Article

Production potential of *Vanilla planifolia* Jacks in Totonacapan, Mexico, using geographic techniques

Alberto Santillán-Fernández[1]
Maryjose Trejo Cabrera[1]
Araceli Martínez Sánchez[1]
Luis Martínez Ángel[1]
Nehemías Vásquez Bautista[2]
Salomón Luis Mejía[1§]

[1]Forestry Engineering-Higher Technological Institute of Venustiano Carranza. Av. Tecnológico s/n, Col. El Huasteco, Lázaro Cárdenas, Venustiano Carranza, Puebla, Mexico. CP. 73049. (asantillanq@itsvc.edu.mx; marytreca@gmail.com; chelyforestal@itsvc.edu.mx; luismartinezangel99@gmail.com;). [2]Trusts Instituted in Relation to Agriculture. Av. Tulum 238 and 240, lot 81 and 82, super block 4 and block 12, Cancún, Quintana Roo, Mexico. CP. 77500. (nvasquez@fira.gob.mx).

[§]Corresponding author: forestal@itsvc.edu.mx.

Abstract

The Totonacapan region, between the northern limits of Puebla and Veracruz, produces 80% of the vanilla in Mexico, and is considered the center of origin of the species *Vanilla planifolia* Jacks. However, the area sown has decreased, which affects the competitiveness of the sector. In the present work a socio-economic characterization of the producers of *Vanilla planifolia* Jacks was carried out during 2017 and 2018 and the productive potential for the cultivation in the Totonacapan region was determined through the use of geographic information systems (GIS) based on factors edaphoclimatic and physiographic. Results show that production is a secondary economic activity, among producers over 55 years of age and in a smallholder situation. The highest productive potential is located northwest of the Totonacapan region and is conditioned by the increase in rainfall in the driest month (April: <60 mm year^{-1}) and temperatures no higher than 30 °C in the warmest quarter (June-July-August). These areas are mostly destined to livestock and agriculture of more profitable cyclical crops, so in the expansion of the crop should consider the socioeconomic aspects of producers.

Keywords: maxent, maximum entropy, multicriteria evaluation, potential distribution.

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Introduction

The cultivation of vanilla (*Vanilla planifolia* Jacks) had its origin in Mexico, particularly in the northern area of Veracruz, where the Totonac culture settled (Lubinsky *et al*., 2008), which used and domesticated vanilla for the first time (Sinha *et al*., 2008). In the Totonacapan region, the cultivation of vanilla has been determinant for the socioeconomic development of producers (Herrera-Cabrera *et al*., 2012). The vanilla produced there is considered the best quality and largest aromatic compounds worldwide, these characteristics are attributable to the geographical environment in which it develops, natural factors and crop management practices (Lubinsky *et al*., 2008; Flores *et al*., 2017).

Despite being the center of origin, as a result of a reduction in the planted area, historically Mexico went from being the largest center of vanilla production at the international level, to occupy the fifth place, with 4.97% of the annual net volume, behind from Indonesia (34.93%), Madagascar (31.81%), China (11.63%) and Papua New Guinea (6.97%) (FAOSTAT, 2018). Particularly in Mexico, Veracruz is the main producer with 70% of the volume of production, in order of importance continue Puebla and Oaxaca, which together contribute 29% of total production and in smaller quantities, also occurs in San Luis Potosí, Hidalgo, Chiapas and Quintana Roo.

The most important production area in Mexico is located north of Puebla and in north-central Veracruz and is known as the Totonacapan region with more than 80% of the national production (SIAP, 2018), where germplasm is also located of greater biological and commercial importance (Herrera-Cabrera *et al*., 2012). However, the regional and, in general, the national sector, faces low productivity, attributed to the reduction of the sown area and the abandonment of the crop, as a consequence of a fragile organization of producers and problems associated with crop management. The good field yields presented by Mexico (0.41 t ha^{-1}) are insufficient to reverse this situation (Barrera-Rodríguez *et al*., 2011; Jaramillo *et al*., 2012; Barrera *et al*., 2014; Santillán-Fernández *et al*., 2018).

Given this scenario, the vanilla production system in the Totonacapan region seems destined to disappear; however, according to Lubinsky *et al*. (2008); Barrera-Rodríguez *et al*. (2011) the production of vanilla in the region has an ancestral connotation that can revalue the product as a center of origin and have the slogan of producing the best quality vanilla in the world. For this purpose, INIFAP (2011); SAGARPA (2012); Santillán-Fernández *et al*. (2018) propose that at the same time as solving the socio-economic and crop management problems associated with production, areas with productive potential should be identified that consider edaphoclimatic aspects, to increase the sown areas, which is the problem of international competitiveness of the national vanilla producer sector.

