Revista Mexicana Ciencias Agrícolas volume 13 number 2 February 15 - March 31, 2022

Article

Loss of cultivated areas of rainfed corn due to frosts in the Toluca valley

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Abstract

Corn production in the State of Mexico is of great importance, however; this crop is affected by some elements of the climate, mainly frosts. In the Rural Development District of Toluca (DRRT), due to its location and altitude, frequent periods of frosts are recurrently recorded, which inhibit the growth, development and physiological maturity of corn. The objective of this work was to analyze the geospatial behavior of frosts in the cultivation of rainfed corn of the spring-summer 2019 agricultural cycle in the DDRT. With tools of Geographic Information Systems and remote sensing, the causes and effects that this phenomenon causes to the cultivation of corn in the Toluca Valley were determined. To this end, a monitoring of the normalized difference vegetation index (NDVI) and an analysis of minimum temperatures were carried out; all this to identify the period with frosts that caused losses in 3 511 ha of corn. Statistical technique was applied to determine that the altitude, minimum temperature and frequency of cold days are related to the manifestation of frosts. These variables as a whole made it possible to identify susceptible areas with different levels of frost risks in the study area.

Keywords: *Zea mays* L., damaged area, freezing temperatures, natural disasters, State of Mexico.

Reception date: December 2021
Acceptance date: February 2022

Introduction

The Mexican Republic is affected year after year by different meteorological phenomena, some of them impact the population directly as hurricanes, others, such as frosts, manifest themselves in a way that causes severe damage. The frost phenomenon, depending on its intensity, can affect the population of rural areas. In the north and center of the Mexican Republic, during the cold months of the year (November-February), temperatures below 0 °C occur due to the entry of continental polar air, usually dry and that come from the north (CENAPRED, 2021).

Variations in seasonal climate cycles, with respect to the normal, result in partial or total crop losses, since these are vulnerable to frosts, which occur when the air temperature drops until ice crystals form inside plant cells over a period; the process of deterioration of plants depends on the vegetative stage in which it is and the species to which it belongs (FAO, 2010).

Susceptibility to frosts generates an abiotic stress that impairs plant growth and production (Chinnusamy *et al*., 2007), especially corn, which is sensitive to low temperatures (Restrepo *et al*., 2013) and irregularity in diurnal temperature changes can inhibit the development of the crop phases, from sowing, flowering and maturity, since plants are not able to maintain their temperature constant (Rawson *et al*., 1998).

On the other hand, the severity of damage to crops due to frosts is increasing (Granados and Sarabia, 2013), and the vulnerability is greater in rainfed corn, as well as decreases in the areas sown and decrease in its yield (Granados and Sarabia, 2013).

At the national level, the regions most affected by frosts are the Mesa Central del Altiplano, the Sierra Madre Occidental in the states of Chihuahua and Durango, as well as in the Sierra Tarahumara, Sierra de Durango and Tepehuanes. In addition, in the upper parts of the Transverse Volcanic System over the parallel 19° north latitude, essentially in the states of Mexico, Puebla and Tlaxcala, seasons with more than 100 days a year with frosts are recorded (CENAPRED, 2001). The early frosts that occur in early September in central Mexico cause considerable damage to agriculture in the spring-summer cycle and in northwestern Mexico to crops of the autumn-winter (A-W) cycle, whose losses are considerable.

As an example, one can mention the severe frosts recorded in 2011 in the state of Sinaloa, with losses of more than 95% in vegetables and annual crops (Soria-Ruiz *et al*., 2012). During recent years, about 260 000 ha cultivated with corn are affected annually by low temperatures (CONAGUA, 2013), mainly at altitudes above 2 200 m. The Rural Development District of Toluca (DDRT, for its acronym in Spanish) that is in this region, very low temperatures are recorded during the winter and part of the summer, influenced by its altitude that attracts the cold air masses that constantly favor the frost process in this region.

Regarding the study area, it is important to mention that, in 2019, the State of Mexico reported an agricultural area of 667 709 ha, which represented 29% of the territory’s area, of which 71.2% were with grain corn (SIAP, 2019). The DDRT represents for the state the second Rural Development District with the highest volume of corn production, with an average of 113 102 ha of sown area (SIAP, 2015), whose average yield is 3.5 t ha^{-1}, below the state average. This is partly due to the limited capitalization, lack of credits, increased production costs and frosts that occur in the development and grain filling phases of the crop, which considerably affect the yield and quality of the harvested grain.

The present study aimed to perform a spatial analysis to measure the loss of rainfed corn area because of frosts, with remote sensing techniques and Geographic Information Systems (GIS) tools, through the spatial relationships between the corn area affected by frosts and the variables that cause them. This with the purpose of a better management of the crop in the decision making in the rural sector of the Toluca Valley, State of Mexico.

