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Multivariate analysis to characterize flaxseed production environments in Brazil

Análise multivariada para caracterizar ambientes de produção de linhaça no Brasil

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Highlights

The PCA explained 78% of the environment variability to flaxseed in Brazil.
Organic carbon and rainfall influencing flaxseed yield in Inceptisol.
Temperatures and the Oxisol loads balance acting in the flaxseed performance.
The first study on the assessment of environments for flaxseed production in Brazil.

Abstract

The environments for flaxseed production and its soil-plant-atmosphere relationship, it is essential for distinguish and adapt them to the soil and crop management to obtain high sustainable yields and food diversification. Our goal was to characterize the main edaphoclimatic conditions for flaxseed production in South-Central, Brazil. The experiments were carried out in two locations representative of the edaphoclimatic conditions of South-Central, Brazil: 1 - Dourados, MS, with an Aw climate and LATOSSOLO VERMELHO Distroférrico (Haplustox) and 2 - Curitibanos, SC, with a Cfb climate and CAMBISSOLO HÚMICO (Haplumbrept), both cultivated with four flaxseed varieties: Aguará and Caburé from Argentina, UFSC (reddish-brown color) and Golden (golden-yellow color) from Brazil, grown under no-tillage system and few resources. Data from weather (air temperature and rainfall), plant growth, soil chemical and physical-hydric attributes, and post-harvest quality of flaxseed were monitored. The data were submitted to Pearson's correlation matrix ($P < 0.05$) and multivariate principal component analysis (PCA). PCA segregated edaphoclimatic environments and varieties into four distinct groups. Each edaphoclimatic condition there was specific attributes discriminated by PCA (> 78%). The lowest plant height (< 0.85m), shorter cycle length (120-142 days) and high yield (≈1.13

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Mg ha^{-1}), especially golden-yellow flaxseed, were found in Dourados. The soil organic carbon and rainfall acted directly in Curitibanos, while charge balance and air temperature responded in Dourados influence flaxseed production. Soil physical and grain attributes were similar between the environments investigated. Both agricultural environments showed feasibility for flaxseed sustainable production in Brazil, it is important to emphasize that these results are pioneers, especially the edaphoclimatic conditions from Dourados.

Key words: Agroecosystem. Edaphoclimate condition. *Linun usitatissimum L.* Principal components. Sustainable production.

Resumo

Os ambientes de produção de linhaça e sua relação solo-planta-atmosfera é fundamental para distingui-los e adaptá-los ao manejo do solo e da cultura para obtenção de elevados rendimentos sustentáveis e diversificação alimentar. Nosso objetivo foi caracterizar as principais condições edafoclimáticas para a produção de linhaça no Centro-Sul, Brasil. Os experimentos foram conduzidos em dois locais representativos das condições edafoclimáticas do Centro-Sul, Brasil: 1 - Dourados, MS, com clima Aw e LATOSSOLO VERMELHO Distroférrico (Haplustox) e 2 - Curitibanos, SC, com clima Cfb e CAMBISSOLO HÚMICO (Haplumbrept), ambas cultivadas com quatro variedades de linhaça: Aguará e Caburé da Argentina, UFSC (coloração marrom-avermelhada) e Dourada (coloração amarelo-ouro) do Brasil, cultivadas em sistema plantio direto e baixo input. Foram monitorados dados de clima (temperatura do ar e precipitação), crescimento da planta, atributos químicos e físico-hídricos do solo e qualidade pós-colheita da semente de linhaça. Os dados foram submetidos à matriz de correlação de Pearson's ($P < 0,05$) e a análise multivariada de componentes principais (PCA). O PCA segregou os ambientes edafoclimáticos e variedades em quatro grupos distintos. Em cada condição edafoclimática a PCA identificou atributos específicos que os diferenciaram (> 78%). A menor altura de planta (< 0,85m), menor comprimento do ciclo (120-142 dias) e alto rendimento (≈1,13 Mg ha-1), especialmente a linhaça amarelo-ouro, foram encontrados em Dourados. O carbono orgânico do solo e a chuva atuaram diretamente no ambiente de Curitibanos, enquanto o balanço de carga e a resposta a temperatura do ar em Dourados influenciam a produção de linhaça. Os atributos físicos dos grãos e do solo foram semelhantes entre os ambientes investigados. Ambos os ambientes agrícolas apresentaram viabilidade para a produção sustentável de linhaça no Brasil, é importante ressaltar que esses resultados são pioneiros, principalmente nas condições edafoclimáticas de Dourados.

Palavras-chave: Agroecossistemas. Condições edafoclimáticas. *Linun usitatissimum L.*. Componentes principais. Produção sustentável.

Introduction

Generating knowledge on the interactions between soil, plant, and atmosphere requires the analysis of a large number of variables to distinguish the best agricultural production environments. In this sense, measuring the performance of biotic and abiotic factors, strongly dependent within and between agro-ecosystems, becomes a complex task. Defining the extent to which soil and climate act together in the plant development is the key factor to infer about the quality of the production environment

(Stanck, Becker, & Bosco, 2017; Casa, Russell, Cascio, & Rossini, 1999; Bosco, Becker, Stanck, Carducci, & Harthmann, 2020).

Thus, defining the environment and the most sustainable management system for safe food production and soil conservation, supports a reduction in degradation processes, while increasing carbon stock in the soil (Chen, Zhang, Zhao, Hu, & Zhang, 2018; Zinn, Lal, Bigham, & Resk, 2007). Conservationist agro-ecosystems, such as no-tillage and different modalities (crop, livestock, and forest), with or without agroecological techniques, advocate soil conservation by maintaining plant residues on it, in addition to promoting soil quality improvements due to the use of different management practices. In contrast, negative effects of climate change, such as the greenhouse gases, are minimized in those conservationist systems (Serafim et al., 2013; Magalhães, Pedreira, Tonini, & Farias, 2019; Ebmeyer, Fiedler-Wiechers, & Hoffmann, 2021).

Improvements in the diversification of food products, soil quality, and new income for farmers are intensified with the cultivation of alternative plants, such as flaxseed (Bosco et al., 2020; Stanck et al., 2017; Carducci, Schoeninger, Xavier, Ferreira, & Freitas, 2018; Zając Oleksy, Stoktosa, Klimer-Kopyra, & Kulig, 2013). Flax is a winter oilseed that presents easy management and low production costs, in contrast to the high added value of the final product (Casa et al., 1999; Singh, Mridula, Rehal, & Barnwal, 2011; Stanck et al., 2017). This crop is widely produced in Europe (fibers, 96.8%), Asia (grains 43.6%), and North America, with Canada as the main trade representative of grains and fibers (80%) (Food and Agriculture Organization of the United Nations [FAOSTAT], 2020; Flax Council Canada [FCC], 2020).

Flaxseed cultivation is novelty in Brazil, with an estimated yield of 1,916 tons year^{-1}, thus requiring studies that show the environmental potential and limitations, in addition can be an incentive for the production of this plant in the country (Instituto Brasileiro de Geografia e Estatística [IBGE], 2020; Stanck et al., 2017; Kohn, Carducci, Barbosa, Bosco, & Rossoni, 2020; Bechlin, Granella, Christ, Coelho, & Viecelli, 2019). This crop has several uses for industrial purposes (e.g., oils, paints, textiles, plastics, and cosmetics), human food, animal feed, biomaterials and biofuel. It is very versatile for consumption due to its chemical components (e.g., omega-3, proteins, lignans, α-linolenic acid, and soluble and insoluble fibers) and highly durable fibers (Singh et al., 2011; Stanck et al., 2017; Gu et al., 2018).