In this sense, geographic information system (GIS) techniques such as multicriteria evaluation (MCE) and species distribution models are useful tools to characterize the agroecological potential of the area destined for a crop, even more so if in the area of there is no similar background in the study (Jiménez *et al*., 2004; Kazuya *et al*., 2006; Aguilar *et al*., 2010). Within the species distribution models, the Maximum Entropy algorithm (MaxEnt) has the best evaluations in comparison with other programs that model the probability of occurrence and adaptation of a species from edaphoclimatic variables (Hernández *et al*., 2006; Phillips *et al*., 2006; Elith *et al*., 2011; Navarro-Cerrillo *et al*., 2011).

This tool has been applied successfully in the determination of the productive potential of potato crops (*Solanum tuberosum*) (Hijmans *et al*., 2000), papaya (*Carica papaya*) (Scheldeman *et al*., 2007) and vanilla (*Vanilla planifolia*) (Hernández-Ruiz *et al*., 2016; Flores *et al*., 2017). Phillips *et al*. (2006) and Elith *et al*. (2011) mention that many authors prefer the MaxEnt algorithm due to parsimony and its proper adjustment to the distribution of species when only presence information is used.

For its part, the MCE associated with GIS is an exact system when information of an environmental, social and economic nature is combined, which based on the weighting and compensation of determining variables or fitness factors, generates cartography that expresses the productive potential of a region with respect to the specific requirements of a crop (Gómez and Barredo, 2005) and has been applied in the determination of suitable areas for the cultivation of *Agave durangensis* (Olivas *et al*., 2007), of sugar cane (*Saccharum officinarum*) (Aguilar *et al*., 2010) and alternative crops such as amaranth (*Amaranthus* spp.) and nopal (*Opuntia ficus-indica*) (Ceballos-Silva and López-Blanco, 2010).

The cultivation of vanilla relates technical, social, ecological and climatic factors that condition its development, yield, conservation and sown areas, by virtue of which it is necessary to know its current state of production and characterize potential areas with higher yields in the field; knowledge about these factors that influence the management of the crop are determining factors in its expansion (Flores *et al*., 2017; Rocha *et al*., 2018).

In this context, the objectives of this study were to a) characterize socioeconomically the vanilla producers in the Totonacapan region; and b) determine the areas with the greatest productive potential to establish the vanilla crop through MaxEnt and MCE models. This information will allow to make reliable decisions for the establishment of this crop in areas with greater potential, that have the best edaphoclimatic conditions for its development and thus improve yields in the field, which help to improve the international competitiveness of the sector.

Materials and methods

Study area

The Totonacapan region is the most important production area in Mexico and is located north of Puebla (it includes 61 municipalities) and in north-central Veracruz (20 municipalities) (Figure 1). Due to its physiographic and edaphoclimatic characteristics, it is an optimal region for the development of vanilla cultivation, since subtropical, warm and humid climates are located in altitudes below 600 m, with temperatures ranging from 20 °C to 32 °C and average annual rainfall ranging from 1 500 to 3 000 mm, in addition to having land with excellent drainage, organic matter greater than 3.5%, with a pH of 5.5 to 7 and slopes of 10% to 40% (INIFAP, 2011; SAGARPA, 2012).

The Totonacapan region collects the waters of the Panuco, Tuxpan, Cazones and Tecolutla rivers, which allows the development of livestock, forestry and agriculture, with crops of corn (*Zea mays*), beans (*Phaseolus vulgaris*), squash (*Cucurbita* spp.) and pepper (*Capsicum annuum*) as main for self-consumption. In addition to commercial species such as coffee (*Coffea* spp.), sugar cane

(*Saccharum officinarum*), tobacco (*Nicotiana tabacum*), pepper (*Pimenta dioica*), banana (*Musa paradisiaca*), sesame (*Sesamum indicum*), ginger (*Zingiber officinale*), litchi (*Litchi chinensis*), citrus (*Citrus sinensis*) and vanilla (SIAP, 2018).