Materials and methods

The present research work consisted of three stages: a) the analysis of the records of minimum temperatures to identify the period of frosts; b) affected corn areas from the analysis of satellite images before and after frosts; and c) the spatial relationships between the territorial variables (climatic and environmental) that influence the occurrence of frosts.

Study area

The study area comprises the Rural Development District of Toluca (DDRT), one of the eight DDRs in the State of Mexico. It is located in the center-east of the State of Mexico between the parallels 19° 00’ and 19° 35’ north latitude and between the meridians: 99° 54’ and 99° 14’ west longitude, with altitudes between 1 800 and 4 640 masl (Granados and Sarabia, 2013). It has an area of 302 604 ha and is made up of 24 municipalities. It is characterized by its fertile valleys with deep soils (Figure 1). The research work was carried out during the spring-summer (S-S) agricultural cycle of 2019.

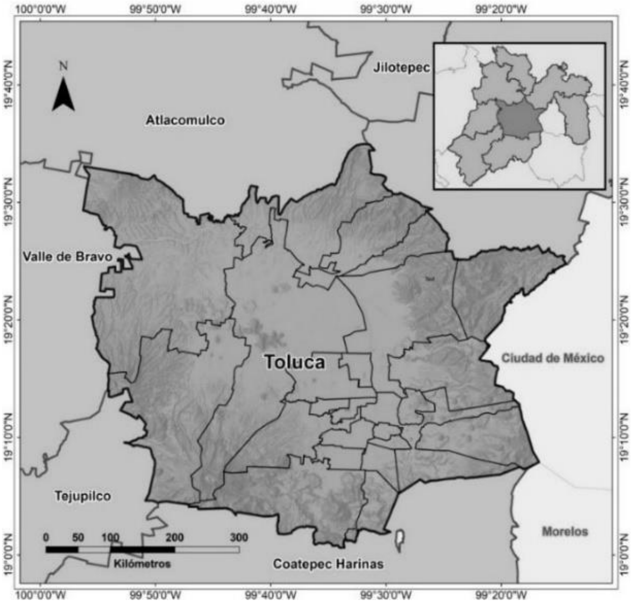


Figure 1. Geographical location of the Rural Development District of Toluca.

In the DDRT, 132 784.9 ha are cultivated under rainfed conditions (Table 1), and it contributes on average 22% of the volume of corn production in the state; however, in this region there are more than 100 days with frosts per year, influenced by the altitude, which leads to recurrent frosts that affect corn production in this region. In order of importance, the municipalities that report the largest area sown with rainfed corn in the DDRT are Almoloya de Juárez, Toluca, Zinacantepec, Tenango del Valle, Lerma and Temoaya (SIAP, 2014), as shown in Table 1.

Table 1. Area sown with rainfed corn by municipality in the DDRT to 2019.

	Municipality	Sown area (ha)	Harvested area (ha)
1	Almoloya de Juárez	29 646.1	25 526.1
2	Toluca	18 724.2	16 614.2
3	Zinacantepec	12 392	12 032
4	Tenango del Valle	11 063.2	11 063.2
5	Lerma	10 751	9 926
6	Temoaya	9 884.22	9 743.57
7	Tianguistenco	7 225.8	7 225.8
8	Calimaya	7 167.25	6 947.25
9	Otzolotepec	7 030	5 995
10	Ocoyoacac	4 756.93	4 756.93
11	Metepec	3 471	3 471
12	Huixquilucan	3 035	3 035
13	Joquicingo	2 715	2 715
14	Xalatlaco	2 617	2 617
15	San Antonio la Isla	2 096	2 096
16	Rayón	1 865.2	1 865.2
17	Xonacatlán	1 842	1 702
18	Capulhuac	1 265	1 265
19	Texcalyacac	1 132.2	1 132.2
20	Mexicaltzingo	768.5	768.5
21	Chapultepec	765.5	765.5
22	Atizapán	570.8	570.8
23	Almoloya del Río	526.2	522.7
24	San Mateo Atenco	429	429

Frost period

To identify the frosts that occurred in the DDRT in the cycle (S-S) and that affect the vegetative cycle of corn, the year 2019 was taken as a sample, which was a year with records of more frosts verified through previous bibliographic research and the analysis of climate data.

Considering that corn is susceptible to a wide range of temperatures between 5 and 45 °C and that, below 4 °C, temperatures can cause damage to the crop (Mondragón, 2005). When the temperature of the plant reaches temperatures of the freezing point of the water, it causes ice crystals intracellularly in the tissues, causing cell death, wilting, dehydrated reproductive organs, sucked grains, flaccidity of fruits and even a possible death of the plant (FAO, 2010).

To identify minimum temperatures less than or equal to 4 °C, since below that value they affect rainfed corn, the daily minimum temperatures below 4 °C during the May-October period were analyzed, whose data were obtained from 20 weather stations located in the study area (CLICOM, 2019). Interpolations were then performed using the inverse distance weighted (IDW) method at a power of value 2, a deterministic distance-weighting procedure. The interpolation of the problem point is done by assigning weights to the data in the environment in inversely function of the distance that separates them Inverse Distance Weighting (IDW). This procedure was performed from the ArcGis 10.4® software platform.