In this sense, knowing the environments for flaxseed production and its soil-plant-atmosphere relationship although scarce in scientific literature, it is essential for distinguish and adapt them to the soil and crop management to obtain high sustainable yields. Thus, through multivariate analysis, a large set of edaphoclimatic and phytotechnical data can be grouped and itemized, showing those most favorable to the development and production of flaxseed (Serafim et al., 2013; Zając et al., 2013; Ebmeyer et al., 2021). Thus, it is hypothesized that A) the best flaxseed production environment can be separated by the association of edaphoclimatic factors and B) South-Central Brazil has a high potential for flaxseed production. This study aimed to characterize the prime edaphoclimatic conditions for flaxseed production in South-Central, Brazil.

Material and Methods

Description of the study areas

The flaxseeds were cultivated in two sowing seasons (April and May) in 2018. One of the experiments was conducted in an area belonging to the Federal University of Santa Catarina, Curitibanos, SC, South region, located in the mountainous mesoregion of the state of Santa Catarina, at the geographic coordinates 27°16′58″ S and 50°35′04″ W and 987 m of altitude. The other experiment was carried out at the Federal University of Grande Dourados, located in Dourados, MS, Midwest region, at the geographic coordinates 22°13′16″ S and 54°48′20″ W and 430 m of altitude. The distance between both experimental areas is 975 km (Figure 1). These areas have been a potential for flaxseed production, which is why they were selected for research.

According to the Köppen classification (Alvares, Stape, Sentelhas, Moraes, & Sparovek, 2013), the regional climate of Curitibanos is Cfb, i.e., a subtropical climate without dry season and temperate summer, annual mean precipitation of 1480 mm well distributed throughout the year, and annual mean maximum and minimum temperatures of 22 and 12.4°C, respectively. The regional climate in Dourados is Aw, that is, a humid mesothermal climate with warm summers and dry winters, annual mean maximum and minimum temperatures of 29.1 and 17.5°C, respectively, and annual mean precipitation of 1442 mm.

The two soils under flaxseed cultivation was classified as: Curitibano's clayey Haplumbrepts (Soil Survey Staff, 2014), they correspond to Humic Cambisols in the Soil World Reference Base (IUSS Working Group WRB, 2014) and CAMBISSOLO HÚMICO álico argiloso (CHa) (2, 325, 673 g kg^{-1} respectively, for sand, silt and clay fraction) in Brazilian classification (Santos et al., 2018), originated from basalt; and Dourado's clayey Haplustox (Soil Survey Staff, 2014), they correspond to Red Latosol (IUSS Working Group WRB, 2014) and LATOSSOLO VERMELHO Distroférrico argiloso caulinítico (LVdf) (149, 181, 670 g kg^{-1}, respectively for sand, silt and clay fraction) (Santos et al., 2018) from basalt, both with an adequate fertility (Table 1).

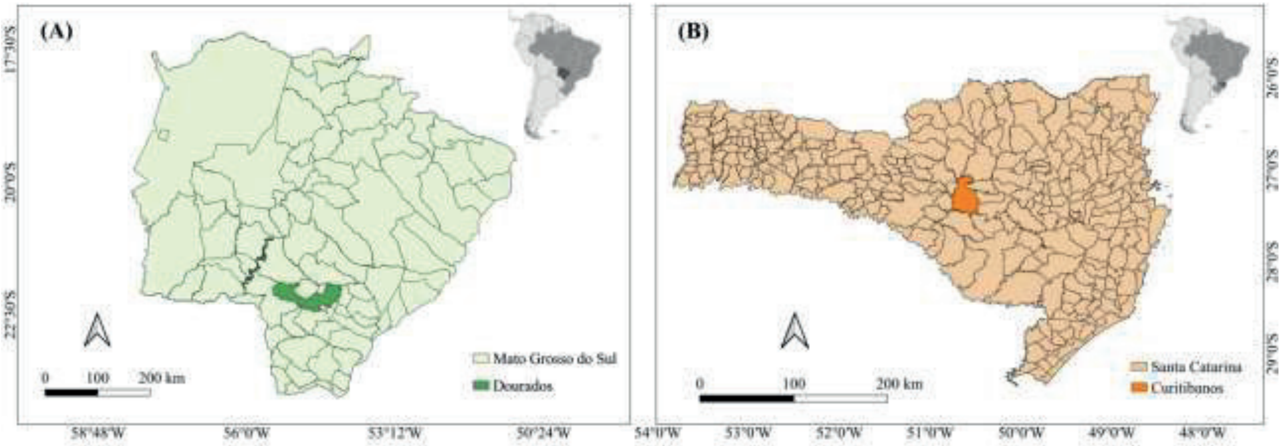

Figure 1. Experimental areas. A) Dourados, Mato Grosso do Sul, B) Curitibanos, Santa Catarina, Brazil.

Table 1
Chemical analyzes of the Haplumbrept (CHa) and Haplustox (LVdf) at 0-0.20 m under flaxseed cultivation in a soil conservacionist management system

Solo	pH	K	P	Ca	Mg	Al	H+Al	SB	T	T	V	m	M.O	P-Rem
		.....mg dm^{-3}.....		..............................cmolc dm^{-3}.........................							........%.......		dag kg^{-1}	mg L^{-1}
CHa	5.9	134.53	6.04	6.76	3.95	0.10	5.77	11.05	11.15	16.82	65.73	0.90	5.53	13.30
LVdf	6.6	282.36	30.09	7.31	2.27	0.04	2.86	10.3	10.34	13.16	78.3	0.39	2.73	22.86

In short, both environments representative of the edaphoclimatic conditions of South-Central Brazil were characterized as a) Curitibanos - Cfb climate and Haplumbrepts and b) Dourados - Aw climate and Haplustox.

Direct sowing was carried out manually in the second half of April and May, with an inter-row spacing of 0.39 m and 0.02 m between plants, with four useful rows per plot.

We started the soil management one year before the experiments in both areas, to improve the edaphic conditions for the flaxseed crop. The area of Haplustox received phosphorus at dose of 12 g m^{-2} per sowing row of the formulated 8-20-20 due to the characteristic of high adsorption of Brazilian Oxisol (Ferrasol) (Ferreira, Fernandes, & Curi, 1999) and 3.9 Mg ha^{-1} of oat hay (*Avena sativa*) was added on the soil surface as a protection against erosion and the sowing system was no-tillage. On the other hand, the area of Haplumbrept received no chemical fertilizer applications, only 100 g m^{-1} of organic fertilizer (cured poultry litter) applied in sowing row and 3.9 Mg ha^{-1} of Jiggs hay (*Cynodon* spp.) after sowing to provide better soil coverage, reducing evaporation and weed occurrence during cultivation. In 2018 in both experimental areas, no-tillage system and the addition of oat hay (Haplustox) and Jiggs hay (Haplumbrept) on the soil surface were repeated. When necessary, weeds were controlled manually.

It is important to know that the soil coverings used, in the form of hay, were selected due to the supply these materials at the time experimental areas implantation.

Four flaxseed varieties were used, three with reddish-brown seeds (Caburé and Aguará) from the National Institute of Agricultural Technology (INTA) of Argentina (Milisich, 2017) and a landrace variety here called UFSC from production in experiments of the Federal University of Santa Catarina, Curitibanos, SC, Brazil. A landrace variety with golden-yellow seeds from this university, here called Golden, was also used.

The daily meteorological data of rainfall and maximum and minimum air temperature in the experimental area located in Dourados were measured with instruments and sensors installed in the center of the flaxseed cultivation area (pluviometer and HOBO® temperature sensor). In Curitibanos, data on precipitation and maximum and minimum air temperature came from an automatic weather station installed 500 m from the cultivation area.

Phytotechnical data

The height of four plants selected and randomly marked in the center of each plot was measured weekly using a ruler graduated in centimeters. These plants were used to identify the stages of emergence (EM), beginning of blooming (BF), appearance of the first visible capsules (VC), and harvest (HAR) in both environments as described by Smith and Froment (2008). Crop production was determined at the harvest stage by the total mass of seeds harvested in each plot. The yield components, that is, number of capsules per plant and number of seeds per capsule were also quantified (Stanck et al., 2017; Carducci et al., 2018).

