such results show a 6-month difference for cassava development between these states. There is also a planting window between April and the end of October in Mato Grosso do Sul, mainly because precipitation is more regular for cassava cultivation in this state. In the other regions, such planting window occurs between October and the end of March, which gives Mato Grosso do Sul an additional month for planting cassava.

Parts of eastern and western Mato Grosso do Sul and southwestern Mato Grosso showed ideal areas for cassava cultivation, mainly for having water resources, clay content, and air temperatures favorable to crop growth and low pest proliferation (Fig. 8). Suitable areas represent 10.1% of the entire territory of the Midwest of Brazil. Corumbá–MS, Cáceres–MT,

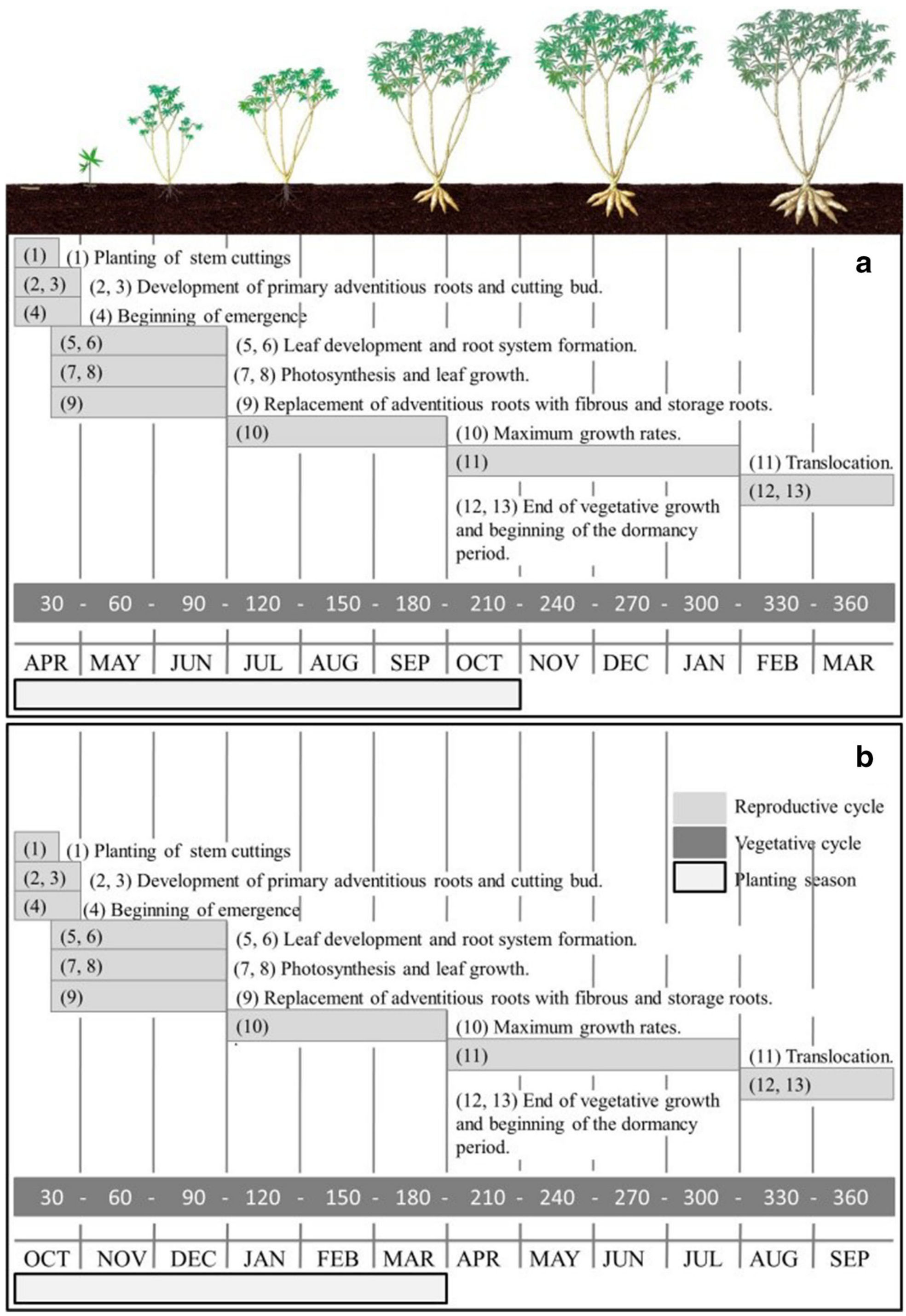

Fig. 7 Phenology of cassava crop in Mato Grosso do Sul (**a**) and Mato Grosso and Goiás (**b**) in the Midwest region of Brazil