Crop monitoring through vegetation indices

The monitoring of the corn was performed from the growth stage to physiological maturity based on the normalized difference vegetation index (NDVI) obtained through multitemporal analysis of MODIS/Terra satellite images. With the increasing and decreasing values of this index, the areas affected by some anomaly, mainly by frosts, were identified. The relationship between the NDVI and the vegetative development phases of corn is high (Soria and Granados, 2005). The S-S agricultural cycle of corn in this region occurs from May to October with different phases of growth: a) growth and development, whose NDVI values increase; b) flowering and grain filling, with greater plant vigor and NDVI values greater than 0.6; and c) physiological maturity and senescence, whose NDVI levels decrease rapidly (Figure 2).

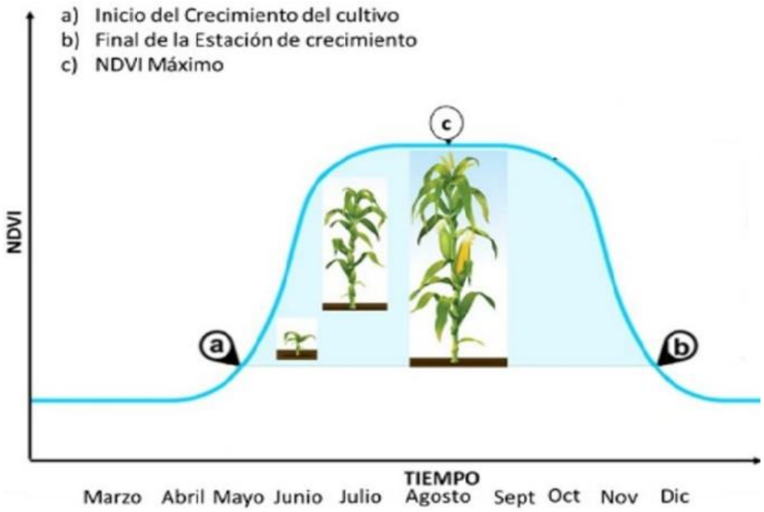


Figure 2. Relationship of the NDVI and the phases of vegetative development of corn in the Toluca valley.

When vegetation suffers some type of stress such as summer water deficit or frosts, its reflectance will be lower in the near-infrared and red region of the electromagnetic spectrum. The greater the contrast of the reflectances between the infrared and red bands, the greater the vegetal vigor of corn. The low values of this relationship indicate a diseased or senescent vegetation, until reaching covers without vegetation such as bare soil that reports indices close to zero (Soria *et al*., 1998).

The NDVI registers values between -1 and 1 and is the most widely used in agronomic applications (Granados *et al*., 2004). An NDVI value of 0.1 can be set as the critical threshold for vegetation covers and 0.5 for dense and healthy vegetation. MODIS/Terra images have a temporality of 16 days and a spatial resolution of 250 m. In the present study, scenes from the May-October 2014 period that covered the entire DDRT were analyzed. For the extraction of the NDVI from these images, the ENVI-Ver. 5.1® software was used, using the following expression: $\text{NDVI} = \frac{R_{Nir} - R_{Red}}{R_{Nir} + R_{Red}}$. Where: R_{Nir} reflectances of radiation in the near infrared of the spectrum and R_{Red} reflectances of the radiation of the visible red of the spectrum.

By means of map algebra procedures, by superimposing and comparing the maps of minimum temperature (T< 4 °C) with the maps of NDVI, it was possible to identify the areas affected by frosts that damaged the cultivation of rainfed corn.

Corn area affected by frosts

To quantify the corn area affected by frosts in the S-S 2014 agricultural cycle, the analysis was carried out in two stages (before and after the event). The procedure consisted of the following: six images of 2019 from the Landsat-8 satellite Operational Land Imager (OLI) were selected, with a percentage of cloudiness less than 15% (USGS, 2019) with a temporal resolution of 16 days, and a spatial resolution of 15 m (Table 2). These images were managed from the platform Landsatlook.usgs.gov/viewer, which were subjected to geometric, radiometric and atmospheric correction processes through the ENVI® processor. Next, mosaics of the previously grouped scenes were generated for analysis (before and after the event). A false-color (RGB) band combination was obtained to highlight the traits of the corn plots and achieve a better discrimination of the crop.

Table 2. Scenes used from Landsat-8 satellite images grouped by date of capture.

