

Indicadores de riesgo climático para el maíz de temporal en un país en desarrollo: el caso del Bajo Balsas, México

Climatic hazard indicators for rainfed maize in a developing country: the case of Bajo Balsas, Mexico

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Palabras clave: maíz de temporal; agricultura; minería de datos; WEKA

Keywords: rainfed maize; agriculture; data mining analysis; WEKA

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Resumen

Introducción: La agricultura de temporal es una de las actividades más vulnerables a los efectos del cambio climático, tanto la sequía como el exceso de humedad dañan los cultivos ocasionando cuantiosos daños económicos. En los países en desarrollo con escasos recursos para la inversión tecnológica, la agricultura de temporal es extremadamente importante para la producción de alimentos. La siembra de maíz de temporal en el Bajo-Balsas es para autoconsumo, de allí la importancia de identificar los indicadores de peligrosidad climática que amenazan la producción agrícola de este cultivo. El propósito de esta investigación fue construir y validar indicadores de riesgo climático considerando las diferentes etapas fenológicas de la planta.

Método: Primero, se identificaron las variables climáticas y se caracterizó el ciclo fenológico de la variedad de maíz que se cultiva en la región; posteriormente se elaboró una base de datos con los siguientes parámetros climáticos diarios y mensuales: precipitación pluvial, temperatura máxima y temperatura mínima. Se aplicó minería de datos con el software WEKA para validar y clasificar la producción de maíz de los 18 años analizados, posteriormente se calificaron los años por producción definiendo tres clases: 1) Peligrosidad baja con 0-10% de la superficie siniestrada y sin reporte de sequía; 2) Peligrosidad media: con 11-50% de la superficie siniestrada, reportes de sequías moderadas 3) Peligrosidad alta con 51-100% de la superficie siniestrada y reportes de sequía severa.

Resultados: Se obtuvieron diez indicadores de peligrosidad climática de los cuales cuatro corresponden al número de días con precipitación menor que cero en los meses de junio, julio, agosto y septiembre (DDL0jun; DDL0jul; DDL0ago; DDL0sep); dos indicadores con precipitación igual a 5 mm en junio y agosto (DDL5jun; DDL5ago); dos indicadores asociados a

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la temperatura máxima en julio y agosto (TX38jul; TX38ago) y dos indicadores con precipitación igual o mayor a 10 mm en octubre y noviembre (WDU10oct; WDU10nov). El resultado del estadístico de Kappa fue de 0.91, lo que indica una alta confiabilidad en la clasificación propuesta de las tres categorías de peligrosidad: alto, moderado y bajo.

Conclusión: El método propuesto sobre la validación de los indicadores de peligrosidad climática con el software WEKA permitió identificar a los indicadores más importantes que afectan el ciclo fenológico del maíz, y por lo tanto su rendimiento; la validación matemática del método muestra tres indicadores primarios, lo cual indica que existen variables primarias y secundarias que determinan el riesgo climático del mismo. Los indicadores de riesgo climático fueron automatizados y ajustaron utilizando el software ICC® (Indicadores de Cambio Climático), lo cual ofrece una herramienta útil para futuras investigaciones sobre el análisis de riesgo climático de otros cultivos de temporal.

Abstract

Introduction: Rainfed agriculture is one of the most vulnerable forms of crop to the effects of climate change producing either drought or excess moisture and thus damaging crops and causing substantial economic damage. In developing countries with scarce resources for technological investment, rainfed agriculture is extremely important for the food production. The sowing of seasonal maize in the Bajo Balsas is for self-consumption, thence the importance of identifying climatic hazard indicators that threaten agricultural production of this culture. The purpose of this study was to build and validate climatic hazard indicators considering the different phenological stages of the plant.

Method: First, we identify the climatic variables and characterize the phenological cycle of maize variety that is cultivated in the region; then we elaborate a database with the following daily and monthly climatic parameters: pluvial precipitation, maximum temperature and minimum temperature. We applied data mining with the WEKA software to validate and classify the maize production of 18 years, then, the years were classified by production defining three classes: 1) low hazard: a sinister area from 0 to 10%, without drought reports; 2) moderate hazard: a sinister area from 11 to 50%, with moderate drought reports; 3) high hazard: a sinister area from 51 to 100%, with reports of severe drought.

Results: We determined ten climatic hazard indicators of which four correspond to the number of days with precipitation lower than zero in the months of June, July, August and September (DDE0jun, DDE0jul, DDE0aug, DDE0sep); two indicators with rainfall equal to 5 mm for June and August (DDL5jun, DDL5aug); two indicators associated with the maximum temperature of July and August (TX38jul, TX38aug), and two indicators with precipitation equal to or greater than 10 mm in October and November (WDH10oct, WDH10nov). The result of the Kappa statistic was 0.91, indicating a high reliability in the classification of three hazardness categories: high, moderate and low.

Conclusion: The proposed method on the validation of climatic hazard with the WEKA software allowed to identify the most important indicators that affect the maize phenological cycle and therefore its yield; the mathematical validation of the method shows three primary indicators, which indicates that there are primary and secondary variables that determine its climatic hazard. The indicators of climatic hazard were automated and adjusted using ICC® (Indicators of Climatic Change) which offers a useful tool for future research on climate hazard analysis of other rainfed crops.

