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SOWING PERIOD AND ESTIMATED MAIZE PRODUCTION FOR SILAGE UNDER TROPICAL CONDITIONS

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Abstract – In Brazil, livestock activity is affected by the seasonality of forage supply, which depends on the distribution of rainfall. The use of silage is one of the strategies to solve the problem during the annual dry season. The objective of this study was to use modeling to assess the productivity and quality of the maize silage in the state of Minas Gerais, Brazil. The CSM-CERES-*Maize* model was used to simulate maize silage production in 18 counties, at 52 sowing dates distributed throughout the year, with and without the use of irrigation. Absence of rainfall during the harvest period was also used as criterion to define the best sowing date in each county. In general, the best sowing dates were concentrated in October and February, respectively, for rainfed water supply and irrigated condition. The maize silage productivity under rainfed condition presented greater interannual variability and lower quality in comparison to that obtained under irrigated conditions. Under optimal soil-water conditions, climatic factors such as temperature and solar radiation are determinant to crop performance.

Keywords: DSSAT, modeling, silage quality, *Zea mays* L., irrigation.

PERÍODO DE SEMEADURA E PRODUTIVIDADE ESTIMADA DE MILHO PARA SILAGEM SOB CONDIÇÕES TROPICAIS

Resumo - No Brasil, a atividade pecuária é afetada pela sazonalidade na oferta de forragem, que depende da distribuição das chuvas. A utilização de silagem é uma das estratégias para resolver esse problema durante a estação seca do ano. O objetivo deste estudo foi empregar modelagem para avaliar a produtividade e a qualidade da silagem de milho no estado de Minas Gerais, Brasil. Empregou-se o modelo CSM-CERES-*Maize* para simular a produção de silagem de milho em 18 municípios, em 52 datas de semeadura distribuídas ao longo do ano, com e sem o uso de irrigação. A ausência de chuva no período de colheita foi também utilizada como critério para definir a melhor data de semeadura em cada município. Em geral, as melhores datas de semeadura se concentraram em outubro e fevereiro, respectivamente, para o cultivo de sequeiro e irrigado. A produtividade de silagem de sequeiro apresentou maior variabilidade interanual e menor qualidade da silagem em comparação à obtida no cultivo irrigado. Em condições ótimas de umidade no solo, fatores climáticos como temperatura e radiação solar são determinantes no desempenho da cultura.

Palavras-chave: DSSAT, modelagem, qualidade de silagem, *Zea mays* L., irrigação.

Livestock is a great economic and social important activity for Brazilian agribusiness. Brazil is the third world's largest producer of cattle milk, only surpassed by the United States and India. In 2020, Brazil was the worldwide top exporter of beef, accounting for roughly 24% of the world's beef exports (FAS/USDA, 2020). Minas Gerais state stands as the highest producer of dairy, representing 26% of the national production (Anuário…, 2018).

In Minas Gerais, the extensive livestock production is affected by the seasonality of forage supply, which in turn depends on the distribution of rainfall. To cope with the low fodder supply, different management strategies are employed, including silage production (Resende et al., 2016; Amaral et al., 2017).

Maize is the most widely used crop for silage production because it is economically viable, has high biomass production, excellent quality of fermentation and maintenance of the nutritive value of the ensiled mass. Besides, maize has high-energy value and great animal consumption in comparison to other crops used as forage (Santos et al., 2010; Ferreira et al., 2011; Amaral et al., 2017).

Maize belongs to the group of plants with C4 photosynthetic metabolism, which is characterized by high efficiency in the use of solar radiation and high productivity. However, the crop is sensitive to variations in meteorological conditions, which may affect it in early stages, leading to a decrease in biomass accumulation, with negative effects on crop productivity (Bergamaschi & Matzenauer, 2014).

The availability of water in the soil is the most important environmental factor for maize productivity. The maize crop requires 350 to 500 mm of water during its cycle under rainfed conditions but, it can require up to 800 mm for maximum productivity (Cruz et al., 2011). Water deficit causes damage at all stages of the crop, but at some stages, such as floral initiation, flowering, and early grain development, maize is more sensitive to soil-water availability. Thus, the irregular distribution of rainfall can explain, largely, the variation in crop performance among the years (Bergamaschi & Matzenauer, 2014).

Crop growth models are useful tools to evaluate the effect of environmental factors on crop yield. The DSSAT platform (Decision Support System for Agrotechnology Transfer) is a computational tool that contains process-based models for different crops, among them, maize, represented by the CSM-CERES-Maize model (Jones & Kiniry, 1986). This model is widely used in Brazil and abroad to define soil management strategies and sowing periods, assess the effects of climate change on crop productivity, analyze the effects of water deficit on crop growth and productivity, define nutritional and fertilizer management strategies, among other applications. Several studies have shown the effectiveness of DSSAT in helping decision-making (Amaral et al., 2015; Li et al., 2015; Tigges et al., 2016; Amaral et al., 2017; Boggione et al., 2018).

Considering the importance of providing

fodder during the dry season, we proposed this study aiming to use modeling to assess the productivity and the quality of maize silage under rainfed and irrigated conditions in the state of Minas Gerais, Brazil.

Material and Methods

The CSM-CERES-Maize model of the DSSAT platform, version 4.6.1.0 (Hoogenboom et al., 2015), was used to simulate maize crop productivity under irrigated and rainfed conditions. The simulations were performed for 18 representative counties of the Minas Gerais state, Brazil (Figure 1). The tropical counties were located between 21.7 degree to 15.8 degree latitude South. For each county, daily data on precipitation and maximum, minimum and average air temperature over a period of 33 years (1981-2013) were obtained from the National Institute of Meteorology (INMET), Brazil (Table 1).The model was previously parameterized for the single-cross hybrid DKB390PRO with available data from Minas Gerais state (Andrade et al., 2016). The simulations were performed weekly from August 1 to July 24, corresponding to 52 sowing dates. The seasonal analysis tool of DSSAT was used to simulate the weekly sowing dates, repeated for each one of the 33 years for which meteorological data was available. Thus, for each of the 52 sowing dates in each county, 33 values of productivity were generated and sowing periods were established for each county.

A row spacing of 0.7 m, a plant population of 68,000 ha^{-1} and 2,000 kg ha^{-1} of residue from the previous crop, *Urochloa* sp were considered for the maize crop management. The CSM-CERES-Maize model does not simulate the harvesting date of maize silage (Amaral et al., 2017). Thus, the harvesting point was considered the day when the grain milk line is halfway between the crown and the grain insertion point in the cob, which corresponds to approximately 13 days before the seeds mature physiologically (Wiersma et al., 1993).