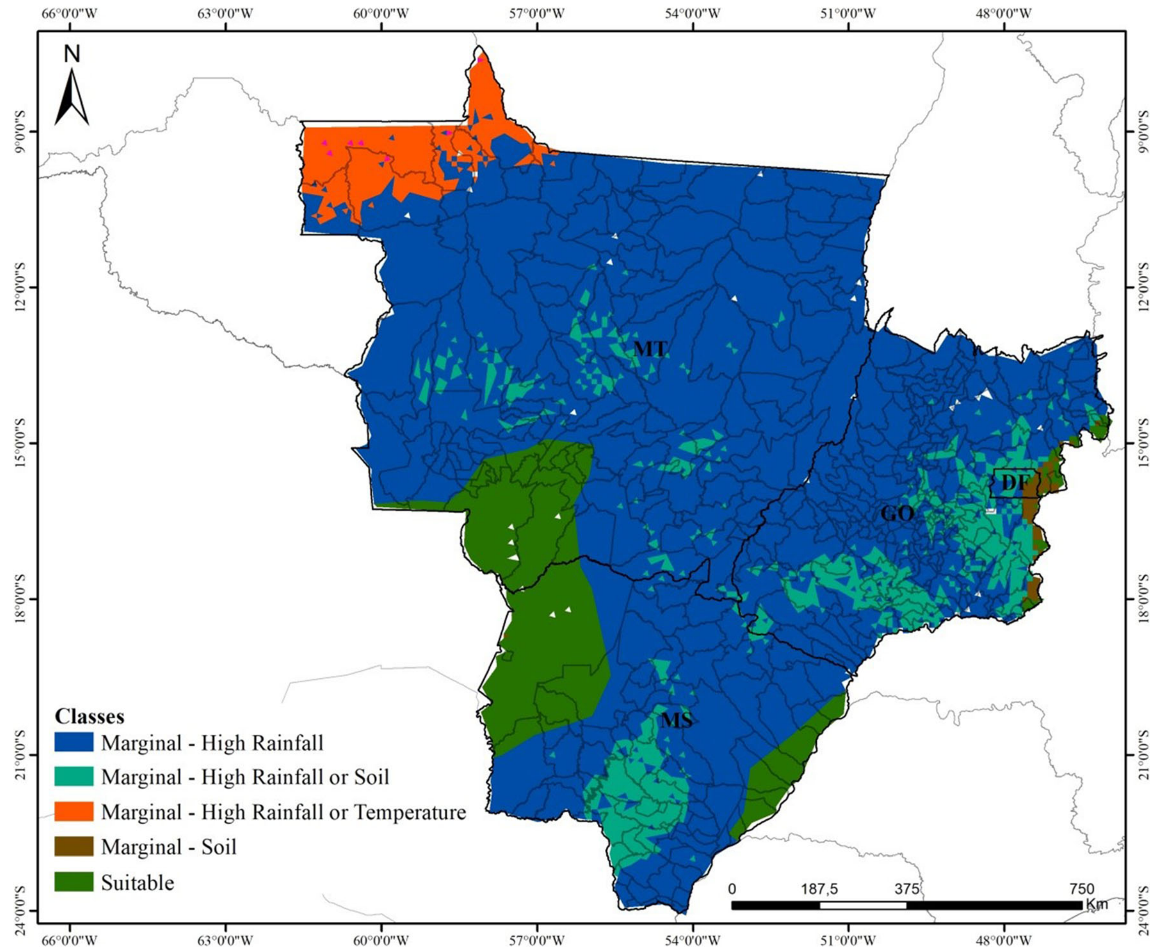

Fig. 8 Agriculture zoning of cassava for the Midwest region of Brazil. DF is Distrito federal, GO is Goias, MS is Mato Grosso do Sul, and MT is Mato Grosso

and Poconé–MT are locations in these areas considered suitable for cassava cultivation. These states are major producers according to IBGE (2018). Cassava yields in the Mato Grosso do Sul, Goiás, and Mato Grosso, and the Federal District were 21718, 15151, 14508, and 16431 kg ha^{-1}, respectively.

Much of the region showed high rainfall, so some precaution care must be taken mainly with regard to excess moisture

Table 3 Area of agriculture zoning of cassava for the Midwest region of Brazil in different climate change scenarios

Classes	Area (%)								
	Current	P (− 30%)	P (− 15%)	P (+ 15%)	P (+ 30%)	T (+ 1.5 °C)	T (+ 3.0 °C)	T (+ 4.5 °C)	T (+ 6.0 °C)
Suitable	10.1	58.8	62.8	9.2	1.0	8.5	4.8	0.1	0.0
Marginal - soil	0.4	4.9	8.2	0.1	0.0	0.4	0.4	0.0	0.0
Marginal - high rainfall	76.5	1.2	22.3	77.4	85.6	73.5	27.5	2.8	0.0
Marginal - high rainfall or soil	8.6	0.0	0.8	8.8	8.9	8.0	7.0	0.4	0.0
Marginal - high rainfall and temperature or soil	0.0	0.0	0.0	0.0	0.0	0.5	1.5	8.1	8.5
Marginal - high rainfall or temperature	4.3	1.2	4.4	4.4	0.0	8.7	53.5	78.3	81.1
Marginal - high temperature	0.0	3.3	0.0	0.0	0.0	0.3	5.2	9.9	10.0
Marginal - high temperature or soil	0.0	0.0	0.0	0.0	4.4	0.0	0.0	0.4	0.4
Marginal - low rainfall	0.0	26.5	1.5	0.0	0.0	0.0	0.0	0.0	0.0
Marginal - low rainfall or soil	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

in the soil. These regions are considered marginal and this warns producers regarding decision-making and the crop management (planting in well-drained soils). Moisture accumulation should be avoided since it causes emergence of diseases in cassava such as root infection by *Phytophthora drechsleri*, a fungus that affects young and adult plants (de Muniz et al. 2006). We observed that 76.5% of the entire territory showed high rainfall (Table 3) and the most predominate climate in these areas is AW (Fig. 1).

Restricted areas were found in northwestern of Mato Grosso due to high air temperatures and precipitations. Such conditions lead to the rise of diseases such as those caused by *Cercosporidium henningsii*, *Cercospora vicosae*, and *Phaeoramularia manihotis* (Bos 1978), which can drastically reduce production of cassava in this region. We note that this class represents 4.3% of the Midwest (Table 3) and the Amazon biome is predominant (Fig. 6).