Introduction

Rainfed or seasonal agriculture is one of the most vulnerable forms of cultivation to the effects of climate change, producing either drought or excess moisture and thus damaging crops and causing substantial economic damage (O'Brien *et al.*, 2004; Zaidi *et al.*, 2008; PNUD, 2010; Martínez-Fernández, 2006). In developing countries with scarce resources for technological investment, rainfed agriculture is extremely important for food production. On a worldwide level, Mexico is one of the top countries in maize consumption, as this product the main source of protein for the population (Conde *et al.*, 2006) in both rural and urban areas (Rangel-Meza *et al.*, 2003; Bertran-Vilá, 2010). Some twenty million habitants depend solely on the maize produced in their sectors (Damián-Huato *et al.*, 2011; González-Merino & Ávila-Castañeda, 2014; Murray-Tortarolo & Jaramillo, 2018).

In Mexico, sixty native varieties of maize are cultivated (Carrera-Valtierra *et al.*, 2011) on approximately six million hectares, which constitutes more than half of the cultivated land in the country. Of this area, only 14% is irrigated, the remaining 86% is under seasonal cultivation

(González-Merino & Ávila-Castañeda, 2014; INEGI, 2017). A high yield in maize production is closely related to the number and quality of seeds per ear of maize that reach physiological maturity (Hall, 1980; Andrade *et al.*, 1999; Traore *et al.*, 2000; Martínez-Álvarez, 2015). Furthermore, the optimal physiological development during each phenological stage is of utmost importance in reaching a high crop yield.

For more than two decades, diverse studies in Mexico have been carried out on the vulnerability of seasonal maize crop, under the effects of climate change (Conde *et al.*, 1997; Ruiz-Corral *et al.*, 2000; Bellón *et al.*, 2011). These studies have focused on the monthly and annual effects of climate variation, such as rising temperatures, the frequency and severity of droughts, and excess moisture, which in turn are the principal factors that affect the quality and quantity of maize harvests (Conde *et al.*, 2000; Tinoco-Rueda *et al.*, 2011; Ahumada-Cervantes *et al.*, 2014; Murray-Tortarolo & Jaramillo, 2018; Reyes-Anistro *et al.*, 2018). However, there are few studies of the damage caused by the daily changes in precipitation and temperature on the various phenological stages of maize (McWilliams *et al.*, 1999; Guevara, 2007).

Climatic hazard is defined as a climatic extremes condition in a determined period of time that has the capacity to threaten a human or ecosystem activity. Climatic hazard can be determined annually by considering the number of times a determined meteorological condition occurs (Zúñiga & Magaña, 2018). Specifically, climatic hazard to maize crop, is defined as the potential propensity of a climatic event that could cause a decrease of yield or total loss.

As of today, there have been no proposals of indicators for climatic hazard, especially for crops; the development of these indicators could be a tool for identifying specific meteorological variables that limit the growth and development of maize in seasonal planting and during specific phenological stages and could be elemental to guarantee greater production.

In the present study we aimed to generate and validate indicators of climatic hazard for the seasonal maize crop in Bajo Balsas, Michoacán, Mexico, considering the different plant phenological stages.

Method

Description of the study area

The Bajo Balsas Sub-basin (Figure 1) is inside of Infiernillo-RTP-116, catalogued as a priority land region for Mexico, included in the Program for Priority Regions for the Conservation of

Biodiversity by the CONABIO (Comisión Nacional para el Conocimiento y Uso de la Biodiversidad). The Sub-basin is extremely important for the water catchment of the region, which favors the establishment of several animal and plant species. It is characterized by deciduous secondary lower forest vegetation and the principal economic activity is seasonal agriculture (Arriaga-Cabrera *et al.*, 2000).

In the Bajo Balsas Sub-basin, the seasonal cultivation of maize occupies 48% of the total planted land, followed by sorghum (26%), sesame (20%) and hibiscus (5%) (SIAP 2018). In this catchment area, planting is done seasonally, mainly on small farms for self-consumption. For maize, the average yield during 1999-2016, in the Bajo Balsas Sub-basin, was 1.9 tons/hectare (t/ha), with a maximum of 2.95 t/ha in 2011 and a minimum of 0.76 t/ha in 2002 (SIAP, 2018).



Figure 1. Location of the study area, the Bajo Balsas Sub-basin

Climatic requirements for maize, and the basis for climatic data

A bibliographic search was performed to identify 1) the climatic requirements for maize according to phenological studies, and 2) the cultivation methods and principal varieties cultivated in the region (Ruiz-Corral *et al.*, 2013; SAGARPA, 2015).

We consulted the CLICOM (2018a) system to identify the meteorological stations of the study area. Then we selected the meteorological stations using two criteria: 1) stations with more than 30 years of continuous daily data, and 2) stations currently operating (CLICOM 2018b).