Period	LANDSAT-8 Scenes	Column/line	Date of acquisition
VPBF	LC08_L1TP_026047_20190726_20170304_01_T1	26/47	26/07/2019
	LC08_L1TP_027046_20190615_20170305_01_T1	27/46	15/06/2019
	LC08_L1TP_027047_20190615_20170305_01_T1	27/47	15/06/2019
VPAF	LC08_L1TP_026047_20191030_20170303_01_T1	26/47	30/10/2019
	LC08_L1TP_027046_20190919_20170303_01_T1	27/46	19/09/2019
	LC08_L1TP_027047_20190919_20170303_01_T1	27/47	19/09/2019

Where: VPBF= vegetative period of corn before frosts and VPAF = vegetative period of corn after frosts.

To determine the cultivated area of corn, the images were subjected to a supervised classification process, which consists of an ordering of the pixels in a finite number of classes or categories, based on the values of digital levels, a procedure that uses the radiometric intensity of each pixel. Polygons known as training camps were previously selected and digitized. Then the maximum likelihood algorithm (maximum likelihood classification) was used. From the classification resulting from the two periods, the cultivated area (hectares) and the spatial distribution of the corn cultivation before and after frost were obtained. The change in corn cover in two vegetative cycles was then estimated using the Thematic Change Workflow tool of ENVI®.

Spatial analysis of the corn area affected by frosts

To explain the spatial relationships between the affected corn area and the environmental variables that have the greatest influence on the manifestation of a frost, an explanatory model was generated using geostatistical methods of regression at the pixel level, as well as GIS tools. To do this, the loss of corn cover (affected corn area), as a dependent variable, and five independent or explanatory variables were used: climatic (minimum temperature, frequency of cold days and precipitation) and environmental (digital elevation model and slope of the terrain) (Table 3).

Table 3. Climatic and environmental factors that influence the manifestation of frosts.

Factors	Variable	Key	Description	Source
Climatic	Minimum temperatures	TEM_MIN	Monthly minimum temperatures in the S-S 2019 agricultural cycle (April to November) were analyzed	Clicom of CONAGUA
	Frequency of cold days	FREC_DIAS_FR GOOD	The total number of cold days that occurred in the S-S 2019 agricultural cycle was analyzed.	Clicom of CONAGUA
	Precipitation	PRECIPT_MM	Total rainfall record (mm) in the S-S 2019 agricultural cycle	Clicom of CONAGUA
Environmental	Digital elevation model	DEM	Altitude of the study area (masl)	INEGI
	Slope	SLOP	Slope of the terrain (%)	INEGI

Temperature and precipitation data were obtained from the record of 20 weather stations distributed in the study area (Clicom, 2019). To calculate the minimum temperatures, daily values of ≤4 °C were extracted from the database, which were averaged per month during the May-October period in the S-S 2019 cycle. From the result of this procedure, the number of times the frost event occurred (T≤ 4 °C) on a monthly basis was estimated, and thus obtain the frequency of cold days. The monthly accumulated rainfall was obtained from the climatological database (Clicom, 2019) for the same period May-October.

The results of these three variables (minimum temperature, frequency of cold days and precipitation) were interpolated using the IDW method. The digital elevation model was obtained directly from the INEGI (2017) platform, and the slope map of the terrain was derived from this product. To perform these processes, the ArcGis® Software was used. All variables were standardized to the UTM projection system with WGS84 datum and converted to raster format.

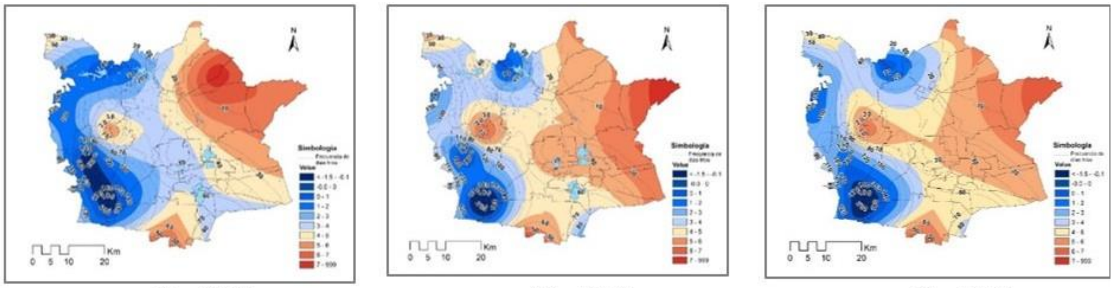
Frost occurrence probability map

The probability of frost occurrence in the DDRT for the year 2019 was obtained from a multiple linear regression (MLR) model with the 'Multireg' tool of the TerrSet software, where the coefficients of each explanatory variable (regression equation) were estimated, and in conjunction with the covers of the values of the dependent and explanatory variables, using a raster calculator, the probability map was obtained, which represents the probability that a pixel occupied by corn is lost due to the effect of frosts. Of the resulting values, ranges (low, medium, high and very high) were assigned.