The management files were prepared considering a system with no biotic and abiotic stresses. Fertilizers were simulated according to recommendations of the Brazilian Corporation for Agricultural Research (Embrapa) for maize silage (Resende et al., 2016). The sowing fertilization were 500 kg ha^{-1} of the NPK formula (08-28-16) and the side-dressing fertilization were 200 kg ha^{-1} of urea at 20 days after sowing (V4 stage). Two more side-dressings were programmed with 350 kg ha^{-1} of NPK 20-00-20 at 27 days after sowing and 200 kg ha^{-1} of ammonium sulfate at 33 days after sowing. In the irrigated scenarios, a sprinkler irrigation system with 80% of application efficiency was set to restore automatically the soil water content to field capacity, when the soil water availability was reduced by 50% (Table 2).

To determine the sowing periods, a reduction of up to 10% in the average silage productivity at certain sowing date in relation to the highest average productivity was admitted. The percentage of reduction was defined, taking as reference the sowing date of highest productivity

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Table 1. Averages of minimum temperature (Tmin), maximum temperature (Tmax), average temperature (Tavg) and precipitation (Precip) over a period of 33 years (1981-2013) for 18 counties of the Minas Gerais state, Brazil.

County	Tmin ºC	Tmax ºC	Tavg ºC	Precip mm $year^{-1}$
Aimorés	20.3	31.8	26.1	976
Araçuaí	19.6	31.8	25.7	757
Araxá	16.8	27.4	22.1	1,572
Bambuí	15.0	28.9	22.0	1,461
Caratinga	16.5	27.6	22.1	1,225
Curvelo	16.5	30.4	23.5	1,123
Itamarandiba	15.2	26.1	20.7	1,129
Janaúba	18.9	31.4	25.2	811
Lavras	15.1	27.3	21.2	1,491
Machado	14.5	27.4	21.0	1,257
Montes Claros	17.8	29.9	23.9	1,025
Paracatu	18.2	29.9	24.1	1,483
Patos de Minas	16.5	28.1	22.3	1,461
Pompéu	16.9	29.8	23.4	1,244
Sete Lagoas	15.1	27.3	21.2	1,491
Uberaba	16.8	29.4	23.1	1,660
Unaí	18.3	31.4	24.9	1,379
Viçosa	15.8	26.9	21.4	1,337

of dry mass in each county, according to equation 1 (Amaral et al., 2015):

$$Pr = \left(1 - \frac{Ys}{Ymax}\right)100 \quad (1)$$

Where: Pr is the productivity reduction for the sowing date “s” (%); Ys is the productivity for the sowing date “s” and Ymax is the maximum productivity among all sowing dates (kg ha^{-1}).

Silage quality was assessed considering the proportion of grains in the total biomass (Cox et al., 1994), and converting the dry matter (DM) of aboveground maize plants into milk forage unit (*Unités Fourragères Lait*, UFL). The UFL is the amount of net energy provided by one kilogram of barley expressed in DM for a lactating cow above its energy maintenance needs, considering that all energy is converted into milk (Vermorel, 1988). The values of energy per unit weight of harvest biomass expressed in DM (EPUWHB; UFL kg^{-1}) and energy per unit area (EPUA; UFL ha^{-1}) were calculated according to equations 2

Figure 1. The location of the 18 representative counties in the Minas Gerais state, Brazil, used to assess maize crop productivity and silage quality under irrigated and rainfed conditions.

and 3 (Braga et al., 2008):

$$EPUWHB = ETBR \cdot EPUWE + (1 - ETBR) \cdot EPUWSL \quad (2)$$

$$EPUA = CWAH \cdot EPUWHB \quad (3)$$

Where: EPUWHB is energy per unit weight of harvest biomass in DM (UFL kg^{-1}); ETBR is ear to total biomass ratio; EPUWE is energy per unit weight of harvest ears in DM (UFL kg^{-1}); EPUWSL is energy per unit weight of harvest stems and leaves in DM (UFL kg^{-1}); EPUA is energy per unit area (UFL ha^{-1}) and CWAH is crop weight at harvest in DM (kg ha^{-1}).

The decision regarding the best sowing date to produce maize silage were based on the highest productivity with absence or small amount of rainfall at harvest period. The occurrence of rainfall raises the susceptibility of the soil to compaction. In fields of silage production, about 60 to 70% of the area is trafficked at the time of harvest (Duttmann et al., 2014), which favors the formation of compacted layers. These compacted layers represent a physical barrier to root growth, soil water infiltration, availability of water and nutrients to plants and to soil aeration, which certainly impair the crop performance in the next seasons. Also, if silage is ensiled too wet, it may ferment poorly and removes nutrients, particularly soluble nitrogen and carbohydrates. Thus, for the sowing date that provided the highest average productivity, the accumulated precipitation of a seven-day period was computed, starting three days before

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Table 2. Soil water content (mm) at saturation (SAT), field capacity (FC) and permanent wilting point (PWP) in the 0.0-0.5 m soil layer for the 18 counties in the Minas Gerais state, Brazil.

County	SAT	FC	PWP
Aimorés	221	135	86
Araçuaí	184	136	66
Araxá	271	211	97
Bambuí	255	208	157
Caratinga	265	179	104
Curvelo	239	192	136
Itamarandiba	263	149	87
Janaúba	204	164	107
Lavras	280	163	101
Machado	266	170	114
Montes Claros	209	131	85
Paracatu	284	178	124
Patos de Minas	276	164	105
Pompéu	259	182	114
Sete Lagoas	292	177	124
Uberaba	242	126	57
Unaí	294	179	127
Viçosa	239	185	139

the date of harvest associated to the best sowing date.

Results and Discussion

Silage production under rainfed conditions

Effect of sowing date on productivity

There was a considerable difference among the counties, at the beginning and at the end of the sowing periods (Table 3). These differences can be related to interactions of the crop with the soil type and meteorological conditions, which differ significantly among the counties. Considering all the counties, the annual precipitation varied from 757 mm in Araçuaí to 1,660 mm in Uberaba (146% greater) and the amplitude of the average air temperature was greater than 5°C (Table 1). Indeed, the silage productivity can be influenced not only by crop-environment interactions reproduced in the CSM-CERES-Maize model, but also by short-term local events not considered in the model, such as high-intensity rains, high wind speeds and hail (Boggione et al., 2018).

The narrowest sowing periods were established for Janaúba, Montes Claros, Araçuaí and Aimorés, while the largest periods were obtained in Uberaba, Lavras and Araxá (Table 3). Tigges et al. (2016) used the same model for simulations of rainfed maize for grain production in 19 counties of Minas Gerais and obtained narrower sowing periods. Nevertheless, similar trends were verified, such as narrower sowing periods, for hotter and drier climates of Janaúba, Montes Claros, Araçuaí and Aimorés.