Within the Bajo Balsas Sub-basin only one meteorological station of the National Meteorological Service (SMN, 2018a) matched our criteria. The climatic station selected is located in the semi-arid zone, which represents 80% of the Bajo Balsas sub-basin area (Burgos & Paez-Bistrain, 2018); belongs to a seasonal maize producing municipality (La Huacana), according to the information reported by the Agrofood and Fishing Information Service of Mexico (SIAP, 2018). A database was elaborated with the following daily and monthly climatic parameters: pluvial precipitation (PP), maximum temperature (Tmax) and minimum temperature (Tmin). These data were later processed to obtain the climatic hazard indicators.

Development of climatic hazard indicators

The climatic hazard indicators were developed as quantitative expressions. These indicators established the relation between the maize phenological stages (growth, development and yield) and climatic elements (Tmax, Tmin and PP) that affect maize production.

Maize (*Zea mays* L.) is a plant that has adapted to a large variety of geographic zones and is cultivated in tropical, subtropical and mild weather regions. Optimal yields occur at altitudes from 0 to 2,500 meters above sea level, although it has been cultivated in altitudes as high as 3,300 masl (Ruiz-Corral *et al.*, 2013).

The cycle for maize maturation varies according to the maize variety. In the Bajo Balsas, sowing start at the beginning of the rainy season, traditionally after the first rain in summer, which usually occurs from May 15 to June 1. Water availability is a yield-limiting factor for maize, as it is especially sensitive to water stress during the flowering stages, and affects the number and size of kernels developed (Traore *et al.*, 2000; Moussa & Abdel-Aziz, 2008; Kahiu *et al.*, 2013). Maize growth can tolerate temperatures above 32°C, but temperatures above 35°C are

detrimental in the flowering stages due to the lost of pollen viability and the reduction of stigmas number (Giménez, 2012).

The available information about the climatic requirements for seasonal maize crop in the studied region confirms that a lack of precipitation during the month of July, combined with temperatures over 38°C, kills the recently emerged seedlings. However, the grower may consider reshooting because, if the climatic conditions improve, it is still possible to achieve a good harvest. Nevertheless, if the combination of drought and temperatures over 38°C occurs during the reproductive stage (when the plant is in the male flowering stage or during the growth and maturation of the kernels), the harvest will suffer a significant decrease in quality (Hall, 1980; Andrade *et al.*, 1999, Giménez, 2012) or will be lost completely (Fassio *et al.*, 1998; Rinski *et al.*, 2009).

Another negative effect of drought and high temperatures is the asynchrony between pollen liberation and the stigmas emergence (Avenidaño-Arrazate *et al.*, 2008), which alters the pollination process and consequently the yield.

An agricultural practice of the seasonal producers in the region to eliminate the moisture from the kernels consists of leaving the ears of maize on the standing stalks to be dried in the sun. Harvesting begins three weeks after the ears reach their physiological maturity. Rainfall during the months of October and November does not allow the ears of maize to dry properly and favors the attack of plagues and fungi, decreasing the quantity and quality of the harvest (García-Lara & Bergvinson, 2007).

Once maize has reached physiological maturity, the kernels will start to lose moisture gradually. About 20 to 22 days after reaching physiological maturity the kernels' water content should be around 20%, and harvest usually takes place at this point. The moisture loss rate in physiologically mature kernels depends mainly on temperature; but the drying speed also varies among maize variety.

The phenological growth stages of maize proposed by Ritchie and Hanaway (1986), with an adjustment for the actual days of growth reported in the region, are described in Table 1. The climatic hazards for each development stage are also shown there.

The growth stages of maize were originally described by Hanway 1963 & Hanway 1966. In this research, was used the BBCH scale (Biologische Bundesanstalt, Bundessortenamt and Chemical industry) to describes in more detail the kernel maturation stages; including 17

vegetative stages (VE-Vn) and seven reproductive stages (R0-R6). Although the duration of each phenological stage varies according to the maize variety, the number of stages is the same.

We determined ten climatic hazard indicators for maize using the climatic variables database and the climatic requirements for cultivation of maize. We analyzed the climatic variables: daily Tmax, Tmin and PP, using ICC® software (Bautista, *et al.*, 2016).

Table 1. Stages of maize growth and hazards

Phase	Stage	Days	Characteristics	Hazards
Sowing		1	Dry kernels (caryopsis)	The kernels will not germinate under drought or low temperatures
Growth	VE	5	Emergence. The coleoptile emerges from the soil.	Loss of the plant by drought, wind and pests
	V1	9	The first leaf is visible.	
	V2	12	The second leaf is visible.	
	V3	15	The third leaf is visible.	
	Vn	54	The “n” leaf is visible. (Definite number of leaves between 16 and 22).	
	VT	55	The male flower is visible (masculine inflorescence)	
Reproductive	R0	57	Before the male flowering.	Pollen begins to be released. Partial or total loss of the recently pollinated kernels due to severe drought and high temperatures.
	R1	59	The stigmas are visible. Female flowering.	
	R2	71	Blister stage where the embryo can be seen.	Reduction in size and number of kernels per ear.
	R3	80	The milk stage.	
	R4	90	Embryo growth stage. The embryo grows to approximately half the width of the kernel.	
	R5	102	Serration stage. The kernel can be observed from the side.	
	R6	112	Physiological maturity. Moisture of the kernel is 35%.	
Harvest		134	The moisture of the kernel must be brought to below 14%.	Precipitation (humidity) can promote the development of fungus during the drying process.