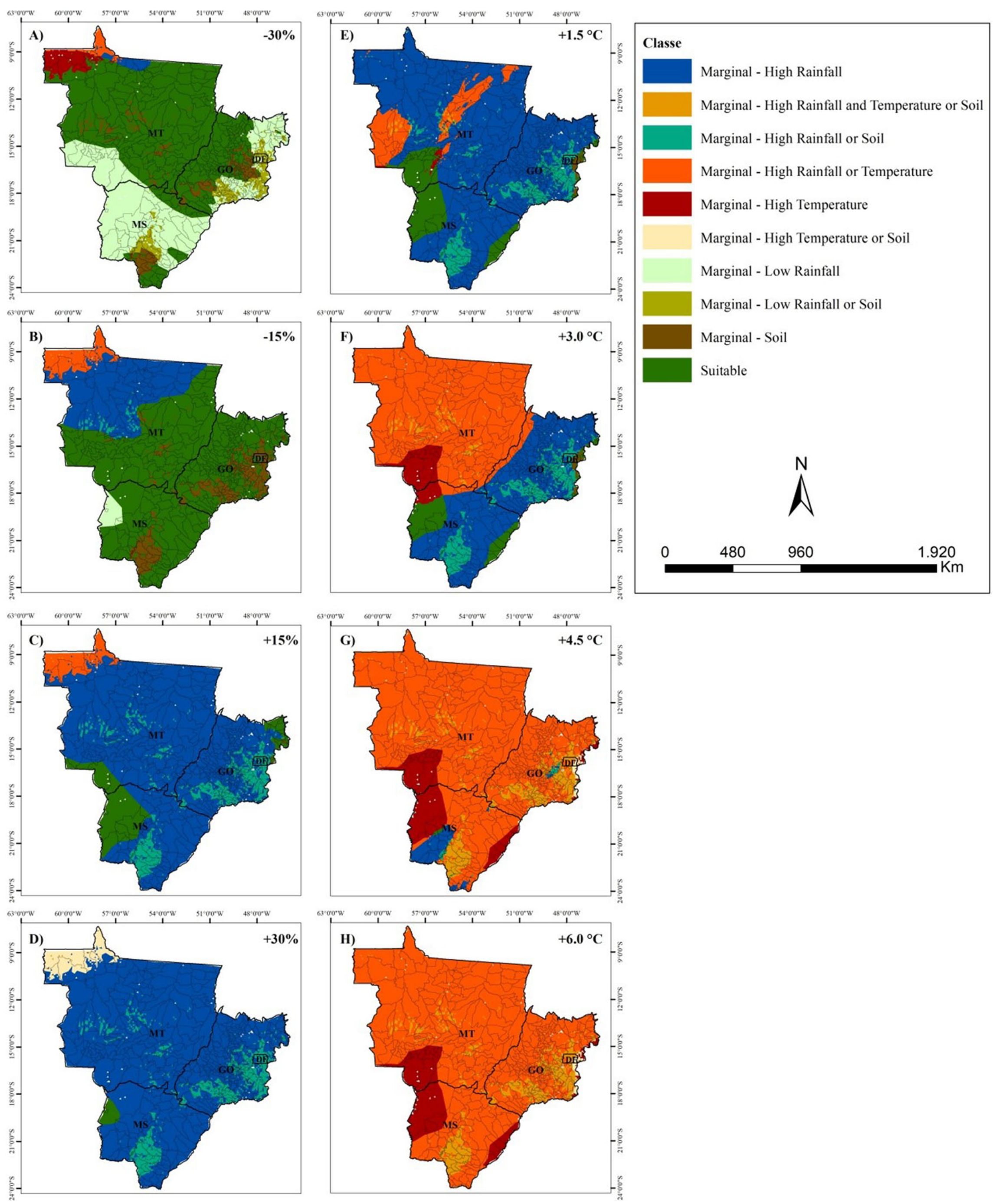

Fig. 9 Agriculture zoning of cassava for the Midwest region of Brazil in different climate change scenarios

The climate change scenarios demonstrated different Agriculture zonings for cassava in the Midwest of Brazil (Fig. 9). The largest amount of suitable areas (62.8%) occurred with a 15% reduction in rainfall, and the smallest suitable area occurred with an increase of 6 °C. As the air temperature increases, marginal areas also increase (Table 3), but it is important to highlight that cassava resists high temperatures (Gabriel et al. 2014b) and requires little handling, which is why it is so attractive to small producers in arid regions of Brazil. The problem of increasing air temperature is the reduction of the crop cycle, which can promote a reduction in cassava yield.