The best sowing dates, that is, those associated with the highest silage productivity, are concentrated in October and in November, which corresponds to the beginning of the rainy season in the majority of the counties. The exceptions were for Araxá, Lavras, Patos de Minas and Uberaba, in which the best sowing

Table 3. Sowing period based on productivity, best sowing date based only on productivity, and best sowing date based on productivity and rainfall at harvest period of maize silage, under rainfed condition, for the 18 counties in the Minas Gerais state, Brazil.

County	Sowing period based on productivity[1]	Best sowing date based on productivity[2]	Best sowing date based on productivity and rainfall[3]
Aimorés	10/17 – 11/28	11/07	11/07
Araçuaí	10/10 –11/21	10/24	10/24
Araxá	08/22 – 02/20	01/30	01/30
Bambuí	10/03 – 01/09	11/07	11/07
Caratinga	09/26 – 01/30	10/31	10/31
Curvelo	10/17 – 12/05	11/07	11/07
Itamarandiba	09/19 – 11/07	10/24	10/24
Janaúba	10/17 – 11/21	10/31	10/31
Lavras	09/05 – 01/23	09/19	12/05
Machado	09/26 – 01/02	10/31	10/31
Montes Claros	10/10 – 11/14	10/31	10/31
Paracatu	10/10 – 12/12	10/31	10/31
Patos de Minas	10/03 – 01/16	12/12	12/12
Pompéu	10/10 – 12/12	11/07	11/07
Sete Lagoas	09/26 – 12/12	10/31	10/31
Uberaba	09/12 – 02/13	01/02	01/02
Unaí	10/10 – 12/12	11/14	11/14
Viçosa	09/26 – 11/21	10/24	10/24

[1]The sowing periods were determined admitting a reduction of up to 10% in the average silage productivity at certain sowing date in relation to the highest average productivity. [2]Date associated with the highest silage productivity. [3]Date associated with the highest silage productivity with small amount of rainfall at harvest period.

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dates were January 30, September 19, December 12 and January 2, respectively. There was great interannual variability in silage productivity for all counties, even at the best sowing dates. The average productivity of maize silage at the best sowing dates ranged from 12,662 (Aimorés) to 19,789 kg ha^{-1} (Araxá) (Figure 2).

Among the highest simulated productivities, the four lowest values were 12,662 kg ha^{-1} in Aimorés, 13,334 kg ha^{-1} in Araçuaí, 14,337 kg ha^{-1} in Janaúba and 14,748 kg ha^{-1} in Montes Claros. These counties are located in the Minas Gerais regions named "*Rio Doce*", "*Vale do Jequitinhonha*" and "*Norte de Minas*", which are characterized by low annual precipitation and concentration of rainfall in a short season. Thereby, the crop is more likely to suffer from the effects of water stress due to water deficit. Water deficit implies abiotic stress, which is one of the most restrictive factors to maize production. Besides, these regions present high temperatures, which shorts the crop cycle and increases the maintenance respiration, with a consequent reduction in productivity (Galon et al., 2011; Amudha & Balasubramani, 2011).

Maize hybrids for silage production were field-assessed by Oliveira et al. (2003) in five counties of Minas Gerais (Bom Despacho, Alfenas, Caldas, São Sebastião do Paraíso and Três Pontas), covering the Central, South and Southwest mesoregions of the state. The annual precipitation ranged from 1,240 to 1,500 mm and the average temperature ranged from 20°C to 21°C at these counties. Sowing was carried out between October 15 and December 15 and the average productivity of the hybrid DKB333B expressed in dry mass ranged from 12,200 kg ha^{-1} (Alfenas) to 18,100 kg ha^{-1} (Bom Despacho). The simulated values at the highest-productivity dates were similar to those obtained in this study (Figure 2), which confirm the model's adequate predictive capability of maize crop performance under rainfed conditions in Minas Gerais state.

Regarding the variation of the simulated productivities among the 33 years, it was verified that all counties had amplitudes higher than 4,000 kg ha^{-1} (Figure 3). The highest amplitudes were simulated for Aimorés, Araçuaí, and Janaúba. These counties present lower annual precipitation and higher average temperatures (Table 1). Precipitation has a significant effect on productivity in tropical environments as it determines the water supply to plants (Adamgbe & Ujoh, 2013). High temperatures also significantly affect maize crops, though the soil-water deficit is the major and consistent reducer of productivities (Basso & Ritchie, 2014).

Quality of silage

The energy per unit weight of harvest biomass (EPUWHB) ranged from 0.81 to 0.89 UFL kg^{-1} for the best dates (Figure 4A). The lowest average values were 0.81 UFL kg^{-1} in Aimorés, 0.83 UFL kg $^{-1}$ in Araçuaí and 0.84 UFL kg^{-1} in Janaúba. The highest values were 0.89 UFL kg^{-1} in Araxá and Lavras and 0.88 UFL kg $^{-1}$ in Patos de Minas and Uberaba (Figure 4A).

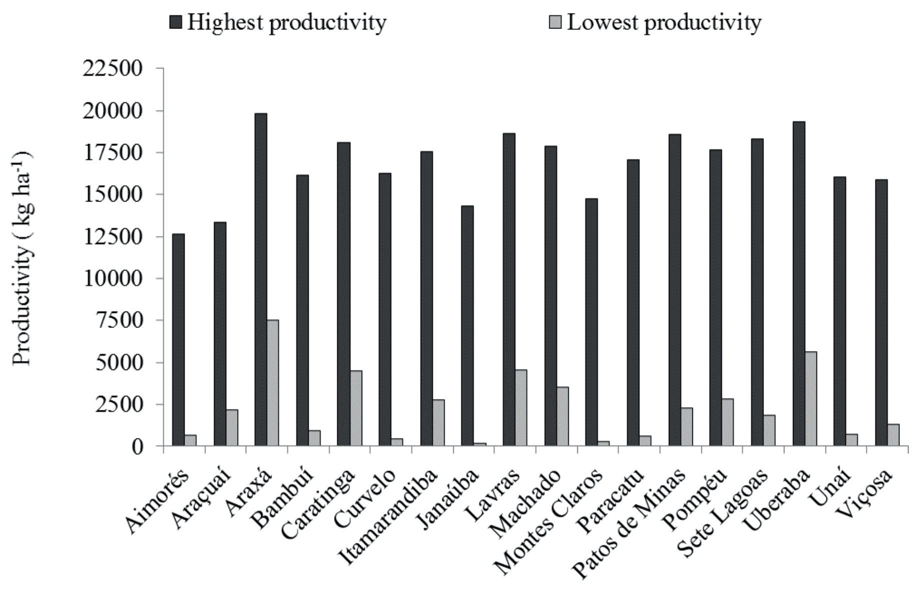

Figure 2. Highest and lowest maize silage productivity under rainfed condition simulated for the 18 counties in the Minas Gerais state, Brazil, considering the best and the worst sowing date for each county, respectively.