Source: Author's own elaboration

The developed indexes required daily meteorological information to determine the variations in temperature and precipitation, which are crucial for the maize growth cycles. We developed and integrated new programming module with the ICC® (Indicators of Climatic Change) software (Bautista, *et al.*, 2016), which offers flexibility and ease of daily climatic data processing.

The programming module “climatic hazards for the maize crop” was designed and developed based on the stages for software defined by the Mexican law of technological information and life process (in NMX-I-O45-NYCE-2005). The stages involved are: a) process instrumentation; b) requirements analysis; c) architecture design; and d) codification and tests (NYCE, 2005). The tools used for the development of the module were open code and multiplatform: the programming language was Java version 1.8 (JDK), eclipse photon 4.8.0 was used as interface for integrated development (IDE), and Derby was applied as the managing system for databases (MSDD).

The development of the new module began with the analysis of the requirements of each of the indexes. We first defined the meteorological data that served as a beginning for the algorithms. Following this, the sequence began with the structuring of the retrieved data from MSDD and the ordering of matrices by day, month, and year and for the climatic variables. Missing data were replaced with the value 999.99, which was not taken into account in the computation of each indicator. The procedure was concluded with the display of the tabular results in the interface “Climatic hazards for maize crop”.

Classification of climatic hazards and mathematic validation

We used a series of 18 years from the climatic database; the chosen period being from 1999 to 2016 because it is the period in which there is available data of agricultural disaster by SIAP. This information was qualified in two ways: 1) according to the loss magnitude in maize production or size of sinister area for each year reported by the SIAP (2018a) supplementary Table1; and 2) according to incidences of severe drought reported in Mexico by SMN (2018b) supplementary Table 2.

Each of the 18 years with their ten calculated climatic hazard indicators were qualified. The production for these years was qualified into three classes: 1) low hazard: a sinister area from 0 to 10%, without drought reports; 2) moderate hazard: a sinister area from 11 to 50%, with

moderate drought reports; 3) high hazard: a sinister area from 51 to 100%, with reports of severe drought.

The classification by maize production for each of the 18 years elaborated with the 10 indicators of climatic hazard was validated by data mining with WEKA software (Legrand & Nicoloyannis, 2005; Hall *et al.*, 2009) using the following sequence: 1) selection of the climatic hazard, 2) qualification of the years by hazard level, and 3) application of the “J48” algorithm with the option *Use training set* for the elaboration of the decision tree, with the test mode 10-fold cross-validation and the metrics: true positive, false positive, precision, recall, f-measure and Matthews correlation coefficient.

The qualification of the climatic hazard was validated by the comparison between: 1) the decision tree of WEKA with a Kappa coefficient greater than 0.7, which would indicate the observed concordance over the total observations made by the “J48” algorithm and derives from the comparison of the metrics used by the algorithm (Cerdeira & Villarreal, 2008), and, 2) The information of the climatic variables that determine irreversible physiological damage in the maize plant during the different phenological stages of the plant.

Results

Indicators of climatic hazard

Understanding the maize growth stages is important to make agricultural practices more efficient and to improve production. The maize growth stages are (Figure 2): 1) vegetative phase (the development of 20 to 21 leaves or VT-Vn), and 2) reproductive phase (the flowering or R0-R1, 54 days after emergence, and physiological maturity or R6, 112 days after planting). Generally, maize plants follow the same pattern of growth, but the time between stages can vary depending on the variety cultivated, the location and temperature (SIAP, 2007).

The present model was made under the assumption that the maize follows the physiological development stages proposed here, although we are aware that the duration of the stages may vary according to the climatic conditions of each year. The ten indicators that reflect the climatic hazards to the seasonal cultivation of maize come from the analysis of the variables of Tmax, Tmin and PP (Table 2).

The number of dry days (DDE0) affects the maize development in both the vegetative and the reproductive phases, which influence the yield (t/ha) and production (t) of the crop. Both,

yield and production depend on the behavior of the precipitation, temperature and the soil water retention capacity.

For the development of this model we use a series of 18 years from the climatic database; the chosen period being from 1999 to 2016 qualified as described in methods (Table 3).