Soil sampling, physical and chemical analysis

Trenches with dimensions of 0.30 m length x 0.30 m wide x 0.30 m deep were dug at each experimental plot in both production environments. Undisturbed soil samples were collected using volumetric cores (≈ 95 cm^3) and disturbed soil samples were taken from the layers identified by the visual structure analysis performed in the field (Moncada, Ball, Gabriels, Lobo, & Cornelis, 2015), with the identification of two contrasting layers (0-0.07 and 0.07-0.20 m).

The disturbed soil samples allowed determining the particle size by the pipette method and particle density by the volumetric flask method. The organic carbon content was determined by the wet oxidation method of organic matter based on the Walkley-Black recommendations (Teixeira, Donagemma, Fontana, & Teixeira, 2017; Zinn et al., 2007). The data from particle size and organic carbon analysis allowed determining the structural quality index, which expresses the risk of structural soil degradation based on the organic carbon, according to the method presented by Moncada et al. (2015).

The pH in H_20 and KCl, which evaluate the active and exchangeable acidity, respectively, was determined to estimate the net soil charge balance (ΔpH) according to the equation $\Delta pH = pH_{KCl} - pH_{H2O}$ and the zero charge point (PZC) according to the equation $PCZ = 2\ pH_{KCl} - pH_{H2O}$, Teixeira et al. (2017).

The undisturbed soil samples allowed determining the soil bulk density (BD), total porosity (TPd) was obtained using the saturated ring method, while the calculated total porosity (TPc) was obtained considering Ds and the particle density (PD), according to TPc = 1 − (Ds/Dp). Blocked pores were determined according to BP = TPd − TPc and air-filled porosity according to AP = TPV − 0.1. Soil micropores (MI) were determined on a tension table at −6 kPa, according to the capillarity equation h = 0.3/d, while soil macropores (MA) were obtained by the difference between MI and TPd, in addition to soil pore distribution. Hydric attributes, such as field capacity (FC = Ψm −6 kPa, considering the limit between macro- and micropores), permanent wilt point (PWP = −1500 kPa), and available water capacity (AWC = FC − PWP) were also analyzed (Serafim et al., 2013; Teixeira et al., 2017).

Physical and chemical attributes of flaxseed

Grain water content was determined after harvesting using the oven at temperature of 105±3°C until constant mass (MAPA, 2009). The 100-grain mass was measured in five subsamples of each replication, with grains counted manually and mass measured on a precision scale (0.01 g). The specific apparent mass was determined by adding the mass of grains into a 25 mL beaker, allowing the calculation of the mass to volume ratio, presented in kg m^{-3} (Mohsenin, 1970; Coskuner & Karababa, 2007; Instituto Adolfo Lutz [IAL], 2008).

The flaxseed dimensions were measured using a digital caliper with a 0.01 mm precision in the three perpendicular axes (length, width, and thickness), according to Coskuner and Karababa (2007). Ten grains from each experimental unit were used. The geometric diameter of the flaxseed was calculated using the values of these measurements (Mohsenin, 1970).

The color evaluation was performed on whole flaxseed placed in Petri dishes by direct measurement with a Konica Minolta® CR 400 colorimeter. The measurements were presented using the chromatic coordinates L (lightness), C (chroma), and H (hue), according to the Commission Internationale de l'Eclairage (CIE) color model. The illuminant D65 was used and the device was calibrated on a white ceramic plate before the readings using the standards pre-established by the manufacturer (Y = 87.7; x = 0.3189, and y = 0.3361) (Bechlin et al., 2019; IAL, 2008).

The chemical quality parameters were estimated by processing the product in flax flour. The acidity index (AI) and oleic acid index (OAI) were determined according to the potentiometric method (IAL, 2008), considering AOA per 100 g molecular weight equal to 282.47 g mol^{-1}. All analyzes of flaxseed were carried out in triplicate within each experimental plot, which makes it possible to increase the accuracy of the data

Statistical analyses

The experiment was carried out in Curitibanos, SC, South region and Dourados, MS, Midwest region from Brazil with four varieties (Aguará, Caburé, UFSC, and Golden) in two sowing seasons (April and May), two soils (Haplumbrept and Haplustox) was analyzed two soil layers (0-0.07 m and 0-0.07-0.20 m) with three field repetitions.

The datas were subjected to the Shapiro-Wilk analysis, which tested the normality of variances. The datas were fit the distribution normal were compared by the t test ($P<0.05$). Pearson's correlation analysis was used at a significance level of 5% probability, performed by correlogram in R language (R Core Team [R], 2019).

Subsequently, the datas were submitted to the principal component analysis (PCA) method, from the Pearson's correlation matrix, using all the mentioned responses as original variables. We used 1714 observations and 49 variables, which corresponds to the physical and chemical variables of the soil and grains, in addition to the plant phenometry, rain and air temperature (maximum and minimum), all analyzed with three repetitions to soil, plant and grain.

The PCA allowed interpreting the relationships between physical, hydric, and chemical soil variables with the weather data, plant phenometry, and physical quality of grains in the four varieties (Aguará, Caburé, UFSC, and Golden), two sowing seasons, two soil classes and two depth. The components extracted from the correlation matrix of the original variables were considered sufficient when they explained more than 70% of the data variance (Manly, 2008). The analyses were performed using the software XLSTAT (Addinsoft, 2014).

Crop productivity data were evaluated according to the assumptions of variance analyses ($P<0.05$) performed in randomized completely block design with four varieties (Aguará Caburé, Golden and UFSC) x two sowing seasons (April and May) x two environments (Curitibanos, SC and Dourados, MS). The averages were compared to Tukey's test ($p\leq0.05$).

Results

Metereological conditions in both production environments

The highest rainfall volume accumulated (612 mm) during the crop cycle occurred in Curitibanos, as well as the lowest temperatures followed by three frost events (8/26, 8/27, and 9/5), coinciding with the blooming and grain filling period (BF-VC) (Figure 2 and 3). In most of the crop cycle temperatures above 20ºC were recorded in Dourados, although low temperatures had been recorded from June to August (≈ 13°C).

Both locations registered the lowest rainfall in July. Dourados presented merely 9 mm, while Curitibanos accumulated 50 mm (Figure 2).

Height, phenology, and productivity of flaxseed in both production environments

The phenological stages allowed observing differences between the development environments of flaxseeds and between varieties within the same environment. The longest developmental cycle of the flaxseed was observed in Curitibanos, where plants show a prolonged vegetative period, reaching more than 100 days (EM-BF, emergence to the beginning of blooming). In the first growing season (April), varieties with reddish-brown seeds (Aguará, Caburé and UFSC) completed their productive cycle with 221 days (Figure 3).

The crop cycle in Dourados varied from 124 to 142 days, with the highest period from sowing to emergence (PL-EM) occurred in April. The variety Golden completed its development cycle in 125 days, regardless of sowing time, and its EM-BF stage was shorter compared to the other varieties, thus anticipating the grain harvest (Figure 3).

Plant height was similar within each studied environment. Just in case, the Golden flaxseed was the smallest size in the final development cycle when sown in April in the two experimental areas. Plants reached the highest mean height in Curitibanos in April (130 cm). However, in Dourados the plants height did not exceed 85 cm, regardless of the variety (Figure 4).