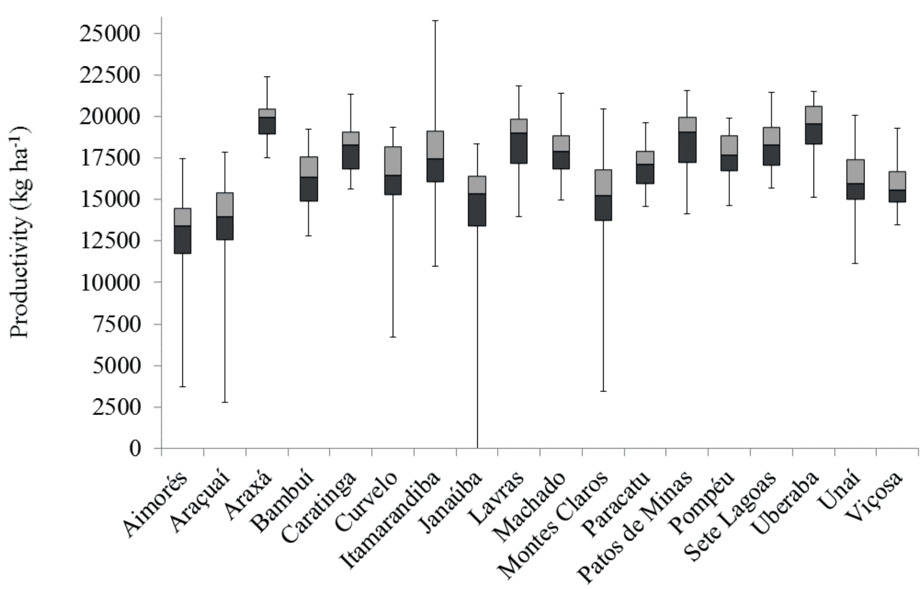

Figure 3. Interannual variation of maize silage productivity under rainfed condition at the highest-productivity sowing date for the 18 counties, Minas Gerais state, Brazil.

As for the energy per unit area (EPUA), the values ranged from 10,364 to 17,701 UFL ha^{-1}. The four lowest values were 10,364 UFL ha^{-1} in Aimorés, 11,134 UFL ha^{-1} in Araçuaí, 12,149 UFL ha^{-1} in Janaúba and 12,607 UFL ha^{-1} in Montes Claros. The four highest values were 17,701 UFL ha^{-1} in Araxá, 17,049 UFL ha^{-1} in Uberaba, 16,560 UFL ha^{1} in Lavras and 16,366 UFL ha^{-1} in Patos de Minas (Figure 4B).

A good quality of the silage is important to ensure the supply of dairy and meat throughout the year. However, the production of maize silage with high quality depends on several conditions, including meteorological factors. According to Braga et al. (2008), any value of EPUWHB equal to or less than 0.75 UFL kg^{-1} indicates low silage

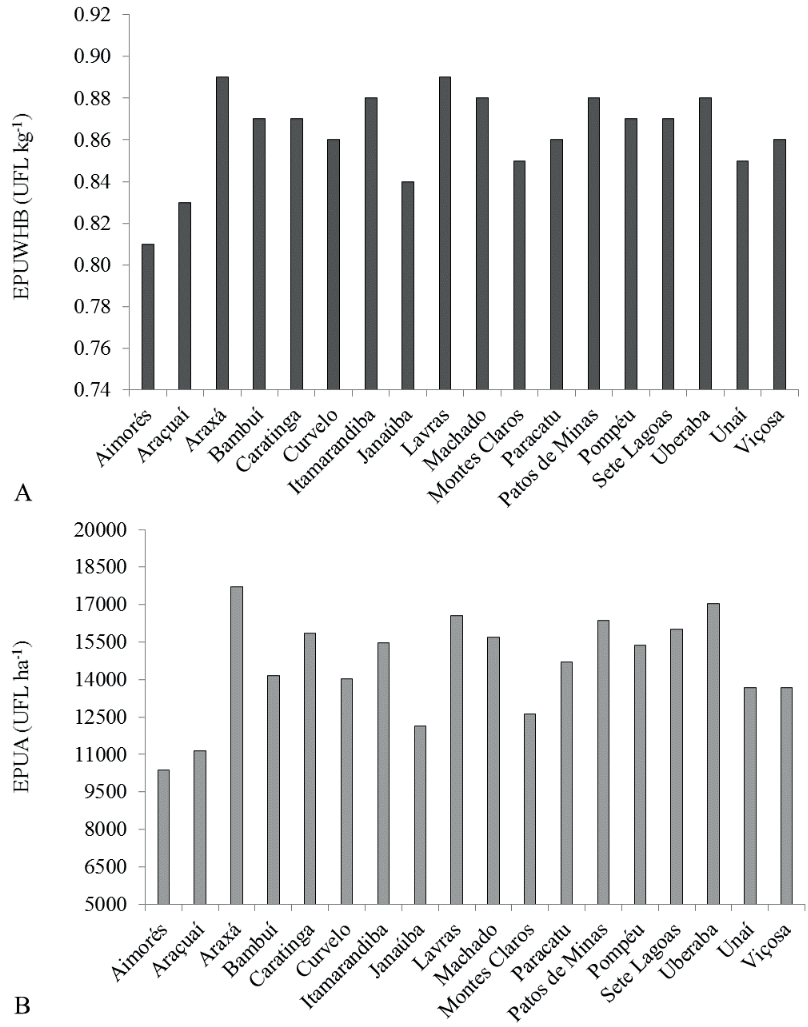

Figure 4. Energy per unit weight of harvested biomass (A) and energy per unit area (B) at the highest-productivity sowing date of maize silage under rainfed condition for the 18 counties, Minas Gerais state, Brazil.

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quality. In all counties, the silage presented good quality, with EPUWHB and EPUA values equal to or greater than 0.81 UFL kg^{-1} and 10,364 UFL ha^{-1}, respectively (Figure 4).

Amaral et al. (2017) found values of EPUWHB and EPUA equal to or greater than 0.91 UFL kg^{-1} and 6,367 UFL ha^{-1} for different maize cultivars in Pelotas, state of Rio Grande do Sul, Brazil. The double and triple-cross maize hybrids plus the open-pollinatted variety used in the study, following the local family farmers' recommendations, present lower genetic potential as compared to the single-cross hybrid DKB390PRO, explaining the lower UFL ha^{-1}.