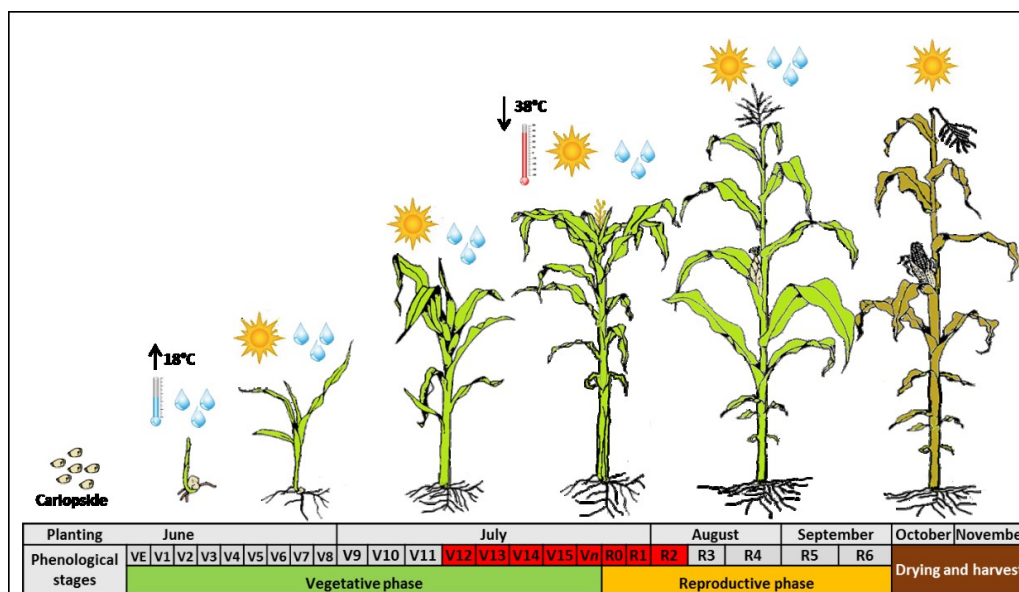


Figure 2. Climatic requirements for maize (the phenological stages of *Zea mays* L. were modified from Meier, 2001)

Table 2. Description climatic hazard indicators for maize

#	Indicator	Description	Phenological stage
1	DDE0jun	Number of dry days with precipitation equal to 0 mm for the month of June.	VE-Vn
2	DDL5jun	Number of dry days with precipitation lower than 5 mm for the month of June.	
3	DDE0jul	Number of dry days with precipitation equal to 0 mm for the month of July.	R0-R1
4	TX38jul	Number of days with temperatures higher than 38°C for the month of July.	
5	DDE0aug	Number of dry days with precipitation equal to 0 mm for the month of August.	R2-R4
6	DDL5aug	Number of dry days with precipitation lower than 5 mm for the month of August.	
7	TX38aug	Number of days with temperatures higher than 38°C in the month of August.	
8	DDE0sep	Number of dry days with precipitation equal to 0 mm for the month of September.	R5-R6
9	WDH10oct	Number of wet days with precipitation higher than 10 mm for the month of October.	Dry
10	WDH10nov	Number of wet days with precipitation higher than 10 mm in the month of November.	

Source: Author's own elaboration

Figure 3 shows the algorithms developed and used in the ICC® software (Bautista *et al.*, 2016) to obtain the ten climatic hazard indicators for maize crop, and the index with three categories of climatic hazard

Validation of the index of climatic hazard

The metrics obtained by the 18 qualified years and the 10 climatic hazard indicators for maize is show in Table 4, here we observed high values in all the metrics evaluated, for example the accuracy greater than 0.87.

Table 3. Climatic series of 18 years with the indicators of climatic hazard calculated and the classification by maize crop production per year

Year	WDH10 oct	WDH10 nov	DDE0 jun	DDE0 jul	DDE0 aug	DDE0 sep	DDL5 jun	DDL5 jul	TX38 jul	TX38 aug	Production classification
1999	4	0	21	21	16	21	23	25	0	0	Moderate
2000	0	0	25	24	21	27	28	24	0	0	High
2001	1	0	24	22	20	19	26	23	0	0	High
2002	2	2	21	20	21	18	24	20	0	0	Moderate
2003	4	0	22	24	22	19	22	24	0	0	Low
2004	1	0	22	24	25	21	24	25	0	0	Low
2005	2	0	25	23	20	21	25	26	0	0	Moderate
2006	4	0	25	18	18	19	25	23	5	0	Moderate
2007	0	0	26	24	14	24	29	27	5	0	High
2008	1	0	25	23	25	20	27	27	2	6	Low
2009	3	0	26	24	26	23	29	26	10	28	Low
2010	0	0	22	20	13	19	22	24	2	0	High
2011	4	0	21	14	22	22	21	21	0	0	Low
2012	2	2	24	20	19	26	28	22	22	5	Moderate
2013	2	1	20	18	25	14	25	18	29	13	Low
2014	1	1	19	25	23	22	21	26	11	24	Low
2015	4	0	25	20	24	26	25	23	27	31	Low
2016	0	0	15	16	20	17	18	19	0	0	High