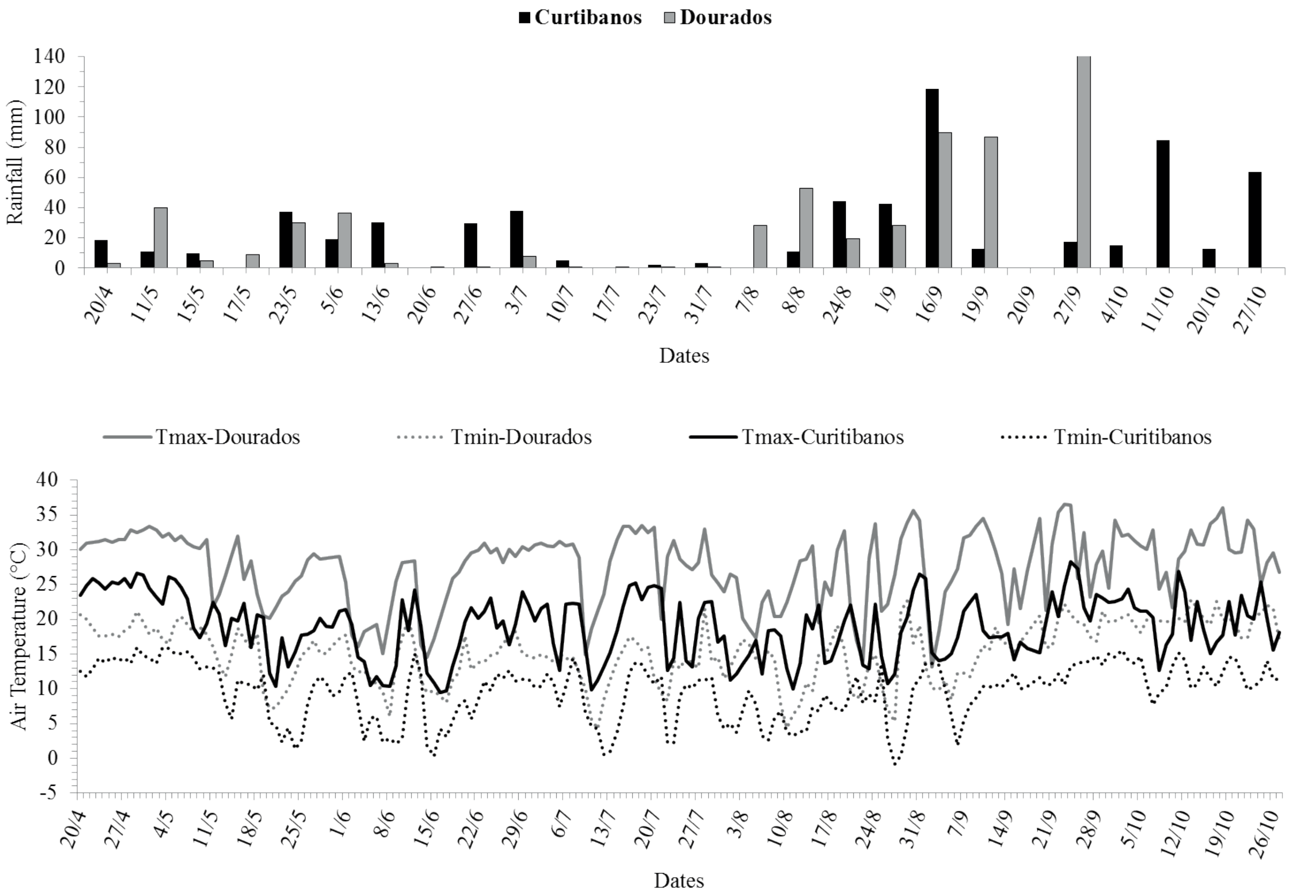

Figure 2. Rainfall (mm), maximum (Tmax) and minimum (Tmin) temperature for two flaxseed production environments: Curitibanos, SC and Dourados, MS.

The period from seedling emergence until the beginning of blooming (EM-BF) was similar in the two sowing seasons in each production environments, with the longest duration for Curitibanos in April sowing date. The final period of grain maturation (BM-HARV) varied from 15 to 34 days, with the longest period recorded for varieties with reddish-brown seeds (Aguará, Caburé, and UFSC) sown in April, especially in Dourados (Figure 3). Productivity showed significant differences only between the production environments, with the highest values for Dourados in both sowing seasons (Table 2).

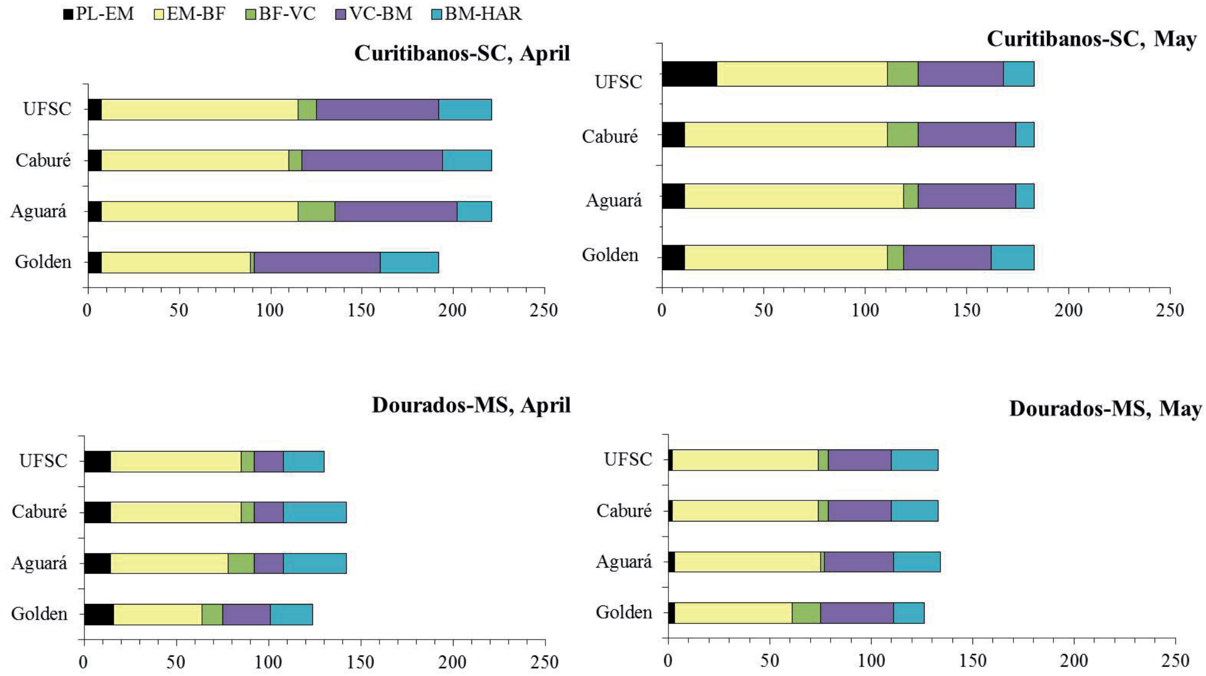

Figure 3. Development cycle of flaxseed varieties: Aguará, Caburé, UFSC and Golden, in two sowing dates (April and May) cultivated under conservationist soil management in Curitibanos and Dourados. PL-EM: sowing to emergence; EM-BF: emergence to beginning of blooming; BF-VC: beginning of blooming to visible capsule; VC-BM: visible capsule to beginning maturation; BM-HAR: beginning maturation to harvest.