Precipitation at the harvest period

In the counties which presented the four highest productivities (Araxá, Lavras, Patos de Minas and Uberaba), the cumulative values of precipitation at harvest period, considering only the highest maize silage productivity, ranged from 1.44 mm to 49.95 mm week ^{1}. In Araxá, the average daily precipitation was less than 1.00 mm day ^{1} and the cumulative value was 1.44 mm week ^{1}. Lavras presented 7.14 mm day ^{1} of precipitation, accumulating 49.95 mm week ^{1}. In Patos de Minas, the average daily precipitation was 1.84 mm day^{1} and the cumulative value was 12.91 mm $week^{1}$. In Uberaba, the average daily precipitation was 3.10 mm day^{1}, accumulating 21.67 mm week ^{1} (Figure 5).

The value of accumulated precipitation in Lavras during the ideal harvest period (highest silage productivity) indicates high susceptibility to soil compaction. In this case, the farmer must change the sowing date. Within the recommended sowing period for this county (Figure 6A), the date which provides the lowest precipitation in the harvest period is December 5, with 16.45 mm week ^{1} (Figure 6B). Compared to the highest-productivity sowing date (September 19), this value represents a reduction of 67% in accumulated precipitation and confers much lower risk to soil compaction. Regarding the silage quality, the EPUA and the EPUWHB presented a reduction of only 5% in comparison to the highest-productivity sowing date (Figures 6C and 6D). Thus, the best sowing date for Lavras would not be the highest-productivity date, but rather the date which most ensures the maintenance of good soil physical quality, with a small reduction in productivity and quality of silage (December 5). For the other counties, the best sowing date was the highest-productivity date (Table 3).

Silage production under irrigated condition

Effect of sowing date on productivity

The narrowest sowing periods were obtained in Bambuí, Lavras, and Machado counties (Table 4). Bambuí presented a sowing period between January 23 and March 27. In Lavras, the sowing period was from January 2 to March 13, while in Machado, the sowing period was from December 5 to March 6 (Table 4). By

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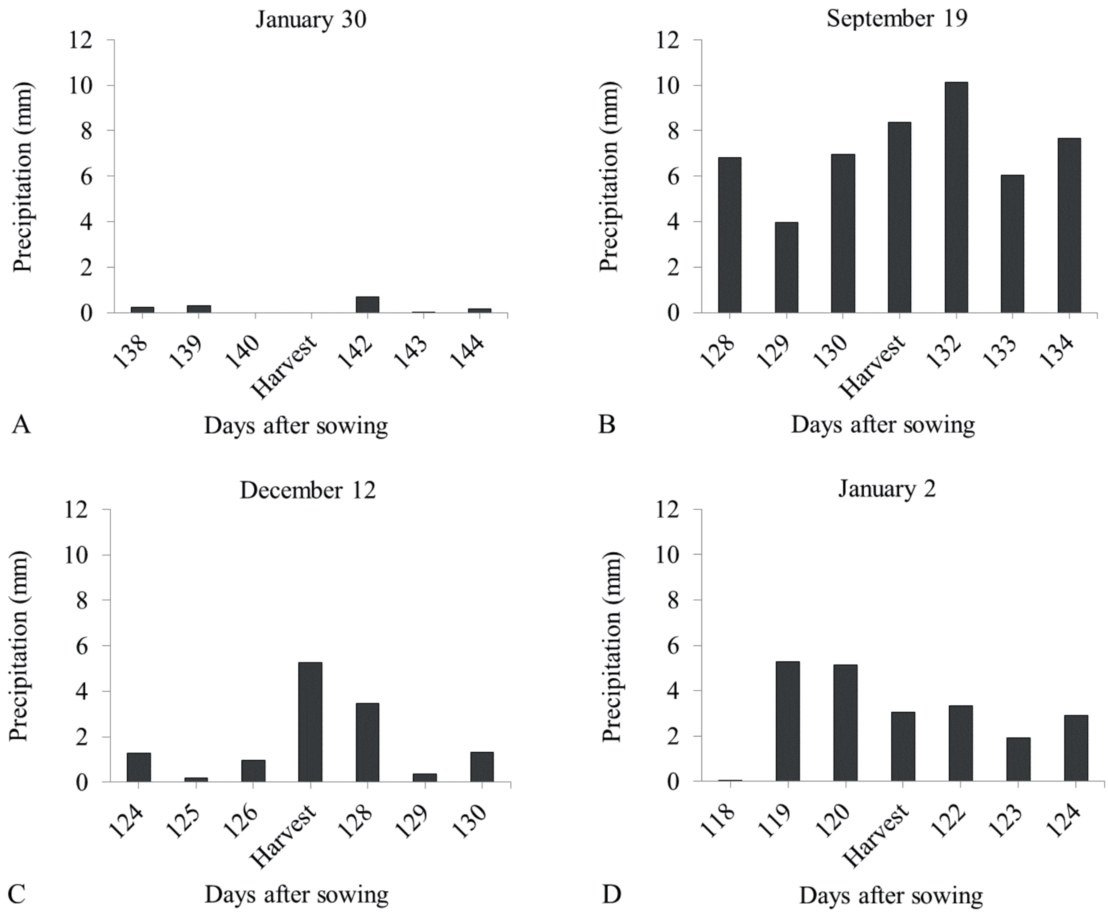

Figure 5. The average daily precipitation at the harvest period of maize silage for the highest-productivity sowing date, under rainfed condition, in the counties of (A) Araxá, (B) Lavras, (C) Patos de Minas and (D) Uberaba, Minas Gerais state, Brazil.

sowing at these periods, the risk of obtaining low productivity is low due to favorable temperature and solar radiation conditions to crop growth.

The largest amplitudes in the sowing periods were obtained in Janaúba, Montes Claros, Araçuaí, Paracatu and Unaí (Table 4). In 15 out of the 18 counties, February was the most adequate month for sowing maize for silage production under irrigated conditions, with February 6, 13 and 20 being the most suitable dates. The only exceptions were Aimorés (01/30), Araçuaí (12/19) and Janaúba (12/19) (Table 4).

Using the CSM-CERES-Maize model and data from counties of the Minas Gerais state, Tigges et al. (2016) and Boggione et al. (2018) indicated February as the best month for sowing irrigated maize for grain production. They found that the highest average yield simulated in February were due to the favorable weather conditions, especially low nighttime