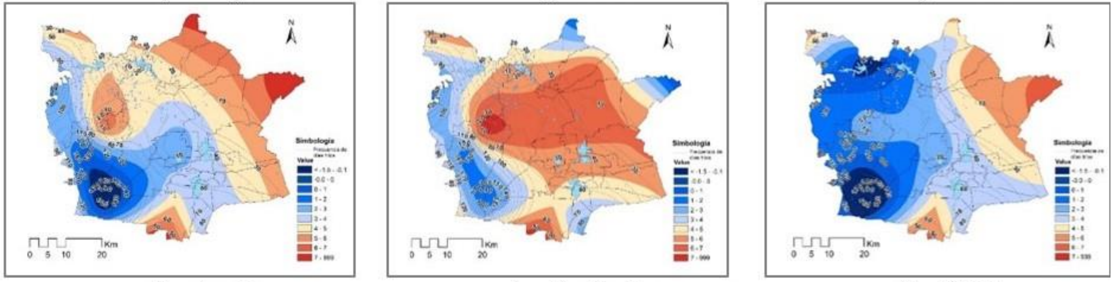
Results and discussion

Period of frosts that affect the cultivation of corn

Figure 3 shows the maps of the monthly minimum temperatures (<4 °C) for the period from May to October 2019, the same period that corresponds to the vegetative cycle of corn. It is observed that the months where temperatures below the critical threshold that affected the growth and development and corn (<4 °C) were recorded were May and August, with more than 40% of the territory of the study area, mainly in hillside areas. In October, the largest affected area was recorded, with temperatures below 0 °C in the mountain areas that correspond to the west, northwest and southwest region of the study area.



a) Mayo **b) Junio** **c) Julio**



d) Agosto **e) Septiembre** **f) Octubre**

Figure 3. Behavior of the minimum temperature from May to October in the DDRT.

The monthly minimum temperatures values (<4 °C) recorded in the study area significantly affected the cultivation of corn, mainly in the growth stage in some areas. In other areas, frosts coincided with the flowering and grain filling stage, a stage in which the plant is more sensitive to frost damage, affecting its productivity (Barrales *et al*., 2002). When comparing Figures 3 and 4, we found that the largest area with temperatures below 4 °C, which were recorded in May, August and October, these coincide with the stages of emergence, flowering and physiological maturity of corn (Granados and Sarabia, 2013), where those recorded in August could cause more damage since the corn was in the flowering stage.

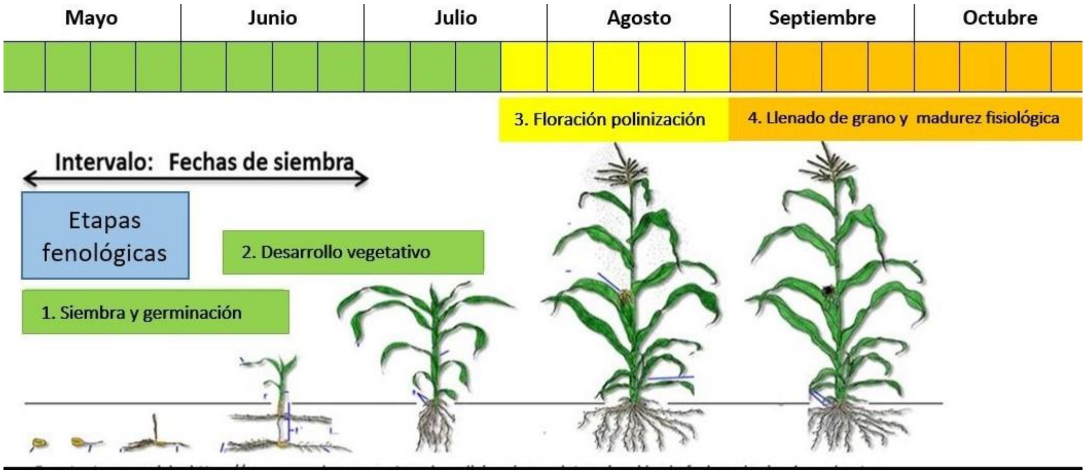


Figure 4. Behavior of the phenological stages of corn in the Toluca Valley.

Vegetation index and crop vigor (NDVI)

Climate variability can be obtained by means of remote sensing tools, for the understanding of the phenology of ecosystems based on the temporal variation of vegetation greenness (Gómez, 2013), therefore, continuous monitoring of the total cultivated area of corn was carried out based on the normalized difference vegetation index (NDVI), through the multitemporal analysis of MODIS/Terra satellite images with a frequency of 16 days during the May-October period, where the effect of low temperatures that caused temporary wilting to the foliage of the corn in the S-S 2019 agricultural cycle was observed.

As shown in Figure 5, the values of the NDVI that indicates the greenness index; with the map algebra it was possible to identify the dynamics of the behavior of this variable, since it increases in the first half of September and subsequently descends in the second half of the same month, which is combined with the presence of temperatures below 4 °C affecting the agricultural area of the municipalities of Almoloya de Juárez, Zinacantepec, south and north of Toluca, Temoaya, Huixquilucan, Calimaya and Tenango del Valle.