Source: Author's own elaboration

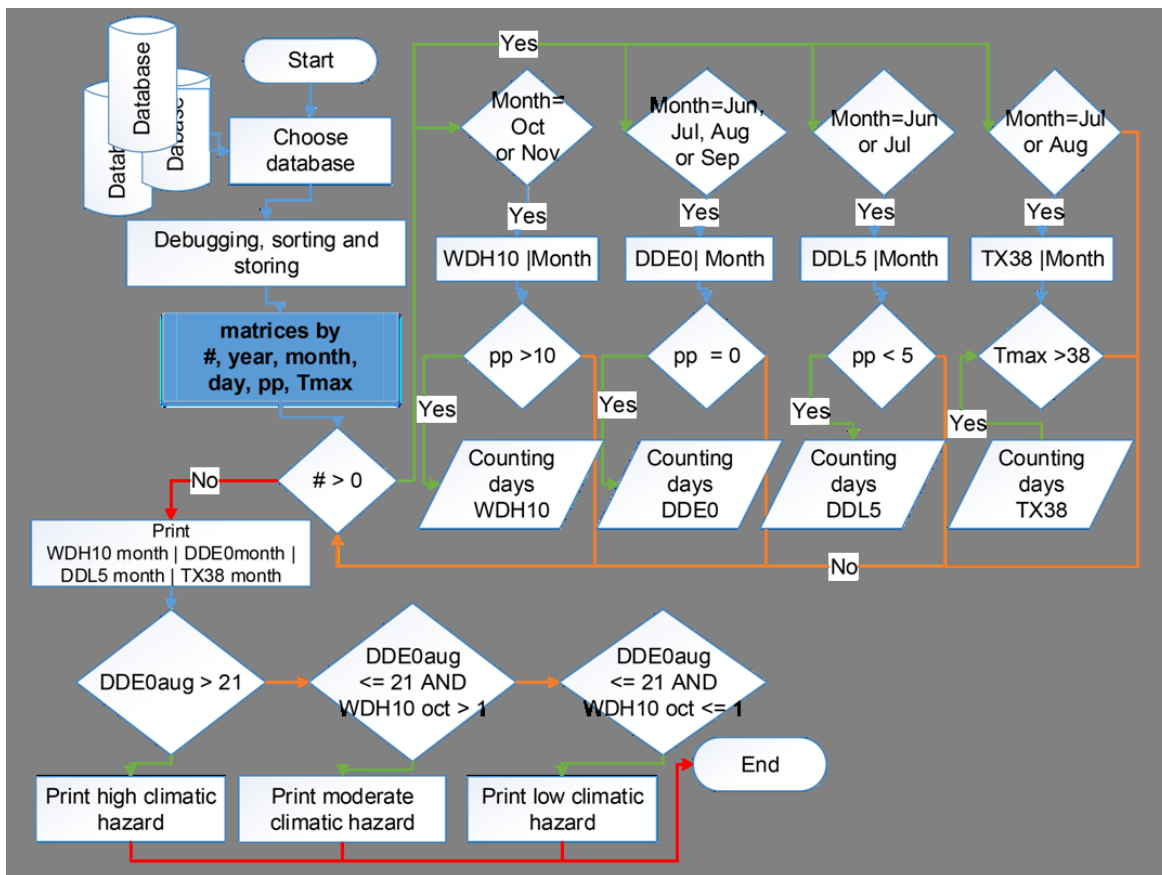


Figure 3. Development of the algorithms in ICC® software to analyze the climatic hazard indicators for rainfed maize crop

In the confusion matrix (Table 5) we observed that from the 18 years evaluated with the classification proposed, only one year was not correctly qualified. Which validates the model proposed in this work.

Table 4. Metrics used in the Weka software by the J48 algorithm in the evaluation of the concordance between the climatic hazard indicators and the classification by maize production

True positive	False positive	Precision	Recall	F-Measure	Matthews correlation coefficient	Production Classification
0.8	0	1.0	0.8	0.889	0.862	High
1.0	0.07	0.83	1.0	0.877	0.877	Moderate
1.0	0	1.0	1.0	1.0	1.0	Low

Table 5. Confusion matrix produced by Weka software by the J48 algorithm in the evaluation of the concordance between the climatic hazard indicators and the classification by maize production

High	Classified as		Production Classification
	Moderated	Low	
4	1	0	High
0	5	0	Moderate
0	0	8	Low

The validation analysis of the climatic hazard index for the cultivation of maize, produced a correct classification in 94.4% of the cases (years) with an error of 5.5%. From the results obtained in the metric the Kappa statistics had a value of 0.91, indicating a very high concordance between the proposed classification by production and the 10 climatic hazard indicators for maize. According to the WEKA analysis, we obtained a decision tree with three leaves, which were produced by two main variables: DDEaug and WDHoct (Figure 4). The three leaves indicate the main variables responsible of assigning a year to a category when meeting specific requirements; the rest of the variables are considered of secondary importance.

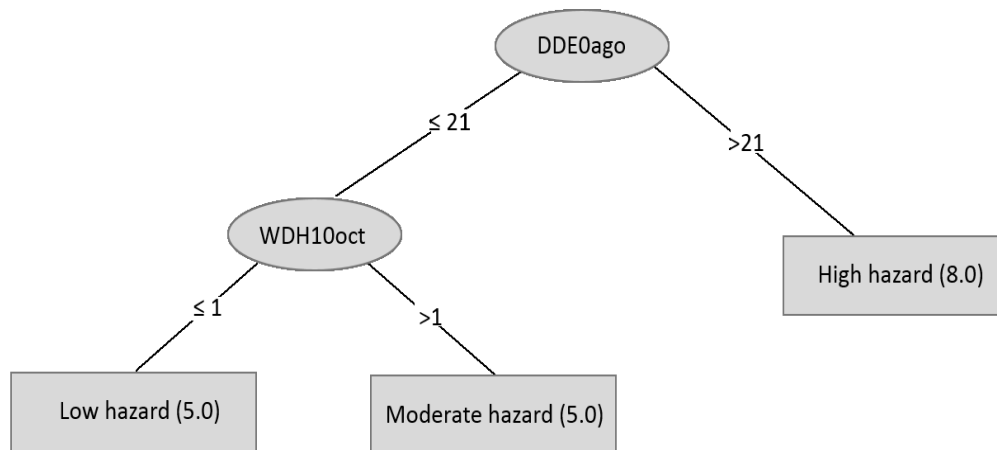


Figure 4. Decision tree obtained from WEKA software for the classification of climatic hazard of maize with a Kappa statistic of 0.914