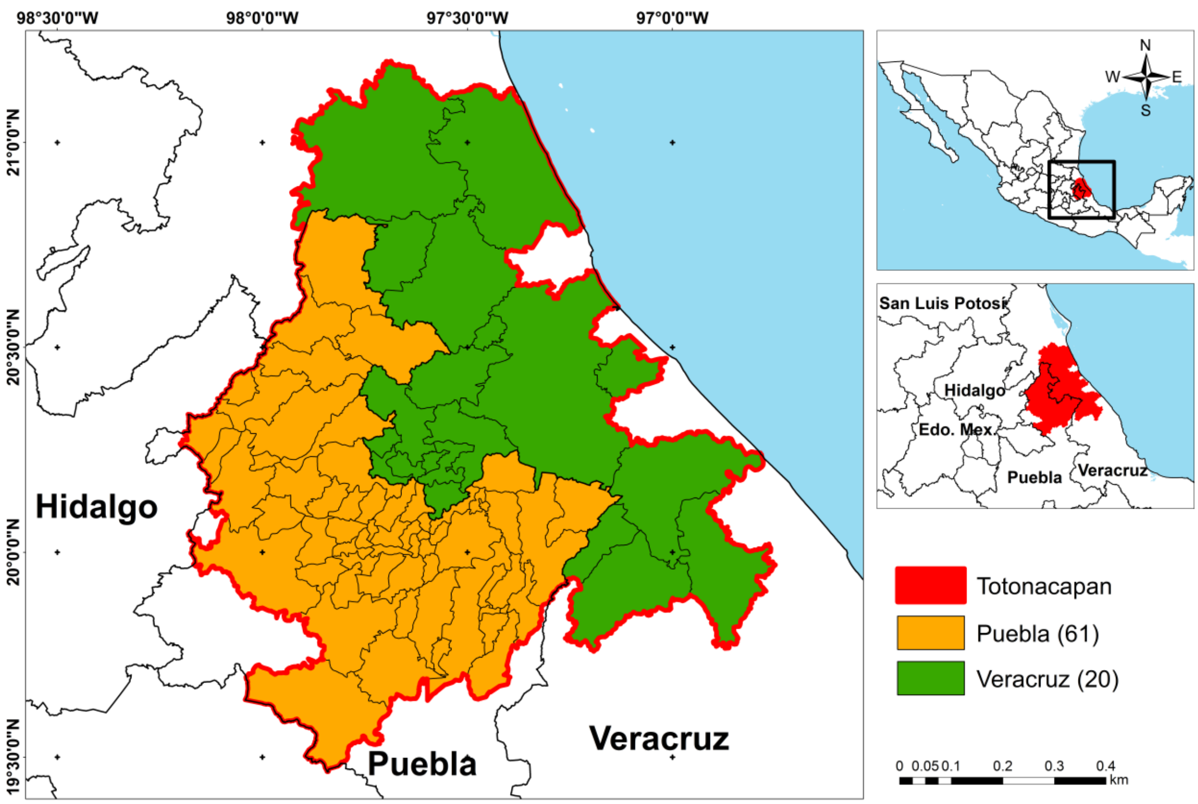

Figure 1. Spatial location of the Totonacapan region composed of municipalities of Puebla and Veracruz.

Socioeconomic characterization of vanilla production in the Totonacapan region

To determine the socioeconomic factors that explain the changes in area planted and yield in the field in Totonacapan, a survey was conducted between November 2017 and February 2018 to 175 vanilla producers (20% of the total, statistically sufficient sample according to the theory of sampling) based on their availability and references in the region. In addition, specialists from the Autonomous University of Chapingo (2), the Postgraduate School (1) and representatives of the Product System Committee of Puebla (2) were interviewed. The interview guide considered phytosanitary, climatic, social and market aspects.

The survey included questions about age, schooling, cultivated area, land tenure and percentage that represents the activity in the family income. According to the CIMMYT survey design guide (1993), aspects regarding the knowledge that the producer has about irrigation, fertilization, pest and disease control, as well as other factors that could condition the expansion of the crop and increase its productivity, such as the climate, the physiography of the plot, production costs, management of subsidies and credits, management and parcel equipment, among others.

Vanilla productive potential using the maximum entropy algorithm (MaxEnt)

Through *in situ* tours in 2016 and with the help of the directors of the Association of Vanilla producers of the State of Puebla, a total of 167 points with presence of vanilla in the field of the municipalities with production were georeferenced for their accessibility; this information was combined with climatic and edaphic variables of the area, with a resolution of 30 s (1 km^2), the first correspond to the 19 bioclimatic variables and annual evaporation, and the second are: calcium, electrical conductivity, organic carbon, potassium , magnesium, organic matter, sodium, pH and sodium adsorption ratio, available in the global database of climatic surfaces WorldClim.