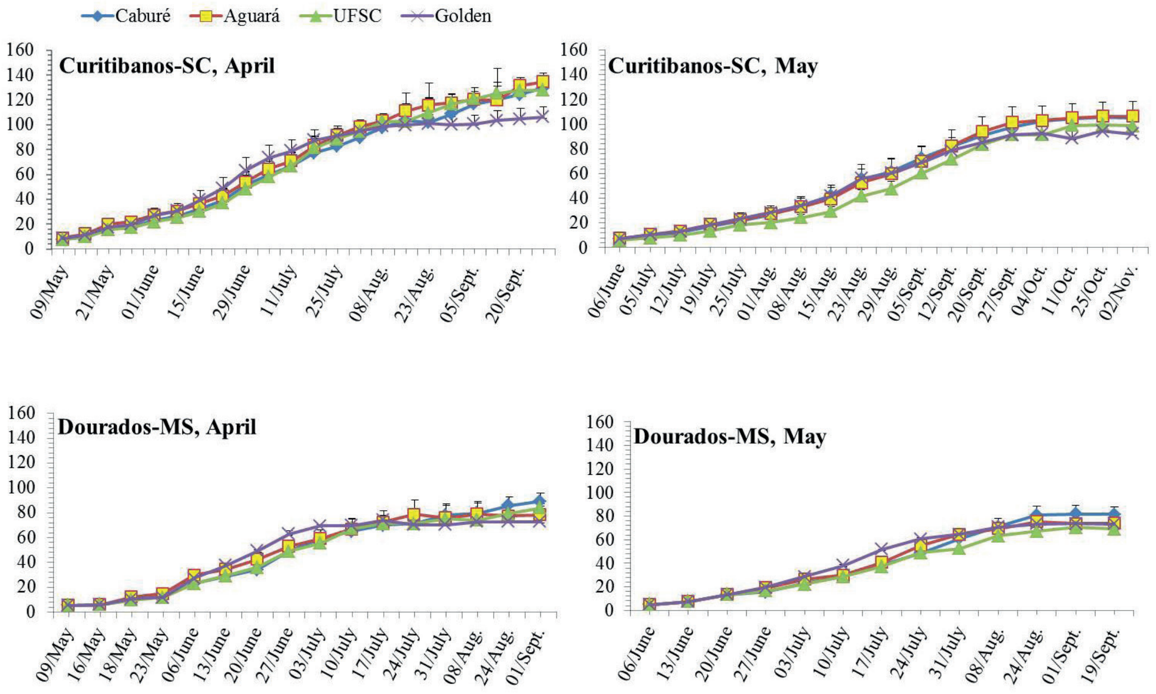

Figure 4. Height (cm) of flaxseed varieties: Aguará, Caburé, UFSC and Golden, in two sowing dates (April and May) cultivated under soil conservation management in Curitibanos and Dourados.

Table 2
Chemical analyzes of the Haplumbrept (CHa) and Haplustox (LVdf) at 0-0.20 m under flaxseed cultivation in a soil conservacionist management system

Sowing Season	Curitibanos*			
	....Mg ha^{-1}..			
	Caburé	Aguará	UFSC	Golden
April	0,19±0,14^{bA}	0,30±0,09^{bA}	0,30±0,11^{bA}	0,12±0,06^{bA}
May	0,14±0,05^{bA}	0,20±0,07^{bA}	0,22±0,09^{bA}	0,13±0,06^{bA}
Sowing Season	Dourados*			
	....Mg ha^{-1}..			
	Caburé	Aguará	UFSC	Golden
April	1,18±0,29^{aA}	0,97±0,25^{aA}	1,44±0,31^{aA}	1,19±0,28^{aA}
May	0,83±0,09^{aA}	1,12±0,44^{aA}	0,92±0,02^{aA}	1,41±0,25^{aA}

*Significant (P<0.05). Lower case letters in the line do not differ between production environments inside the variety. Capital letters in the column do not differ between sowing season dates by Tukey test ($p \leq 0.05$).

Pearson's correlation in both production environments

Pearson's correlation showed in Figure 5 that the total of 22.4% of the analyzed variables had a positive and strong correlation ($0.6>|r|<1.0$), that means, the positive direction and the value above 0.5 suggest the strength of the linear relationship between the evaluated variables (Figueiredo & Silva, 2009), that was represented by the blue color and large circles. Positive correlations occurred between soil resistance and grain quality variables, besides chemical and physical attributes with plant height and grains quality. The soil and meteorological attributes strongly influenced yield flaxseed. The data showed a positive and strong interaction between penetration resistance (PR) with capsules (0.792), grain (0.839), grain diameter (Gdiameter, 0.724), water content (WC, 0.849) and between soil bulk density (BD) with Capsules (0.915), Grains (0.962), Gdiameter (0.807), grain thin (Thin, 0.832), and WC (0.793).