According to the decision tree, the correct classification by maize production and climatic hazard for each year has the following assertions: If the total dry days (0mm) for August (DDE0aug) is higher than 21, then the production of maize is correctly classified as low, and this year is under a high climatic hazard. (Table 5). However, if the total of dry days (0 mm) for August (DDE0aug)

is less than 21, then the climatic hazard classification is dependent on the total rainy days (higher than 10 mm) for October (WDH10oct). If October had zero days with a precipitation higher than 10 mm, then the year was correctly classified as having moderate production, and this year was considered to be under a moderate climatic hazard. Finally, if October has more than one day with precipitation higher than 10 mm, then the year was correctly classified as being of high production and under a low climatic hazard.

Another climatic variable that we considered as primary hazard indicator was atypical rain in the dry season. Atypical rain in the study region is important for the recharge of the phreatic layer levels and other water bodies. According to the index of climatic hazard developed in the present study, atypical rains higher than 10 mm of precipitation during October and November (WDH10oct and WDH10nov) can damage and thus reduce the quality of the harvest. The moisture received during the dry season promotes the establishment of fungi and insects, affecting maize during its drying phase and producing irreversible damage to the harvested product (Fassio *et al.*, 1998).

Discussion

In this study we achieved our purpose of defining and identifying the climatic hazard indicators considering the phenological stages, and we also generated a climatic hazard index for maize.

The contribution of the Intergovernmental Panel on Climate Change (IPCC, 2012) on the theoretical construction of risk establishes that climatic hazard increases with exposure to extreme climatic events and with the vulnerability of human and natural systems. For the human systems, the main drivers towards climatic hazard and the vulnerability to climate change (Lavell *et al.*, 2012) are the sum of the alterations in: 1) the climatic system and 2) the socioeconomic processes (including the social process of adaptation). In the present study, climatic hazard refers to the first element of the risk, that is, the exposure to a determining climatic event. There is an ample consensus about the disaster being the materialization of risk (Cardona *et al.*, 2012). For a specific crop, the risk is the result of the combination of climatic hazard, the conditions of vulnerability and the capability of the farmer to reduce negative consequences (i.e. for adaptation).

The World Meteorological Organization (WMO) and the Expert Team on Climate Change Detection and Indices (ETCCDI) formulated and defined 27 indices to identify extreme

climate conditions produced by climate change (Peterson, 2005; Wang & Feng, 2007). These indices were used to identify a series of climatic conditions which could have effects on a physiological level in organisms in general, but omitted information of intervals of physiological tolerance presented for specific organisms. To address the lack of indices for specific crops, in the present study we propose various indicators of climatic hazard that reflect the critical periods for the development of maize in the region of Bajo Balsas, Michoacán.

The simultaneity of high temperatures and low precipitation in the same period is assumed in several studies to be an indicator of drought conditions (Fassio *et al.*, 1998; Conde *et al.*, 2000; Hatfield *et al.*, 2011; Giménez, 2012; Murray-Tortarolo & Jaramillo, 2018), and we observed high values of the indicators DDE0jun, DDE0jul y DDE0aug, TX38jul y TX38aug. If a drought occurred in the months of June, July and August, we can infer a high climatic hazard and consequently a reduction in the yield of maize crops.

Our results showed that a drought for more than 21 days during the month of August (DDE0aug) constituted a primary indicator of high climatic hazard for the production of maize. This is consistent with the findings of another study which proposed that drought has different effects on the phenological stage of the maize crop (McWilliams *et al.*, 1999). In that study, they observed that a drought during the growth stage (V6-V15) produced a daily reduction in the production up to 2%, while a drought in the reproductive stage generated a reduction of up to 6%, and when the drought continued as far as R6, they observed a production loss of 100%. In the maize plant a prolonged drought during the month of August (the reproductive stage) would cause water stress damage and/or a nutrient deficiency, thus reducing the quality and the number and size of kernels per remaining ear in an irreversible manner (Martínez-Álvarez, 2015). Additionally, a study showed that water stress reduces plant growth, diminishing the stomatal conductance and photosynthetic rate (Baiocchi-Riboldi *et al.*, 2016).

Although the mathematical validation with WEKA showed that the indicators DDE0aug and WDH10oct are the variables that generated a correct classification of climatic hazard, this does not mean that other indicators are not crucial in the production of maize but that there are primary and secondary variables that determine climatic hazard (Cerdeira & Villarreal, 2008).