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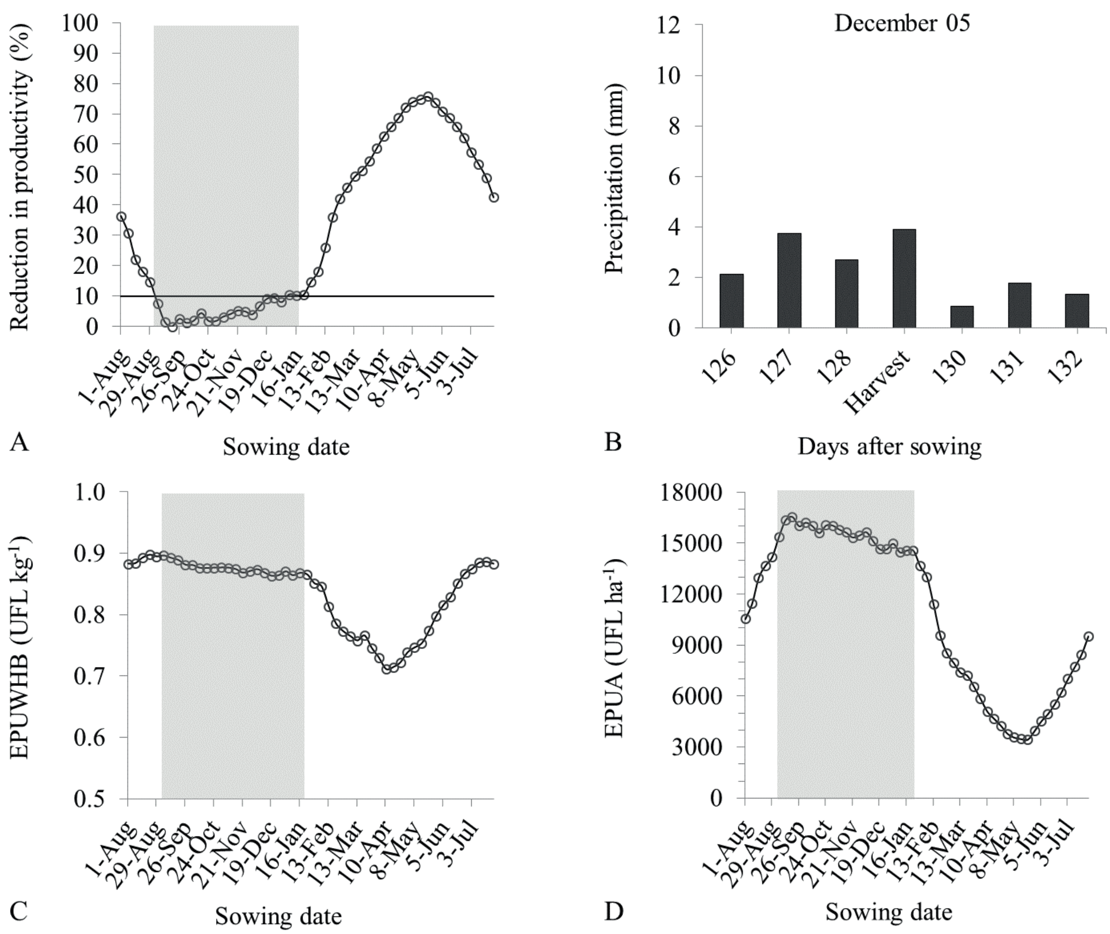

Figure 6. Simulation of maize silage under rainfed condition in Lavras county. (A) Sowing period (highlighted), (B) average daily precipitation in the recommend harvest period, (C) energy per unit weight of harvest biomass and (D) energy per unit area.

temperatures and adequate solar radiation incidence. Low nighttime temperatures reduce the maintenance respiration rate and, consequently, improves the crop energetic balance, which may reflect in higher productivity. For the county of Janaúba, Boggione et al. (2018) also verified productivity peaks between sowings from the second half of November to the second half of December; a period with relatively low average productivity in other counties.

The lowest simulated productivities were 16,989 kg ha^{-1} in Araçuaí, 17,194 kg ha^{1} in Aimorés and 18,812 kg ha^{-1} in Unaí (Figure 7). These values were similar or greater than the highest productivities reached without irrigation (Figure 2), which indicated that the use of irrigation is advantageous for maize silage production in the state of Minas Gerais, Brazil.

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Table 4. Sowing period based on productivity, best sowing date based only on productivity, and best sowing date based on productivity and rainfall at harvest period of maize silage, under irrigation, for the 18 counties in the Minas Gerais state, Brazil.

County	Sowing period based on productivity[1]	Best sowing date based on productivity[2]	Best sowing date based on productivity and rainfall[3]
Aimorés	11/07 – 03/20	01/30	01/30
Araçuaí	08/08 – 03/20	12/19	12/19
Araxá	11/21 – 03/13	02/13	02/13
Bambuí	01/23 – 03/27	02/20	02/20
Caratinga	10/24 – 03/13	02/13	02/13
Curvelo	12/05 – 04/03	02/20	02/20
Itamarandiba	10/24 – 03/20	02/13	02/13
Janaúba	10/31 – 07/10	12/19	12/19
Lavras	01/02 – 03/13	02/06	02/06
Machado	12/05 – 03/06	02/06	02/06
Montes Claros	10/31 – 07/10	02/13	02/13
Paracatu	10/31 – 05/01	02/20	02/20
Patos de Minas	11/14 – 03/20	02/13	02/13
Pompéu	11/28 – 03/20	02/20	02/20
Sete Lagoas	11/28 – 03/27	02/13	02/13
Uberaba	11/28 – 03/20	02/13	02/13
Unaí	11/14 – 06/05	02/20	02/20
Viçosa	11/21 – 03/13	02/13	02/13

[1]The sowing periods were determined admitting a reduction of up to 10% in the average silage productivity at certain sowing date in relation to the highest average productivity. [2]Date associated with the highest productivity. [3]Date associated with the highest productivity with small amount of rainfall at harvest period.

Observed silage productivity for the maize hybrid DKB350YG in the county of Montes Claros, under irrigation, varied from 17,610 kg ha^{-1} to 19,070 kg ha^{-1} (Moreira et al., 2015). These results are similar to those simulated for the same county (Figure 7). In Sete Lagoas, Resende et al. (2016) observed a productivity of 23,480 kg ha^{1} for irrigated maize hybrid DKB390PRO in the summer harvest of 2014/2015. Our results corresponded to an average of 33 years (1981-2013), therefore, the model captures the variation of weather conditions over the years, which

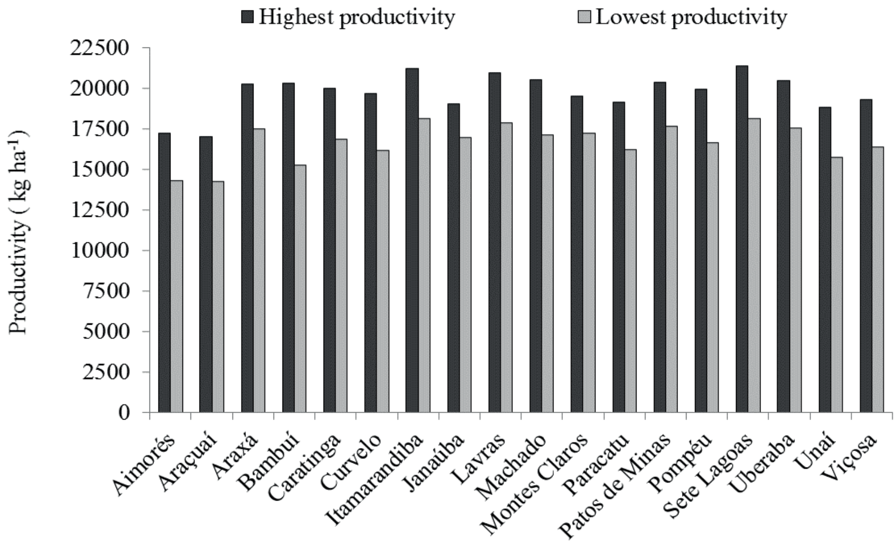

Figure 7. Highest and lowest maize silage productivity under irrigation simulated for the 18 counties in the Minas Gerais state, Brazil, considering the best and the worst county sowing date, respectively.

may reduce or increase the simulated average productivity as compared to an isolated field trial result.