These months are decisive for the good development of corn, where the maximum growth and vegetative development are expressed in August (flowering and grain filling), and it is where maximum NVDI values were obtained.

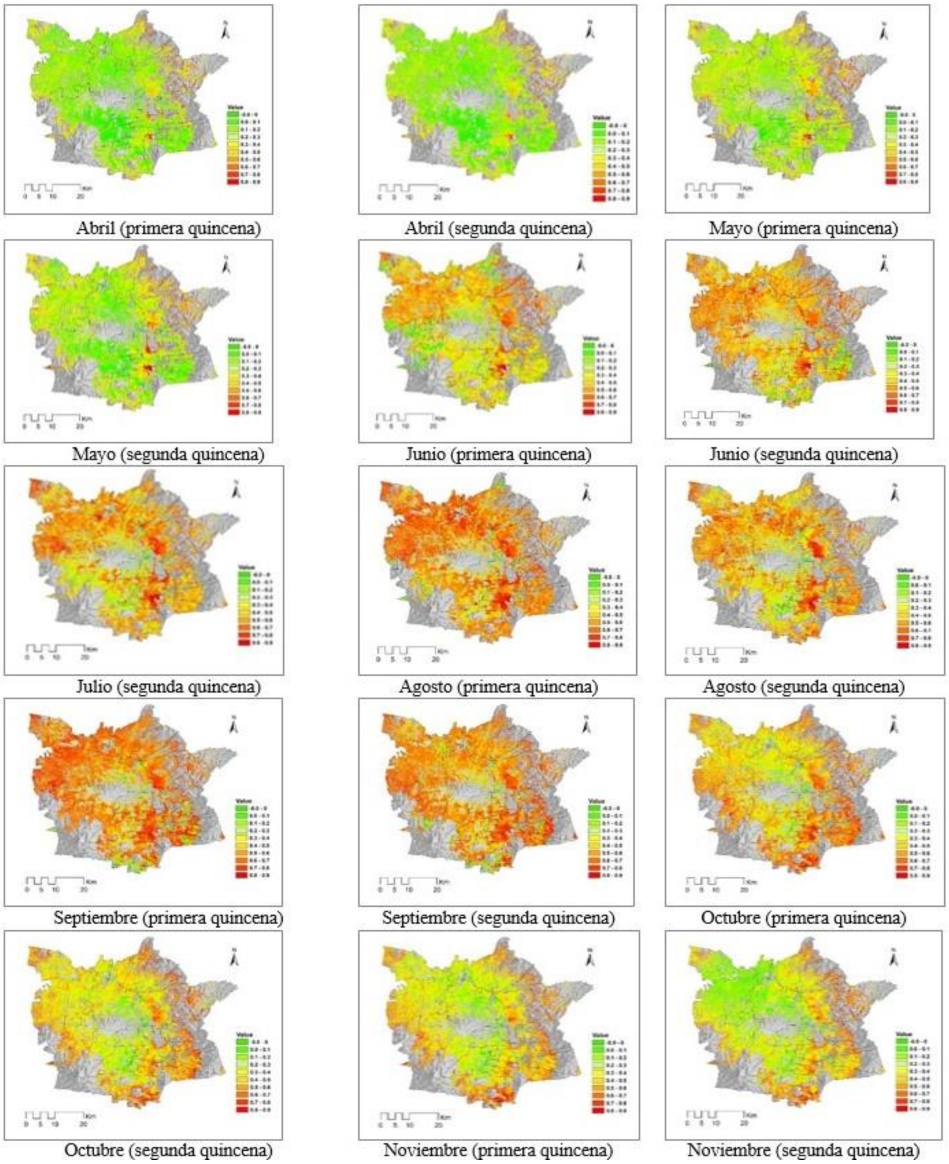
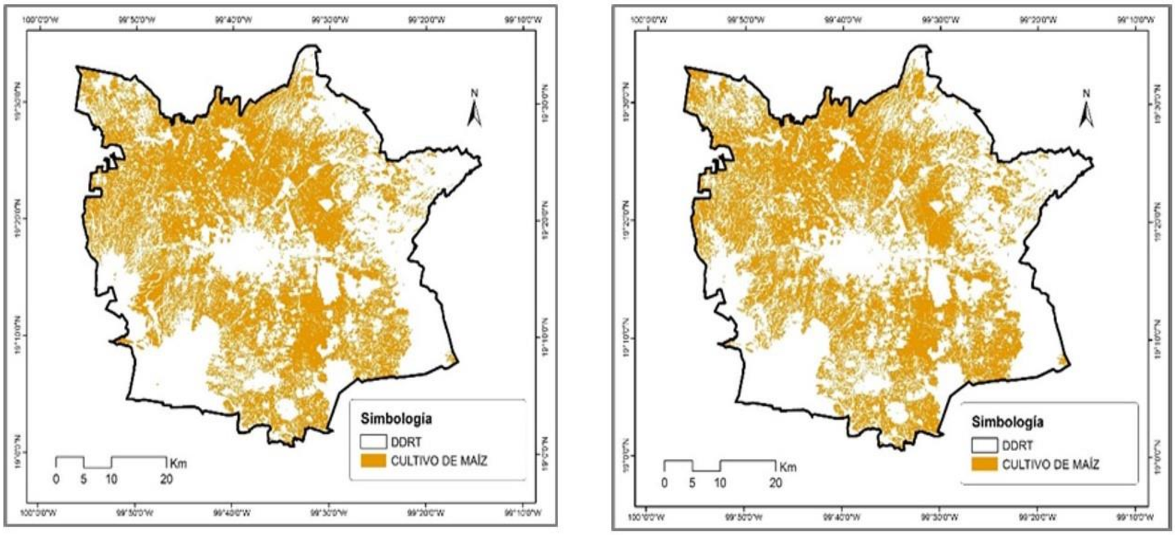