The points with presence of vanilla in field (167), were introduced in the MaxEnt algorithm (MaxEnt, 2016) in comma delimited format (.csv) and the climatic and edaphic variables in ASCII format (.asc), following the methodology de Hijmans *et al*. (2005) was determined the productive potential of the region for the cultivation of vanilla. The results were imported into DivaGis v7.5 (DivaGis, 2016) and converted into grig format (.grd) to be viewed as images. The probability of occurrence of the species was categorized into areas with potential i) very low [0.0 - 0.2]; ii) low (0.2-0.4); iii) medium (0.4-0.6); iv) high (0.6-0.8); and v) very high (0.8-1), according to a Likert scale of homogeneous intervals.

Vanilla productive potential using multicriteria evaluation

From the geoportal of the National Commission for the Knowledge and Use of Biodiversity (CONABIO), the georeferenced data were extracted in vector format 1: 1 000 000 in altitude, precipitation, temperature, pH and soils and in raster format with a resolution of 5 min the digital elevation model that served to delimit the slopes of the region. The climatic and edaphic ranges were used where the highest field yield is obtained: altitude (less than 600 m), precipitation (1 500 to 3 000 mm), temperature (20 to 32 °C), type of soil (with organic matter) greater than 3.5% and pH higher than 5.5) and pending (10 to 40%) (INIFAP, 2011; SAGARPA, 2012), to discriminate those areas that do not meet these specific needs.

For the procedure of weighting and comparison of said aptitude factors, the Weighted Overlay module of ArcMap® (ArcMap, 2010) was used, the evaluation scale (very low, low, medium, high and very high) was determined by routes in field and according to the opinion of specialists in the production of vanilla of the Autonomous University Chapingo (UACH), College of Postgraduates (CP) and representatives of the Committee System Product of Puebla AC.

Discrimination of the productive potential by land use and current vegetation

Finally, to delimit those regions suitable for the expansion of the crop, areas were determined by productive potential (very low, medium, high and very high) based on the use of soil and vegetation reported by the INEGI (2016) scale 1: 250 000 of the VI series. Through field trips with directors of the Association of Vanilla Producers of the State of Puebla AC, the information obtained by the two methods (MaxEnt and MCE) was verified, which served as the basis for the proposal to establish new areas for the cultivation of *Vanilla planifolia* with greater productive potential.

Results and discussion

Socioeconomic characterization of vanilla producers in the Totonacapan region

The Product System Committee of Puebla AC indicates that in the region of Totonacapan there are a total of 871 producers who cultivate 2 653 ha of vanilla, of which 80% are men and 20% women, belong mostly to the Otomi ethnic groups and totonaco. Of the total of producers, 487 have this crop in land of small property with a planted surface of 1 486 ha, and 384 producers develop the activity in lands of common property with a total of 1 167 ha.

95% of the producers surveyed produce vanilla as a secondary activity, and have as main sources of income, the production of corn, beans, coffee, pepper and livestock. In most cases the production of vanilla is practiced more by a cultural factor than by the profitability of the crop, since this activity is inherited from generation to generation and the pods are used for the manufacture of crafts that are occupied in the festivities regional

Experts from the UACH, CP and representatives of the Product System Committee of Puebla AC, consider the smallholding (<0.5 ha in 79% of producers), the low level of study (<8 years), the age (from 55 to 62) years) and the fact that the production of vanilla means a secondary activity that complements the family income (Table 1), impedes the development of the vanilla sector in the region, by limiting the area sown and in many cases converting it to more profitable crops.

Table 1. Socioeconomic characterization of the surveyed producers of vanilla in the Totonacapan region according to the sown area and net production.

Sown Surface (ha)	Production (t)	Producers		Average		IF
		n (175)	(%)	Age	Studies	(%)
< 0.25	< 0.1125	32	18	60	6	5
≥ 0.25 a 0.5	≥ 0.1125 a 0.2245	106	61	62	6	12
≥ 0.5 a 1	≥ 0.2245 a 0.449	23	13	57	7	27
≥ 1 a 6.5	≥ 0.449	14	8	55	8	43

IF= family income that represents the activity.

Alcon *et al*. (2008) point out that older producers are more reluctant to change their production systems, considering that they have always done so and for them it is well done. On the other hand, Soto *et al*. (2006) establish that it is more complicated for producers with small plots to strengthen their production systems with new infrastructure, since in many cases they represent a secondary activity in their family income. In this regard, Álvarez and Crecente (2000) describe the benefits of land consolidation (through rights-of-use session) as a measure of adaptation to smallholdings and crop spraying.