The three highest productivities were 21,369 kg ha^{-1} in Sete Lagoas, 21,216 kg ha^{1} in Itamarandiba and 20,956 kg ha^{-1} in Lavras. Even with the use of irrigation, the productivity presented considerable interannual variability in all counties. Araxá, Sete Lagoas and Montes Claros had the lowest interannual variation, while the highest ones were simulated in Bambuí, Curvelo and Pompéu (Figure 8).

Boggione et al. (2018) simulated weekly maize sowing dates in six counties of the Minas Gerais state (Janaúba, Lavras, Presidente Olegário, Sete Lagoas, Uberaba and Viçosa), under sprinkler irrigation. They also found interannual variability in grain yield, even under adequate soil water content conditions through irrigation. This means that other environmental factors, besides soil-water availability, affect significantly the crop performance. Therefore, the simulated variability in crop productivity can be related to annual variations of air temperature and solar radiation throughout the year.

Although there were considerable interannual variabilities in silage productivity for the irrigated condition, the greatest amplitudes were, in general, smaller than those verified for the rainfed production system. The comparison among the results for rainfed and irrigated conditions demonstrates that, although temperature and solar radiation significantly influence maize production, soil-water availability may be considered one of the most limiting factors for maize silage production in tropical conditions.

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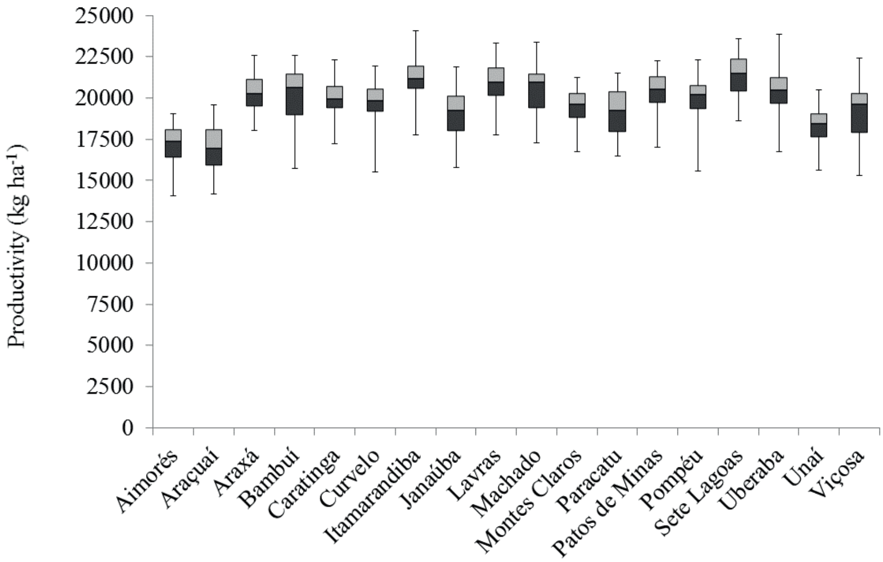

Figure 8. Interannual variation of maize silage productivity under irrigation at the highest-productivity sowing date for the 18 counties, Minas Gerais state, Brazil.

Quality of silage

The simulated energy per unit weight of harvested biomass (EPUWHB) ranged from 0.85 to 0.91 UFL kg^{-1} (Figure 9A). The highest average value for EPUWHB (0.91 UFL kg^{-1}) was simulated in Bambuí, Itamarandiba, Lavras and Machado. The lowest one (0.85 UFL kg^{-1}) was verified in Aimorés and Araçuaí.

The energy per unit area (EPUA) ranged from 14,432 to 19,321 UFL ha^{-1} (Figure 9B). The four lowest values were obtained in Araçuaí (14,432 UFL ha^{-1}), Aimorés (14,652 UFL ha^{-1}), Unaí (16,528 UFL ha^{-1}) and Janaúba (16,579 UFL ha^{-1}). The four highest ones were verified in Sete Lagoas (19,321 UFL ha^{-1}), Itamarandiba (19,320 UFL ha^{-1}), Lavras (19,024 UFL ha^{-1}) and Machado (18,643 UFL ha^{-1}). The EPUA encompasses the silage productivity and quality, which lead to larger variations among counties and years.

Similarly to the rainfed condition, the irrigated maize silage presented good quality in all counties (EPUWHB $\geq$ 0.75 UFL kg^{-1}). However, the minimum values of EPUWHB and EPUA were higher for the irrigated condition as compared to the rainfed condition, which indicated that the use of irrigation provides superior silage quality.

Precipitation at the harvest period

For the counties that presented the four highest silage productivities using irrigation (Itamarandiba, Lavras, Sete Lagoas and Machado), the cumulative values of precipitation

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at the harvest ranged from 1.6 mm week^{-1} (Sete Lagoas) to 6.0 mm week^{-1} (Machado) and the average daily precipitation was less than 2 mm day^{-1} (Figure 10). Considering the direct relation between soil water content and susceptibility to compaction (Lima et al., 2012), it can be deduced that the entry of machinery for harvesting would have minimal implications for soil compaction due to the low precipitation indices. Thus, the best sowing date for each county was the highest-productivity date (Table 4). In this case, it is understood that the farmer must interrupt irrigation at least seven days before the expected crop harvest period.