Abril (primera quincena)
Abril (segunda quincena)
Mayo (primera quincena)
Mayo (segunda quincena)
Junio (primera quincena)
Junio (segunda quincena)
Julio (segunda quincena)
Agosto (primera quincena)
Agosto (segunda quincena)
Septiembre (primera quincena)
Septiembre (segunda quincena)
Octubre (primera quincena)
Octubre (segunda quincena)
Noviembre (primera quincena)
Noviembre (segunda quincena)

Figure 5. Behavior of the NDVI at the biweekly level in the cultivated areas of corn.

One of the advantages of crop monitoring through the NDVI, which indicates the greenness index or degree of health of the crops, is that they can identify anomalies in the foliage of the plants. In this case, a sudden decrease in low levels of corn greenness in the study area was identified. By superimposing the maps of NDVI (Figure 3) and monthly minimum temperatures below 4 °C (Figure 5), it was possible to identify that there is a close relationship between these two variables.

Corn area affected by frosts

Before the frost, the corn area to July was 126 500.7 ha and after the frost (August-September), the area decreased to 122 989.15 ha, a reduction of 3 511.6 ha, which represents 2.77% (Figure 6).



Superficie de maíz antes de las heladas

Superficie de maíz después de las heladas

Figure 6. Cultivated area of corn before and after frosts.

The municipalities that reported the largest area affected by frosts were the following: Almoloya de Juárez with 32%, Zinacantepec with 18% and Tenango del Valle with 9.4%. With smaller affected areas and reporting lower values of 0.5% were Capulhuac, Otzolotepec, Xonacatlán, San Antonio la Isla, Mexicaltzingo, Atizapán, Chapultepec, Texcalyacac and San Mateo Atenco (Table 4).

Table 4. Rainfed corn area affected by frosts in the S-S 2019 agricultural cycle.

No.	Municipality	Affected area (ha)	Extension (%)
1	Almoloya de Juárez	1 132	32.2
2	Zinacantepec	618	17.6
3	Tenango del Valle	331	9.4
4	Tianguistenco	249	7.1
5	Xalatlaco	245	7
6	Calimaya	212	6
7	Toluca	179	5.1
8	Ocoyoacac	100	2.8
9	Joquicingo	91	2.6
10	Temoaya	85	2.4
11	Lerma	71	2
12	Rayón	42	1.2
13	Huixquilucan	37	1.1
14	Metepec	32	0.9
15	Capulhuac	17	0.5

No.	Municipality	Affected area (ha)	Extension (%)
16	Otzolotepec	15	0.4
17	Xonacatlán	13	0.4
18	San Antonio de la Isla	11	0.3
19	Almoloya del Rio	9	0.3
20	Mexicaltzingo	8	0.2
21	Atizapán	5	0.1
22	Chapultepec	4	0.1
23	Texcalyacac	4	0.1
24	San Mateo Atenco	1	0
	Total	3 511	100

Frost-area of corn affected relationship

When applying the multiple linear regression (MLR) model, it was found that some variables have a greater influence on the manifestation of frosts (Eastman, 2015) and as observed in Table 5, altitude has a greater influence on the occurrence of frosts, followed by precipitation and minimum temperature. With less association value are the slope of the terrain and the frequency of cold days.

Table 5. Concentrate of the association value of the variables used.

Variable	Association value (r)	Coefficient of determination (%)	Association
Altitude	0.516	26.69	Positive relationship
Precipitation	0.503	25.31	Positive relationship
Minimum temperature	0.484	23.44	Positive relationship
Slope of the terrain	0.4	16.05	Positive relationship
Frequency of cold days	0.281	7.92	Low positive relationship

All variables have a positive relationship, this means that, with higher altitude, less rain, greater number of days with minimum temperature, greater slope and frequency of cold days, there are more probabilities of frost occurrence.