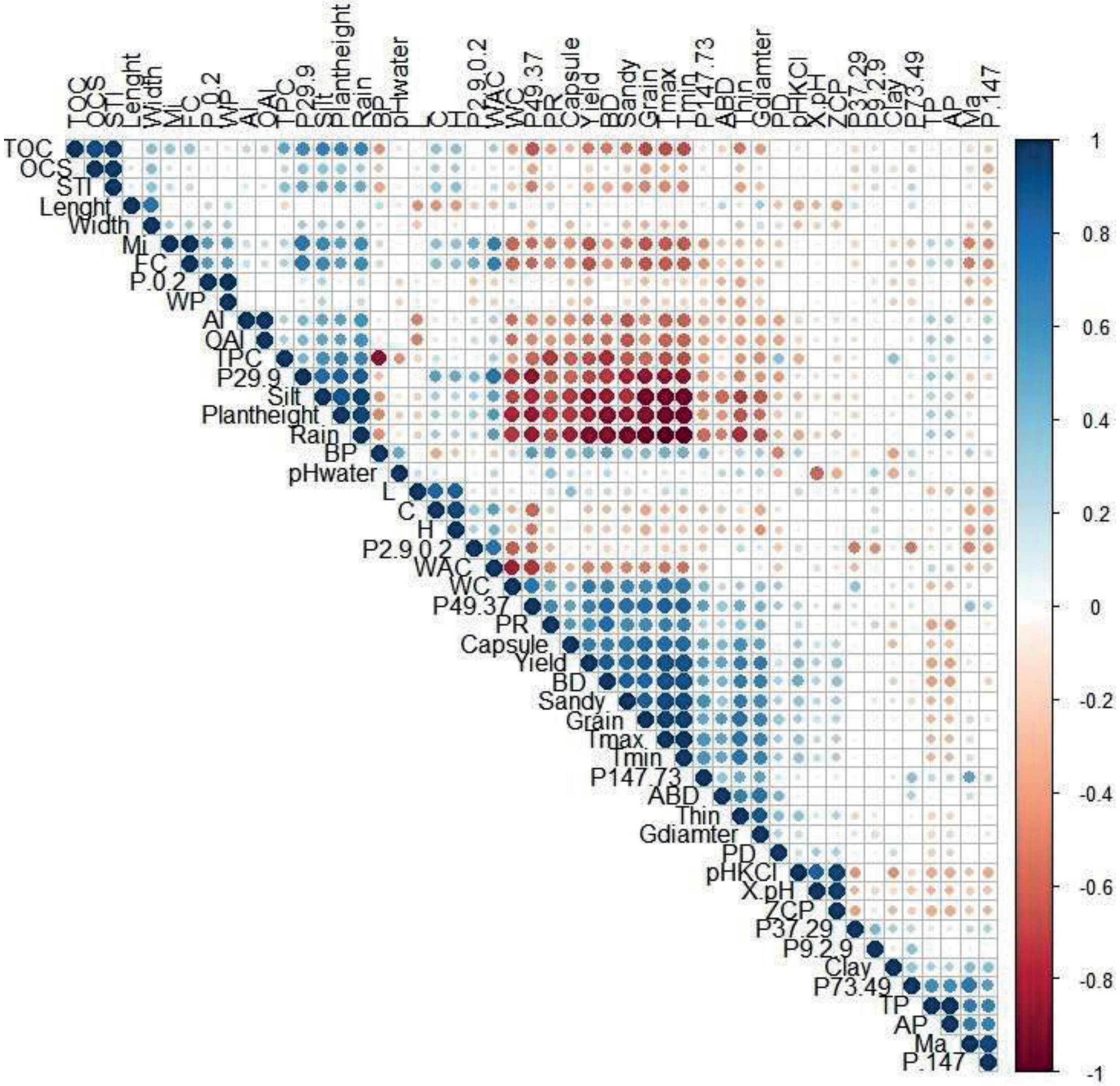

Figure 5. Pearson's linear correlation matrix of the analyzed variables. **Soil Physical variables:** WAC, water available capacity; FC, fields capacity; WP: wilting point; Mi, microporosity; Ma, macroporoity; TPC, calculated total porosity; Clay; Silt; Sand; AP, air porosity; PR, penetration resistance; BD, soil bulk density; PD, particle density; TP, total porosity; BP, blocked pores; P>147, pores with >147μm diameter; P_{147-73}, pores with 147-73μm diameter; P73-49, pores with 73-49μm diameter; P49-37, pores with 49-37μm diameter; P37-29, pores with 37-29μm diameter; P29-9, pores with 29-9μm diameter; P9-2,9, pores with 9-2,9μm diameter; P2.9-0.2, pores with 2.9-0.2μm diameter; P<0.2, pores with <0.2 diameter. **Soil chemical variables:** TOC, total organic carbon; OCS, organic carbon storage; STI, soil quality index; ZCP, zero charge point; pHKCl, pH in sodium chloride; pHwater, pH in destilled water; ΔpH as XpH, electrical charges balance. **Grain physical-chemical variables:** Length, grain length; Thin, grain thin; Width, grain width; Gdiameter, grain diameter; WC, grain water content; L, luminosity; H*, grain color angle or chromatic tone; C, grain chromaticity or saturation; ABD, specific apparent mass; AI, acid index; OAI, oleic acid index. **Meteorological variables:** Rain, Rainfall; Tmin, minimum temperature; Tmax, maximum temperature. **Phytotechnical variables:** Plantheight, plant height; Yield, crop yield; Capsule, capsule number; Grain, grain number.

The correlation between pores diameter with 49-37µm (P_{49-37}, belonging to the mesopores) with Grains (0.905), Thin (0.763), Gdiameter (0.795), WC (0.851), specific apparent mass (ABD, 0.724), and maximum and minimum temperature (Tmax and Tmin, 0.943) was significant and positive. However, negative correlation was observed with Clay and Silt (-0.943), fields capacity (FC, −0.881), water available capacity (WAC, −0.839), total organic carbon (TOC, −0.930), soil quality index (STi,−0.858), plant height (−0.952), and rainfall (rain, −0.943) (Figure 6). Water available capacity (WAC) was strongly correlated with pores with 29-9 µm diameter (P_{29-9}, 0.804), microporosity (MI, 0.749), FC (0.749), TOC (0.719) and plant height (0.763) (Figure 5).

Plant height had a positive correlation with WAC (0.763), FC (0.861), rainfall (0.977), MI (0.861), P_{29-9} (0.962), calculated total porosity (TPC, 0.833), STI (0.737), TOC (0.847), and Clay and Silt (0.977) (Figure 5). These results showed a high correlation between the soil, plant and atmosphere variables that we are testing.

Principal component analysis: soil, plant, and atmosphere

The environments differed significantly for most of the analyzed variables: soil, plant and grains (Table 3 and 4) exceptions occurred regarding the distribution of smaller pores (textural pores) and, consequently, the permanent wilting point, in addition to the pH in water and grain length, which were similar. Regarding the flaxseed varieties, the environments differed in relation to the quality of the produced grains. In Dourados, the grains presented greater dimension and density, as well as less acidity.

The greatest results are obtained when the original variables are highly correlated, positively or negatively (Figure 5), which allowed the representation by two or more principal components (Manly, 2008). In this case the principal component analysis (PCA) discriminated four groups explained 78.25% of the variability of the soil physical, hydrical and chemical attributes, weather, plant phenometry, and physicochemical attributes of flaxseed evaluated, totaling 39 variables analyzed after exploring the datas through variance analyze and Pearson's correlation (Figure 6).

The component F1 explained 64.54% of the original data variability, with the highest contribution of the variables: soil bulk density (BD), micropores (MI), pores diameter with 29-9µm (P29-9), pores diameter with 49-37µm (P49-37), field capacity (FC), particle size (Clay, Sand and Silt), particle density (PD), plant height (Plantheight), number of grain (Grain), rainfall (Rain) and temperature (Tmax and Tmin) directly influences the crop yield (Yield).

The component F2 explained 13,71% of the original data variability, with the contribution of the variables:, structural quality index (STI), soil organic storage (OCS), Lightness (L), Chroma (C), and Hue (H), air-filled porosity (AP), acid index (AI) and oleic acid index (OAI)(Figure 6).

The flaxseed varieties were separated by color: Golden occupied the upper quadrants of the PCA. The association of soil and flaxseed variety both in the Haplustox (LVdf) and Haplumbrept (CHa) with the Golden flaxseed stood out from the others with the highest observation contribution the CHa-Golden was 16 and 17% in F1 and F2 respectively, while the LVDf-Golden was 8.4 % in F1 and 46% in F2 (Figure 6).

Table 3
Soil physics and chemical attributes in both environmental evaluated

				Soil physics attributes				
Environmental	PR	BD	PD	TP	Ma	Mi	P>147	P147-73
	MPa	Mg m^{-3}				...........................m^3 m^{-3}...........................		
Curitibanos, SC	0.11	0.99	2.45	0.62	0.12	0.50	0.0773	0.015
Dourados, MS	0.32	1.33	2.82	0.59	0.13	0.46	0.0804	0.025
p(1)	*0.0001*	*0.0001*	*0.0020*	*0.0146*	*0.5035*	*0.0002*	*0.7293*	*0.0136*
	P73-49	P49-37	P37-29	P29-9	P9-2.9	P2.9-0.2	P<0.2	TPC
				....m^3 m^{-3}..				
Curitibanos, SC	0.029	0.004	0.007	0.072	0.025	0.059	0.347	0.59
Dourados, MS	0.024	0.034	0.013	0.023	0.299	0.057	0.335	0.52
p	*0.1910*	*0.0001*	*0.1789*	*0.0001*	*0.3570*	*0.6884*	*0.1345*	*0.0001*
	BP	FC	WP	WAC	AP	Clay	Silt	Sandy
			............................m^3 m^{-3}........................				..............g kg^{-1}.............	
Curitibanos, SC	0.05	0.50	0.35	0.15	0.52	671	354	28
Dourados, MS	0.09	0.46	0.34	0.13	0.49	669	181	150
p	*0.0105*	*0.0002*	*0.1345*	*0.0018*	*0.0146*	*0.5884*	*0.0128*	*0.0001*
				Soil chemical attributes				
	pHwater	pHKCl	ΔpH	ZCP	TOC	OCS	STI	
					.....g kg^{-1}....			
Curitibanos, SC	5.65	5.51	0.136	5.37	32.90	3.30	5.52	
Dourados, MS	5.59	5.95	0.359	6.31	16.44	2.33	3.33	
p (soil)	*0.6794*	*0.0072*	*0.0277*	*0.0112*	*0.0001*	*0.0088*	*0.0001*	
p (variety)	*0.3891*	*0.2657*	*0.7531*	*0.5683*	*0.00034*	*0.0099*	*0.0026*	

(1)**t Teste (P<0.05). Soil Physical variables:** WAC, water available capacity; FC, fields capacity; WP: wilting point; Mi, microporosity; Ma, macroporoity; TPC, calculated total porosity; Clay; Silt; Sand; AP, air porosity; PR, penetration resistance; BD, soil bulk density; PD, particle density; TP, total porosity; BP, blocked pores; P>147, pores with >147μm diameter; P$_{147-73}$, pores with 147-73μm diameter; P73-49, pores with 73-49μm diameter; P49-37, pores with 49-37μm diameter; P37-29, pores with 37-29μm diameter; P29-9, pores with 29-9μm diameter; P9-2,9, pores with 9-2,9μm diameter; P2.9-0.2, pores with 2.9-0.2μm diameter; P<0.2, pores with <0.2 diameter. **Soil chemical variables:** TOC, total organic carbon; OCS, organic carbon storage; STI, soil quality index; ZCP, zero charge point; pHKCl, pH in sodium chloride; pHwater, pH in destilled water; ΔpH, electrical charges balance.