4 Conclusions

Agroclimatic zoning is a tool for decision-making and guiding public policies in these states. A large extension of the Midwest region of Brazil is climatically and soil favorable or has little restriction for cassava cultivation due to excess water. In this region, programs and policies to encourage cassava production must take into account the fact that most of its territory has restrictions on cassava cultivation due to excess soil moisture, which can be circumvented by planting area management.

The Midwest is a region with high rainfall, so we recommend planting in well-drained soils to avoid phytosanitary problems. In the Midwest, the greatest predominance of clay occurs from 15 to 35% which contributes to the planting of cassava. Producers taking this care can plant cassava in 86.6% of the territory.

The climate change scenarios demonstrated different Agriculture zonings for cassava in the Midwest of Brazil. With the increase in air temperature, greater marginal classes occurred, but cassava is resistant to this condition. But, this increase in temperature can reduce the cycle and consequently reduce production.

Funding This study was financially supported by the Science and Technology of Mato Grosso do Sul - Campus of Naviraí, IFMS - Federal Institute of Education, Naviraí, Brazil.

References

Adefisan E (2018) Climate change impact on rainfall and temperature distributions over West Africa from three IPCC scenarios. J Earth Sci Clim Change 09: https://doi.org/10.4172/2157-7617.1000476

Almeida TS, Calijuri ML, Pinto LB (2013) Zoneamento agro-climático da cana-de-açúcar para o estado de Minas Gerais com base em regressões múltiplas. Rev bras meteorol 28:352–355. https://doi.org/10.1590/S0102-77862013000300011

Alves AAC (2006) Cassava physiology. In: Souza LS, ARN F, PLP M, WMG F (eds) Cassava socioeconomic and agronomic aspects, 1a edn. Embrapa Mandioca e Fruticultura Tropical, Cruz das Almas, pp 138–169

Arshad M, Amjath-Babu TS, Krupnik TJ, Aravindakshan S, Abbas A, Kächele H, Müller K (2017) Climate variability and yield risk in South Asia's rice–wheat systems: emerging evidence from Pakistan. Paddy Water Environ 15:249–261. https://doi.org/10.1007/s10333-016-0544-0

Atwijukire E, Hawumba JF, Baguma Y, Wembabazi E, Esuma W, Kawuki RS, Nuwamanya E (2019) Starch quality traits of improved provitamin A cassava (Manihot esculenta Crantz). Heliyon 5: e01215. https://doi.org/10.1016/j.heliyon.2019.e01215

Ayoade JO (1983) Introduction to climatology for the tropics. Wiley, Chichester, p 258

Bos L (1978) Symptoms of virus diseases in plants. 3[a] edn. Wageningen, Centre for Agricultural Publishing and Documentation, pp. 225

Bray EA (1994) Alterations in gene expression in response to water deficit. In: Basra AS (ed) Stress-induced gene expression in plants, Hardwood Academica Publishers, 1a edn, Chur, pp 1–23

Castro CN (2014) Agriculture in the Midwest: limitations to future development and challenges, Institute of Applied Economic Research

Chatzopoulos T, Lippert C (2015) Adaptation and climate change impacts: a structural Ricardian analysis of farm types in Germany. J Agric Econ 66:537–554. https://doi.org/10.1111/1477-9552.12098

de Aparecido LEO, Batista RM, da SC de Moraes JR et al (2019) Agricultural zoning of climate risk for Physalis peruviana cultivation in Southeastern Brazil. Pesq agropec bras 54:e00057. https://doi.org/10.1590/s1678-3921.pab2019.v54.00057

de Morisson VM, de Fátima RD (2012) Topodata: Brazilian full coverage refinement of SRTM data. Appl Geogr 32:300–309. https://doi.org/10.1016/j.apgeog.2011.05.004