Frost risk probability map

With the RLM model, the coefficients of each explanatory variable were estimated, and by the relationship between a dependent variable (frost) and a set of independent variables (the variables that cause a frost): climatic and environmental (Pineda *et al*., 2010). The risk probability map indicates the probability that a minimum area of corn represented on the map (pixel) will be lost because of frosts (Figure 7). Of the total area that is lost due to frosts, the probability obtained is: with low risk 96%, medium risk 2%, high risk 2% and with very high risk 0.3%.

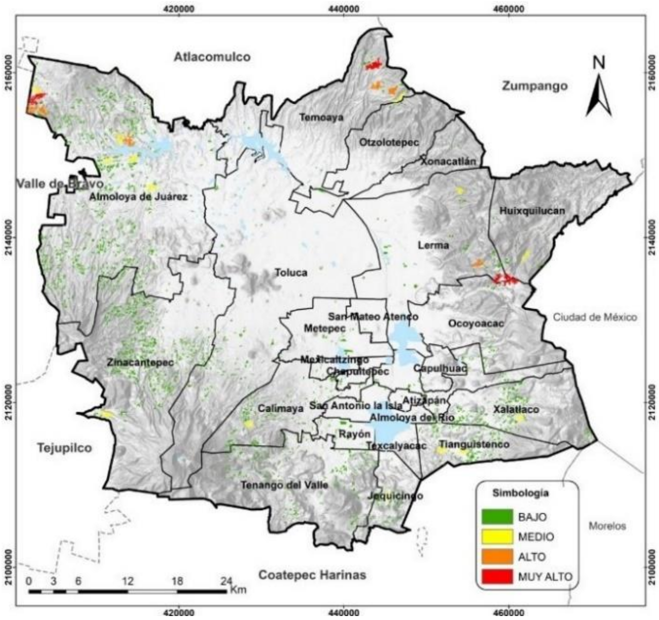


Figure 7. Spatial distribution of the risk of frost occurrence in the DDRT.

The risk levels for each of the 24 municipalities that make up the DDRT are shown in Table 6, where it is observed that the municipalities with the largest area are: Almoloya de Juárez with 1 132 ha (32.2%), Zinacantepec with 618 ha (17.6%), Tenango del Valle with 331 hectares (9.4%) and Santiago Tianguistenco with 249 ha (7.1%). Together, these municipalities represent more than half of the area with a probability of corn loss due to frosts.

The only municipality where there is no risk of frosts is San Mateo Atenco. Those municipalities with high and very high risk make up an area of 65 ha; that is; 1.8% of the total estimated corn area in 2019, which are located in the center and northwest of Almoloya de Juárez, north of Temoaya and east of Lerma (Figure 7). Municipalities with different levels of frost risk are shown in Table 6.

Table 6. Cultivated areas of corn with a probability of frosts. S-S 2019 agricultural cycle.

Municipality	Area with frost risk level (ha)				Total area	
	Low	Medium	High	Very high	(ha)	(%)
Almoloya de Juárez	1 057	37	28	10	1 132	32.2
Zinacantepec	617	1			618	17.6
Tenango del Valle	331				331	9.4
Tianguistenco	241	8			249	7.1
Xalatlaco	243	2			245	7
Calimaya	205	7			212	6
Toluca	179				179	5.1
Ocoyoacac	99			1	100	2.8
Joquicingo	88	3			91	2.6

Municipality	Area with frost risk level (ha)				Total area	
	Low	Medium	High	Very high	(ha)	(%)
Temoaya	59	4	20	2	85	2.4
Lerma	64	2	2	3	71	2
Rayón	42				42	1.2
Huixquilucan	32	5			37	1.1
Metepec	32				32	0.9
Capulhuac	17				17	0.5
Otzolotepec	14	1			15	0.4
Xonacatlán	13				13	0.4
San Antonio la Isla	11				11	0.3
Almoloya del Río	9				9	0.3
Mexicaltzingo	8				8	0.2
Atizapán	5				5	0.1
Chapultepec	4				4	0.1
Texcalyacac	4				4	0.1
San Mateo Atenco	1				1	0
Total:	3 375	70	50	16	3 511	100

Conclusions

Of the S-S agricultural cycle of rainfed corn of the year studied, 2019, of the months analyzed, in August and September, the most intense frosts occurred in the Rural Development District of Toluca (DDRT), with temperatures below 4 °C, which caused the decrease in the areas of this crop, estimating at 3 511 ha, whose most affected municipalities were Almoloya de Juárez and Zinacantepec. The variables that have the greatest relationship in the manifestation of frosts in DDRT are altitude, precipitation and minimum temperature. In the spring-summer agricultural cycle of 2019. The highest probability of frost occurrence occurred in the municipalities of Almoloya de Juárez, Temoaya, Zinacantepec, Lerma and Ocoyoacac; however, all the municipalities that make up the DDRT presented different levels of risk and were exposed to the loss of cultivated areas because of frosts during the flowering and grain filling stage of corn.

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