Table 4
Grains physical and chemical attributes and yield components in both environmental evaluated

Environmental	Plant eight cm	Number Capsules	Number Grain	Crop Yield Mg ha^{-1}	Length	Thin	Width	Grain Diameter	WC
					....................mm.................				g g^{-1}
Curitibanos, SC	71	9	3	213	4.41	0.69	2.26	1.89	0.08
Dourados, MS	45	45	8	1194	4.40	0.86	2.21	2.02	0.10
p (soil)[1]	*0.0001*	*0.0001*	*0.0001*	*0.0001*	*0.8737*	*0.0001*	*0.0419*	*0.0002*	*0.0001*
p (variety)	*0.0929*	*0.2968*	*0.3286*	*0.5074*	*0.0023*	*0.0854*	*0.0002*	*0.0554*	*0.0268*
	L	H	C	AI	OAI	ABC			
				.....g $100g^{-1}$.....		kg m^{-3}			
Curitibanos, SC	43.58	56,67	18.72	3.65	0.51	648			
Dourados, MS	46.25	51,49	15.27	1.57	0.22	685			
p (soil)	*0.0004*	*<0.0001*	*<0.0001*	*0.0001*	*0.0001*	*0.0087*			
p (variety)	*<0.0001*	*<0.0001*	*<0.0001*	*0.0017*	*0.0017*	*0.1170*			

[1] **t Teste (P<0.05). Grain physical-chemical variables:** Length, grain length; Thin, grain thin; Width, grain width; WC, grain water content; L, luminosity; H, grain color angle or chromatic tone; C, grain chromaticity or saturation; ABD, specific apparent mass; AI, acid index; OAI, oleic acid index.

The Haplustox cultivated with reddish-brown flaxseeds, Aguará and Caburé from Argentina, were grouped into the quadrant corresponding to the highest eigenvectors of the components F1 and smallest F2, while the Haplumbrept had the smallest eigenvectors of the component F1 and F2 with the same varieties (Figure 6).

Soil physical-hydric attributes and organic carbon influenced flaxseed development in Curitibanos, as well as correlated with the grains acidity indices (IA and OAI) and color (H and C). The edaphoclimatic conditions of Dourados connected the physical attributes of grains with the some soil physical (PR, BD,, P_{147-73}, P_{49-37}, BP, PD, and Sand) and chemical attributes (pH_{KCl}, ΔpH, and ZCP), which showed the highest contribution value of the component F1. Nevertheless, according to the PCA, it was found that the air temperature positively affected the flaxseed yield, as well as the number of grains and capsules, notably to Golden flaxseed (Figure 4 and 5).

Discussion

Flaxseed development in the production environments

The longest vegetative period of the evaluated varieties was observed in Curitibanos due to the higher exposure of plants to low temperatures for more days, leading to the lowest thermal and photoperiod accumulation. Precipitation was abundant and above what was necessary for the hydric requirements of the flaxseed crop (400-750 mm) (Bosco et al., 2020; Stanck et al., 2017) in Curitibanos (612 mm). However, although not

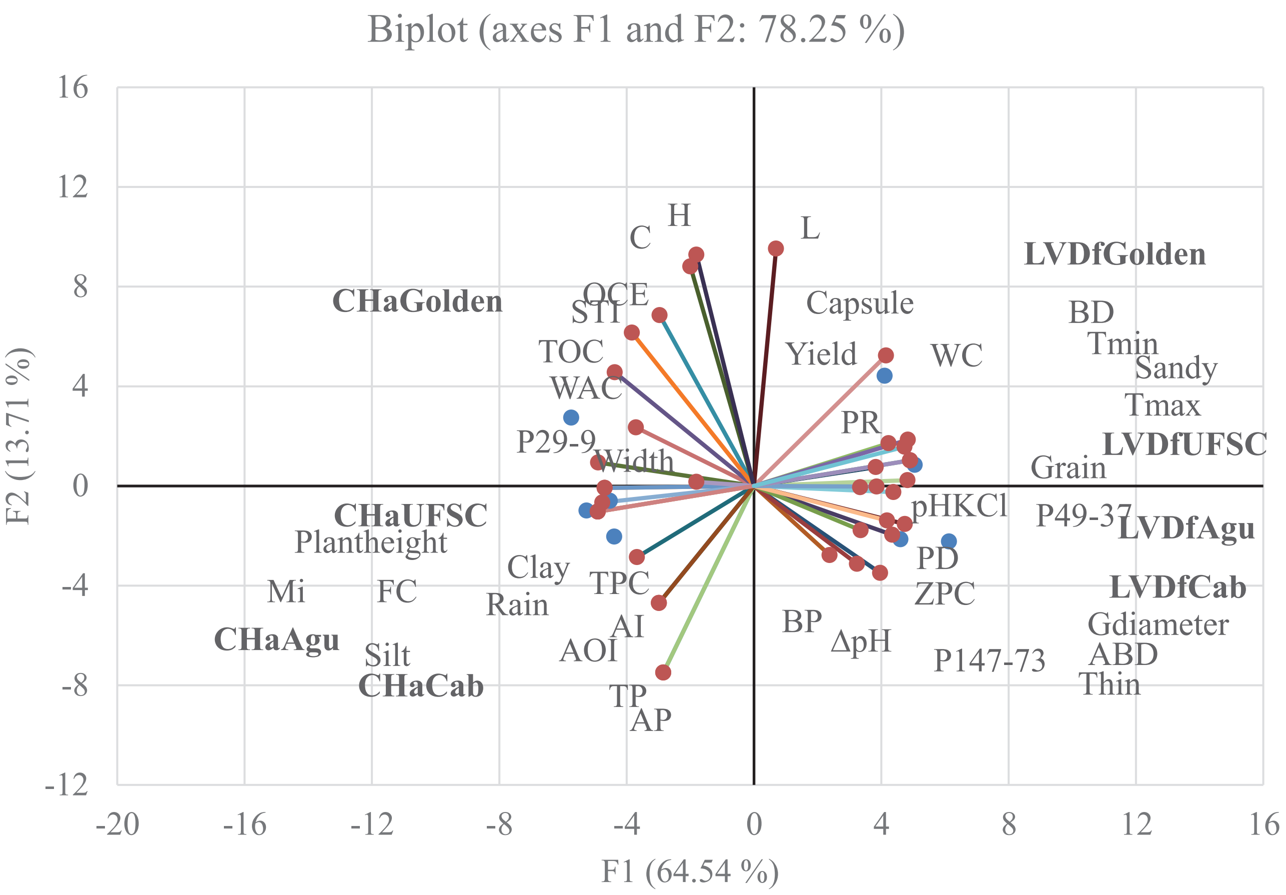

Figure 6. Variables contribution (%) of principal component analysis of the physical, hydrical and chemical soil attributes, flax phenometric, meteorological and physical-chemical attributes of the grains of four flaxseed: Aguará, Caburé, Golden and UFSC on Haplustox (Dourados) and Haplumbrept (Curitibanos) in conservationist soil management system. LVdf-Agu: Oxisol and variety Aguará; LVdf-Cab: Oxisol and variety Caburé;LVdf-Golden: Oxisol and variety Golden, LVdf - UFSC:Oxisol and variety UFSC. CHa-Agu: Inceptsol and variety Aguará; CHa-Cab: Inceptsol and variety Caburé; CHa-Golden: Inceptsol and variety Golden; CHa-UFSC: Inceptsol and variety UFSC. **Soil Physical variables:** WAC, water available capacity; FC, fields capacity; Mi, microporosity; TPC, calculated total porosity; Clay; Silt; Sand; AP, air-filled porosity; PR, penetration resistance; BD, soil bulk density; PD, particle density; TP, total porosity; BP, blocked pores; P147-73, pores with 147-73µm diameter; P49-37, pores with 49-37µm diameter; P29-9, pores with 29-9µm diameter; **Soil chemical variables:** TOC, total organic carbon; OCS, organic carbon storage; STI, soil quality index; ZCP, zero charge point; pHKCl, pH in sodium chloride; ΔpH, electrical charges balance. **Grain physical-chemical variables:** Thin, grain thin; Width, grain width; Gdiameter, grain diameter; WC, grain water content; L, luminosity; H*, grain color angle or chromatic tone; C, grain chromaticity or saturation; ABD, specific apparent mass; AI, acid index; OAI, oleic acid index. **Meteorological variables:** Rain, Rainfall; Tmin, minimum temperature; Tmax, maximum temperature. **Phytotechnical variables:** Plantheight, plant height; Yield, crop Yield; Capsule, capsule number; Grain, grain number.