de Muniz MFS, de Andrade FWR, Queiroz FM et al (2006) Caracterização de isolados de Phytophthora drechsleri, agente causal da podridão mole de raízes de mandioca. Fitopatol Bras 31:195–198. https://doi.org/10.1590/S0100-41582006000200013

de Oliveira Aparecido LE, Moreto VB, de Souza RG et al (2018) Climatic potential for summer and winter wine production: climatic potential for summer and winter wine production. J Sci Food Agric 98:1280–1290. https://doi.org/10.1002/jsfa.8575

de Oliveira Aparecido LE, de Souza RG, da Silva Cabral De Moraes JR et al (2020) Machine learning algorithms for forecasting the incidence of *Coffea arabica* pests and diseases. Int J Biometeorol 64: 671–688. https://doi.org/10.1007/s00484-019-01856-1

de Oliveira EJ, de Oliveira SAS, Otto C, Alicai T, de Freitas JPX, Cortes DFM, Pariyo A, Liri C, Adiga G, Balmer A, Klauser D, Robinson M (2020) A novel seed treatment-based multiplication approach for cassava planting material. PLoS One 15:e0229943. https://doi.org/10.1371/journal.pone.0229943

Doorenbos J, Pruitt WD (1977) Crop water requirements. FAO Irrigation and Drainage Paper no 24, p 144

El-Sharkawy MA (2007) Physiological characteristics of cassava tolerance to prolonged drought in the tropics: implications for breeding cultivars adapted to seasonally dry and semiarid environments. Braz J Plant Physiol 19:257–286. https://doi.org/10.1590/S1677-04202007000400003

FAO (2001) The state of food and agriculture 2001. Food & Agriculture Org

Gabriel LF, Streck NA, Roberti DR, Chielle ZG, Uhlmann LO, da Silva MR, da Silva SD (2014a) Simulating cassava growth and yield under potential conditions in southern Brazil. Agron J 106:1119–1137. https://doi.org/10.2134/agronj2013.0187

Gabriel LF, Streck NA, Uhlmann LO et al (2014b) Climate change and its effects on cassava crop/ Mudanca climatica e seus efeitos na cultura da mandioca. Revista Brasileira de Engenharia Agricola e Ambiental 18:90+

Guimarães EN, Leme HJC (2002) Historical characterization and spatial configuration of the productive structure of the Midwest. In: Hogan