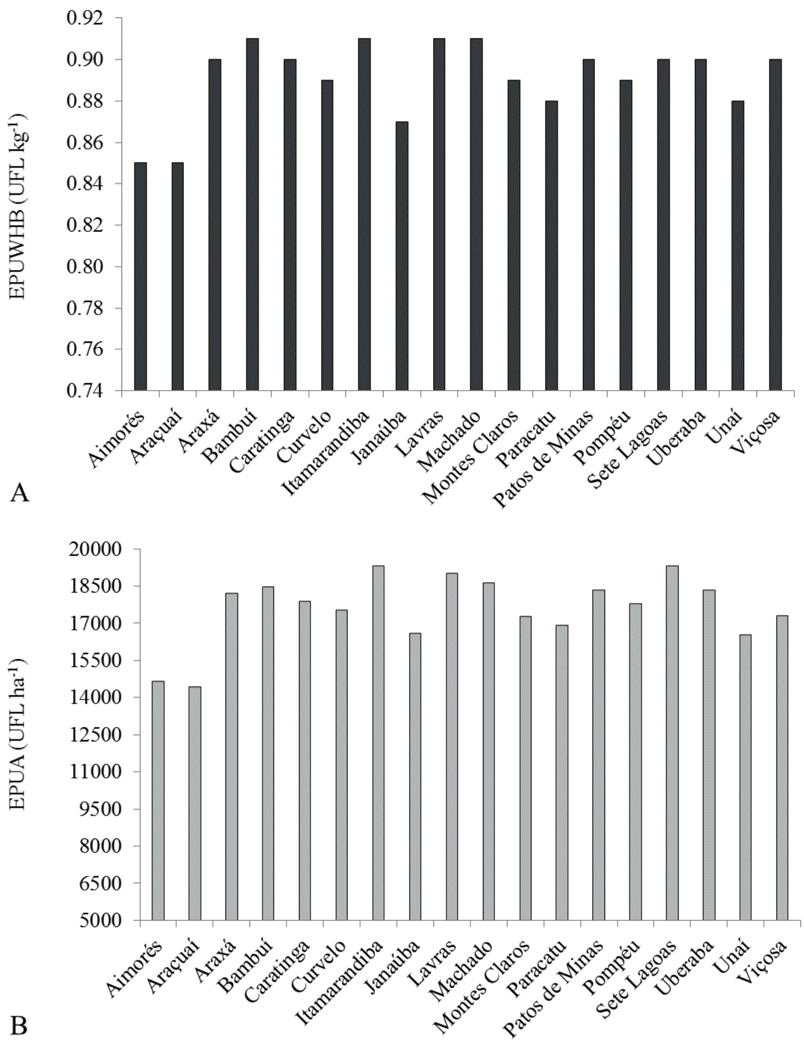

Figure 9. Energy per unit weight of harvested biomass (A) and energy per unit area (B) at the highest-productivity sowing date of maize silage under irrigation for the 18 counties, Minas Gerais state, Brazil.

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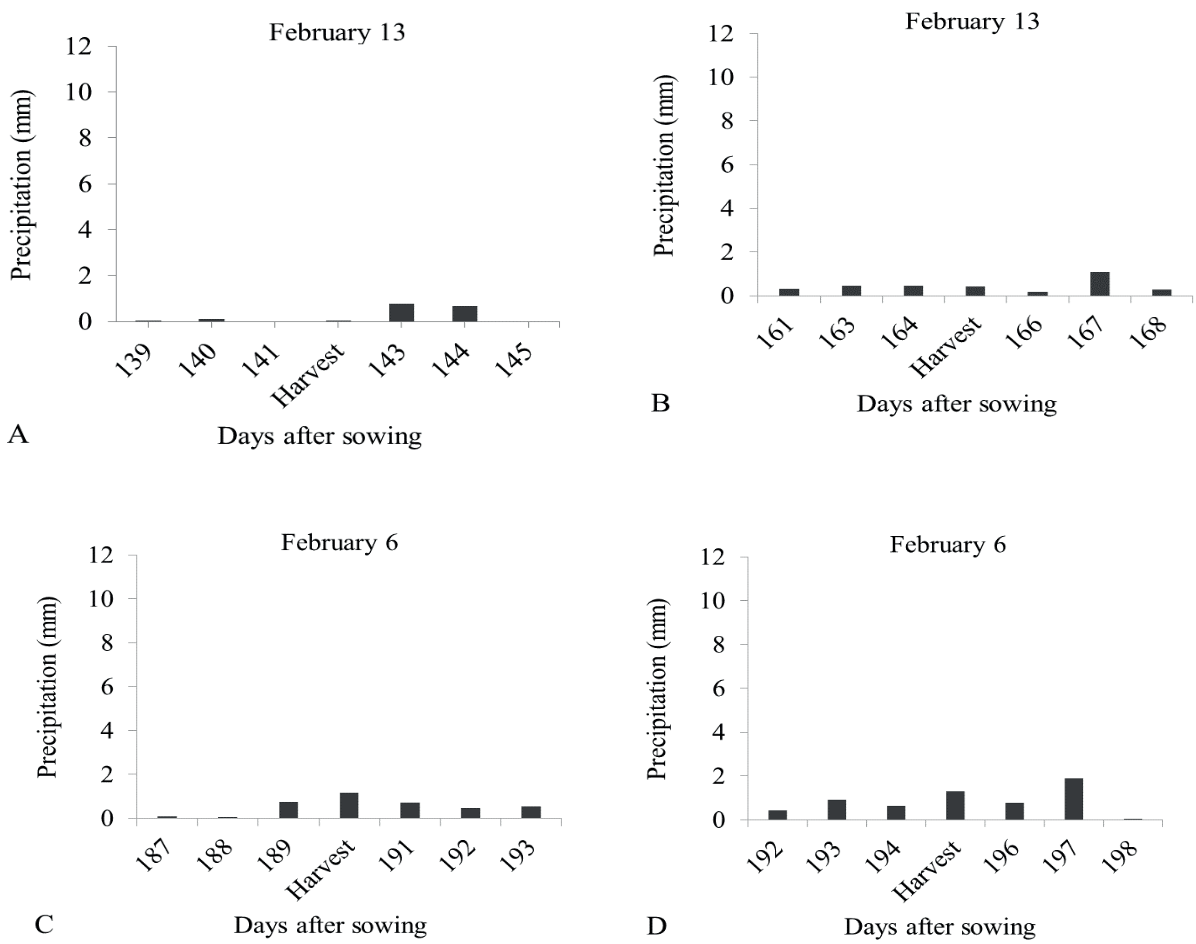

Figure 10. The average daily precipitation at the harvest period of maize silage under irrigation in the counties of (A) Sete Lagoas, (B) Itamarandiba, (C) Lavras and (D) Machado, Minas Gerais state, Brazil, considering the highest-productivity sowing date.

Conclusions

In general, the best sowing dates for maize silage under rainfed condition occur in October. For the irrigated condition, the best dates are concentrated in February.

For the best sowing dates, i.e., dates associated with the highest silage productivity among other sowing dates, the rainfed condition provided lower maximum silage productivity and greater interannual variation than the irrigated condition.

The quality of silage under irrigation condition tends to be higher than under rainfed condition, and with lower risks to soil compaction at harvest due to low precipitation amounts.

Optimal conditions of soil water availability, air temperature and solar radiation determine maize silage productivity in tropical agriculture.

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