abundant in Dourados (442 mm), precipitation was sufficient to meet the hydric requirements of the crop and promote a productivity of up to 1.41 Mg ha^{-1} (Table 2 and Figure 2).

The association of edaphoclimatic factors influenced productivity (Figure 5 and 6). The highest frequency of temperatures close to 20°C (Figure 2) and, consequently, the lowest thermal amplitude and longest photoperiod (≈ 12 h day) (Bosco et al., 2020; Casa et al., 1999) in Dourados led the plants to shorten their development cycle with an increase in productivity compared to Curitibanos (Bosco et al., 2020; Darapuneni, Morgan, Ibrahim, & Duncan, 2014) (Figure 3 and Table 2). According to Casa et al. (1999) and Bosco et al. (2020), the knowledge of environmental and agronomic factors is essential to estimate the production variability.

Moreover, the occurrence of extreme events such as frosts, especially during the grain filling stage (BM-HAR) has a negative effect on flaxseed productivity (Casa et al., 1999; Heller et al., 2015; Bosco et al., 2020) and in its chemical composition, thus increasing the grains acidity values (Bechlin et al., 2019; Singh et al., 2011) (Figure 6), as observed in Curitibanos, which registered three consecutive frosts during that period (Figure 2 and 4). Temperatures lower than 5°C promote intercellular freezing of the seed in formation and paralyze its growth (Bosco et al., 2020). Thus, low productivity was observed (<0.30 Mg ha^{-1}) when compared to the production environment of Dourados, which was not influenced by cold thermal stress (Table 2 and Figure 2).

In recent works on the flaxseed cultivation in Santa Catarina, South region from Brazil, has reported yields of up to 1.5 Mg ha^{-1} in years without consecutive frosts (Kohn et al., 2016; Stanck et al., 2017; Bosco et al., 2020), and these values corroborate the productivity found worldwide, that vary at 0.8 to 3.6 Mg ha^{-1} (Casa et al., 1999; Singh et al., 2011; FAOSTAT, 2020; FCC, 2020; Zając et al., 2013). However, Carducci et al. (2018) found yields of 0.3 to 0.5 Mg ha^{-1} of flaxseed in the Midwest region from Brazil, in a soil conservation system with no chemical fertilizers.

Distinction of environments by principal component analysis

The set of selected variables (49 response variables) was sufficient to explain the differences in both agriculture environments in South-Central Brazil, i.e., Curitibanos and Dourados, according to the principal component analysis (PCA). Thus, the four groups indicated a specific distribution pattern of the soil and meteorological attributes, being possible to group them into different environments, both with potential for flaxseed production, however with some particularities (Figure 5 and 6). Other authors have observed before promising results in the Brazilian flaxseed production (Bosco et al., 2020; Kohn et al., 2020; Carducci et al., 2018; Stanck et al., 2017; Kohn et al., 2016). However, it is worth mentioning that the Brazilian edafoclimate conditions for the flaxseed production has not been investigated yet.

The most important variables for the production environment of Dourados were the soil chemical variables, porosity, resistance and temperature associated with the Haplustox, regardless of the variety (Figure 6), separated by the effect association of the two axes. Haplustox is a very weathered soil, favoring the simple mineralogy of the clay fraction, that is, kaolinite and Fe and Al oxides, which includes oxides, hydroxides, and oxyhydroxides. These soils are also very deep, chemically poor, very acidic (high pHKCL), with pH-dependent surface charges (high zero charge point, ZCP and electrical charges balance, ΔpH), but physically they have a stable porous structure, allowing their chemical correction using agricultural inputs (Ferreira et al., 1999; Severiano et al., 2013; Santos et al., 2018).

The contribution of physical attributes related to water availability, retention and organic carbon in the Haplumbrept in Curitibanos is very clear (Figure 5). These variables were significant in the performance of all flaxseed varieties as verified also by Carducci et al. (2017) with the monitoring the physical-hydric conditions of that same flaxseed growing soil for two consecutive years, specially of the Golden in this Inceptisol, as well as in the plant height and grain color, although rainfall also affected the other varieties in this environment. Haplumbrept is young soil that have high silt contents, incipient structure of low stability, and little depth, but have high organic matter contents in its volumetric composition from their genesis (Santos et al., 2018; Carducci et al., 2017). Organic matter accumulation in this soil contributed to increasing the total organic carbon, carbon storage and cation exchange capacity (Figure 5 and 6), which are favored by the precipitation regime, resulting in more humid environments (Zinn et al., 2007; Carducci et al., 2017).

It is worth mentioning that the physical and chemical variables that constitute flaxseed grains, such as color, moisture content, size, and acidity, were directly related to the edaphoclimatic conditions and soil management in which they were grown (Casa et al., 1999; Singh et al., 2011; Heller et al., 2015; Zając et al., 2013) as noted in this investigation (Figure5 and 6).

It justifies the separation of the varieties by grain color (reddish-brown and golden-yellow) (Figure 5 and 6). According to Troshchynska et al. (2019), differences in grain color are related to its nutritional quality since lighter or darker integuments are from different concentrations of secondary plant metabolism compounds, such as carotenoids and phenolic compounds, in addition to the exposure to more solar radiation, which contributes to the higher grain pigmentation as observed by Bechlin et al. (2019) in addition to interactions with environmental conditions, changing the amount of bioactive compounds, as well as the acidity indices. Moreover, water content, soil acidity, electric charges, and variables related to soil organic carbon responded directly and indirectly in the acquisition of nutrients from the soil by the plant (Magalhães et al., 2019; Zinn et al., 2007).

The strong correlations between soil-plant-atmosphere attributes allowed the diagnosis of the potential and limitations of different production environments and crops (Figure 6) as also observed by other authors (Carducci et al., 2018; Serafim et al., 2013; Severiano et al., 2013; Bosco et al., 2020; Ebmeyer et al., 2021). However, the flaxseed crop was grown under a conservationist soil management system in both evaluated environments, which can promote an environmentally sustainable production, evidencing the effects of biotic (soil) and abiotic (climate) factors.

Conclusions

Each edaphoclimatic environment presented specific attributes that acted effectively in the flaxseed productivity. Attributes associated with organic carbon and rainfall had a direct influence in flaxseed yield in the Haplumbrept Curitibano's, while the soil balance electrical charges and the air temperature acted in the environment of Dourados (Haplustox), as soil and grain physical attributes were similar between environments. Also, rainfall favored the productivity of varieties with reddish-brown grains, while air temperature favored golden-yellow grain. Both environments under study showed feasibility for flaxseed sustainable production in Brazil, especially the edaphoclimatic conditions of Dourados, MS, for the Golden variety due to the better results of the yield and production components.

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Conflicts of interest

The authors declare no conflicts of interest.

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