Even if the number of days with a temperature higher than 38°C for the month of August (TX38aug) were not considered in the main classification variables proposed by the decision tree of WEKA, we observed that the years with more than 10 days with a temperature higher than

38°C (TX38aug) matched with the years of low production and high climatic hazard. We propose that the negative effect of this variable on production remains obscured by the weight of the DDE0aug variable. A study showed that rising temperatures will have a negative effect on maize, especially in its yield, due to the time reduction for all phenological stages (Ruiz-Corral *et al.* 2011).

The principal contribution of the present work consists in its being the first to: a) offer precise information about the climatic variables that affect each stage of maize; b) define the thresholds in the cultivation of maize; c) automate the calculation of the indicators by improving the ICC® software; and d) contribute to the understanding of the meteorological variables that effect maize yield over its full cycle.

For developing countries, this methodology would be useful and valid anywhere precipitation and temperature are important meteorological variables for seasonal agricultural production. However, in other cases, the presence of freezes and strong winds can negative influence good harvests.

Conclusions

We propose the following indicators to evaluate the climatic hazard for maize production in the Bajo Balsas Sub-basin, Mexico: a) DDE0jun, number of dry days with precipitation equal to 0 mm for the month of June; b) DDL5jun, number of dry days with precipitation lower than 5 mm for the month of June.; c) DDE0jul, number of dry days with precipitation equal to 0 mm for the month of July; d) TX38jul, number of days with temperatures higher than 38°C for the month of July; e) DDE0aug, Number of dry days with precipitation equal to 0 mm for the month of August; f) DDL5aug, number of dry days with precipitation lower than 5 mm for the month of August; g) TX38aug, number of days with temperatures higher than 38°C for the month of August; h) DDE0sep, number of dry days with precipitation equal to 0 mm for the month of September; i) WDH10oct, number of wet days with precipitation higher than 10 mm for the month of October; and j) WDU10nov, number of wet days with precipitation higher than 10 mm for the month of November. The absence of precipitation during the month of August (DDE0aug) and the number of rainy days with more than 10 mm for the month of October (WDH10oct) are the two most important indicators of climatic hazard for maize.

The algorithms developed in this study, for the calculation of the indicators of climatic hazard, permit the extraction of values of the climatic hazard indices in a rapid and reliable manner.

The proposed method for the validation of meteorological risk indicators with the WEKA software allowed the identification of the most important indicators that affect the phenology of maize.

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Supplementary material

Supplementary Table 1. Sinister area for each year reported by the SIAP (2018)

Year	Production (ton)	Sinister area (ha)	Sinister harvest (%)
1999	32485.2	1421	9.11
2000	31044	90	0.57
2001	16682.1	6823	44.35
2002	4679.2	7013.2	53.23
2003	21540	1711	12.87
2004	3965.8	10020	76.11
2005	28925	0	0
2006	26765.4	0	0
2007	20700	3570	24.3
2008	21790	5980	40.51
2009	12358	7688	53.96
2010	37706.8	0	0
2011	17583.6	8733	60
2012	7960	8400	60
2013	30352.3	3468	25.31
2014	7991.7	8280.52	61.18
2015	3595.6	9204.5	73.49
2016	10148.4	4971	42.02

Source: http://infosiap.siap.gob.mx/gobmx/datosAbiertos_a.php

Supplementary Table 2. Incidences of droughts reported in the municipality “La Huacana”, Michoacán, México by SMN (2018b) from the years 2003 to 2016

Year	Month	Report of Drought
2003	June	No drought
	July	No drought
	August	No drought
	September	Abnormal drought
	October	Abnormal drought
	November	No drought
2004	June	No drought
	July	No drought
	August	No drought
	September	No drought
	October	Abnormal drought
	November	Abnormal drought
2005	June	No drought
	July	No drought
	August	No drought

	September October November	Abnormal drought Abnormal drought Abnormal drought
2006	June July August September October November	No drought No drought No drought Moderate drought No drought No drought
2007	June July August September October November	Severe drought No drought Abnormal drought Abnormal drought No drought No drought
2008	June July August September October November	Moderate drought Abnormal drought Abnormal drought Abnormal drought Abnormal drought No drought
2009	June July August September October November	Abnormal drought Moderate drought Moderate drought Moderate drought Moderate drought Moderate drought
2010	June July August September October November	No drought No drought No drought No drought No drought No drought
2011	June July August September October November	Abnormal drought Abnormal drought No drought No drought No drought No drought
2012	June July August September October November	No drought No drought No drought No drought Abnormal drought Abnormal drought
2013	June	Abnormal drought

	July August September October November	Abnormal drought No drought No drought No drought Abnormal drought
2014	June July August September October November	Abnormal drought Abnormal drought Moderate drought Abnormal drought Abnormal drought Moderate drought
2015	June July August September October November	No drought Abnormal drought Moderate drought Moderate drought Moderate drought No drought
2016	June July August September October November	Moderate drought Moderate drought Moderate drought Abnormal drought Abnormal drought Abnormal drought

Source: <http://smn.conagua.gob.mx/es/monitor-de-sequia-en-mexico2>