DJ, Carmo RL, JMP C, Baeninger R (eds) Migração e Ambiente no Centro-Oeste. NEPO, Campinas, pp 89–95
Helfand SM, Magalhães MM, Rada NE (2015) Brazil's agricultural total factor productivity growth by farm size. Inter-American Development Bank
Hengl T, Mendes JJ, Heuvelink GBM et al (2017) SoilGrids250m: global gridded soil information based on machine learning. PLoS One 12(2):e0169748
Hernandez-Espinoza LH, Barrios-Masias FH (2020) Physiological and anatomical changes in tomato roots in response to low water stress. Sci Hortic 265:109208. https://doi.org/10.1016/j.scienta.2020.109208
IBGE (2018) Sistema IBGE de Recuperação Automática - SIDRA: Produção Agrícola Municipal. https://sidra.ibge.gov.br/home/pnadcm. Accessed 28 May 2020
IPCC (2014) Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change
IPCC (2018) Global warming of 1.5°C, summary for policymakers. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change
Jiang D, Chen S, Hao M, Fu J, Ding F (2018) Assessing the sustainable development of bioenergy from cassava within "Water-Energy-Food" Nexus framework in China. Sustainability 10:2153. https://doi.org/10.3390/su10072153
Klering EV, Fontana DC, Berlato MA, Cargnelutti Filho A (2008) Modelagem agrometeorológica do rendimento de arroz irrigado no Rio Grande do Sul. Pesq agropec bras 43:549–558. https://doi.org/10.1590/S0100-204X2008000500001
Moreto VB, Rolim GDS (2015) Agrometeorological models for groundnut crop yield forecasting in the Jaboticabal, São Paulo State region, Brazil. Acta Sci Agron 37:403. https://doi.org/10.4025/actasciagron.v37i4.19766
Moreto VB, de Aparecido LEO, de Rolim GS, da Silva Cabral de Moraes JR (2018) Agrometeorological models for estimating sweet cassava yield. Pesqui Agropecu Trop 48:43–51. https://doi.org/10.1590/1983-40632018v4850451
Nabati J, Nezami A, Neamatollahi E, Akbari M (2020) GIS-based agro-ecological zoning for crop suitability using fuzzy inference system in semi-arid regions. Ecol Indic 117:106646. https://doi.org/10.1016/j.ecolind.2020.106646
Peixoto CP (2009) Cassava. In: Castro PRC (ed) Ecophysiology of annual crops, 1a edn. Nobel, Piracicaba, pp 109–126
Pereira AR, Angelocci LR, Sentelhas PC (2002) Agrometeorology: fundamentals and practical applications. Agropecuária, Guaíba, p 478
Pilau FG, Marin FR, Camargo MBP, Assad ED, Silveira Pinto H, Barbarisi BF (2007) Agroclimatic zoning of rubber cultivation for the Southeast and Midwest regions of Brazil. Revista Brasileira de Agrometeorologia 15(2):161–168
Pipatsitee P, Eiumnoh A, Praseartkul P, Taota K, Kongpugdee S, Sakulleerungroj K, Cha-um S (2018) Application of infrared thermography to assess cassava physiology under water deficit condition. Plant Prod Sci 21:398–406. https://doi.org/10.1080/1343943X.2018.1530943
Pirttioja N, Carter T, Fronzek S, Bindi M, Hoffmann H, Palosuo T, Ruiz-Ramos M, Tao F, Trnka M, Acutis M, Asseng S, Baranowski P, Basso B, Bodin P, Buis S, Cammarano D, Deligios P, Destain MF, Dumont B, Ewert F, Ferrise R, François L, Gaiser T, Hlavinka P, Jacquemin I, Kersebaum KC, Kollas C, Krzyszczak J, Lorite IJ, Minet J, Minguez MI, Montesino M, Moriondo M, Müller C, Nendel C, Öztürk I, Perego A, Rodríguez A, Ruane AC, Ruget F, Sanna M, Semenov MA, Slawinski C, Stratonovitch P, Supit I, Waha K, Wang E, Wu L, Zhao Z, Rötter RP (2015) Temperature and precipitation effects on wheat yield across a European transect: a crop model ensemble analysis using impact response surfaces. Clim Res 65:87–105. https://doi.org/10.3354/cr01322
Quaye F, Nadolnyak D, Hartarska V (2018) Climate change impacts on farmland values in the Southeast United States. Sustainability 10:3426. https://doi.org/10.3390/su10103426
Ramcharan A, Baranowski K, McCloskey P, Ahmed B, Legg J, Hughes DP (2017) Deep learning for image-based cassava disease detection. Front Plant Sci 8:1852. https://doi.org/10.3389/fpls.2017.01852
Rocha VPC, Gonçalves-Vidigal MC, Ortiz AHT, Valentini G, Ferreira RCU, Gonçalves TM, Lacanallo GF, Vidigal Filho PS (2020) Population structure and genetic diversity in sweet cassava accessions in Paraná and Santa Catarina, Brazil. Plant Mol Biol Report 38:25–38. https://doi.org/10.1007/s11105-019-01175-0
Sentelhas PC, Monteiro JEBA (2009) Agrometeorology of crops, 3a edn. National Institute of Meteorology, Brasília
Silva DV, Santos JB, Ferreira EA, Silva AA, França AC, Sediyama T (2012) Manejo de plantas daninhas na cultura da mandioca. Planta daninha 30:901–910. https://doi.org/10.1590/S0100-83582012000400025