Factors of crop management and access to credit

Added to the problems of smallholding, the vanilla producer of the Totonacapan region faces a scarce development of technological packages for the management of the crop, which reduce production by not considering programs for the control of pests, diseases, fertilization and irrigation. 98% of the planted area is managed under a rainfed water regime, only 2% uses irrigation. 90% of the producers surveyed mentioned that they have noticed variations in rainfall patterns, so they are aware that in the future watering may be required to maintain the activity. However, they do not consider the climatic factors, nor the physiography of the plots as limiting aspects for production.

95% of the producers surveyed consider that the expansion of the crop is limited by phytosanitary aspects related to the control of pests and diseases such as red bug (*T. confusus*), hairy worm (*P. aunifera*), root and stem rot (*F. oxysporum*) and anthracnose (*C. gloeosporioides*). In addition to the zero support for access to credit and subsidies that facilitate the parcel equipment and incorporate technological packages (especially fertilization) that improve productivity in the region. Practically 100% of producer's self-finance production costs, which in an unstable market in prices causes many of them to abandon the activity by converting their plots to more profitable crops.

INIFAP (2011); SAGARPA (2012), consider that the adequate management of the problems of fertilization, pests and diseases associated with the production of vanilla in the region, substantially improve the productivity of the sector. By virtue of this, as of 2011 they implemented technological packages that included these aspects, with good results in their beginning when increasing the yields in the field. However, due to lack of investment, continuity has been scarce. To solve this problem, the Product System Committee of Puebla AC, currently manages trusts instituted in relation to agriculture (FIRA) credits to the producer to strengthen the production infrastructure.

The market factor: lack of added value

The average yields in field of the region are of 0.449 t ha^{-1} with production costs of \$60 000.00 year ha^{-1} and with gains superior to the \$88 000.00 year ha^{-1}, these gains correspond to the sale of the pod in green whose market value ranges from \$180 to \$200 kg. In the region 94% of the producers do not give the beneficiary service where the selling costs are over \$3 000 kg. This aspect has been addressed by Jaramillo *et al*. (2012), Jaramillo *et al*. (2013) and Xochipa-Morante *et al*. (2016) who consider that this factor is what limits the expansion of the crop, since the producer considers the activity to be unprofitable and prefers to channel its inputs to economically more attractive crops.

Barrera *et al*. (2014) mention that the international vanilla market imposes new and strict quality and safety standards on producers that they must abide by in order to be competitive; so the international market is a factor that directly affects the productivity of vanilla. By virtue of this, the Product System Committee of Puebla AC, implemented a series of workshops to promote among the producers of the region the vanilla beneficiation service, with which it is expected that they will substantially improve their income and the competitiveness of the vanilla sector.

Vanilla productive potential using the maximum entropy algorithm (MaxEnt)

The results obtained by the MaxEnt algorithm are highly significant with a reliability level of 95% (*p*-value <0.0001) and a coefficient of determination (R^2) of 99.6%. Of the 29 edaphoclimatic variables used in the MaxEnt probabilistic model, four contributed with 88.1%

of the prediction of zones with the highest productive potential for the vanilla crop. The most important were: increase in rainfall in the driest month (April: <60 mm year^{-1}) that contributed 56.3% of the prediction, followed by a low content of sodium in the soil with 13.1%, temperatures no higher than 30 °C in the hottest quarter (June-July-August) with 10.7% and high organic carbon content in the soil with 8%.

Therefore, according to the model, the factor that most affects the optimal development of the vanilla crop is the increase in precipitation in the driest month. This aspect was documented by Barrera-Rodríguez *et al*. (2009); INIFAP (2011); SAGARPA (2012); Flores *et al*. (2017); Santillán-Fernández *et al*. (2018) who agree that the adoption of irrigation during periods of low water substantially improves yields in the field, even without fertilization. On the other hand, the surveyed producers mentioned that they have perceived variations in rain patterns, so they do not rule out irrigation in the future.

Figure 2 shows the productive potential of the region classified in: i) very low; ii) low; iii) medium; iv) high; and v) very high. The current production areas and the areas planted during the year 2017 are also located, which were proposed for this crop before the Association of Vanilla Producers of the State of Puebla AC, and which were selected based on the results obtained and availability in the field. , when the producers voluntarily adopt the vanilla crop.

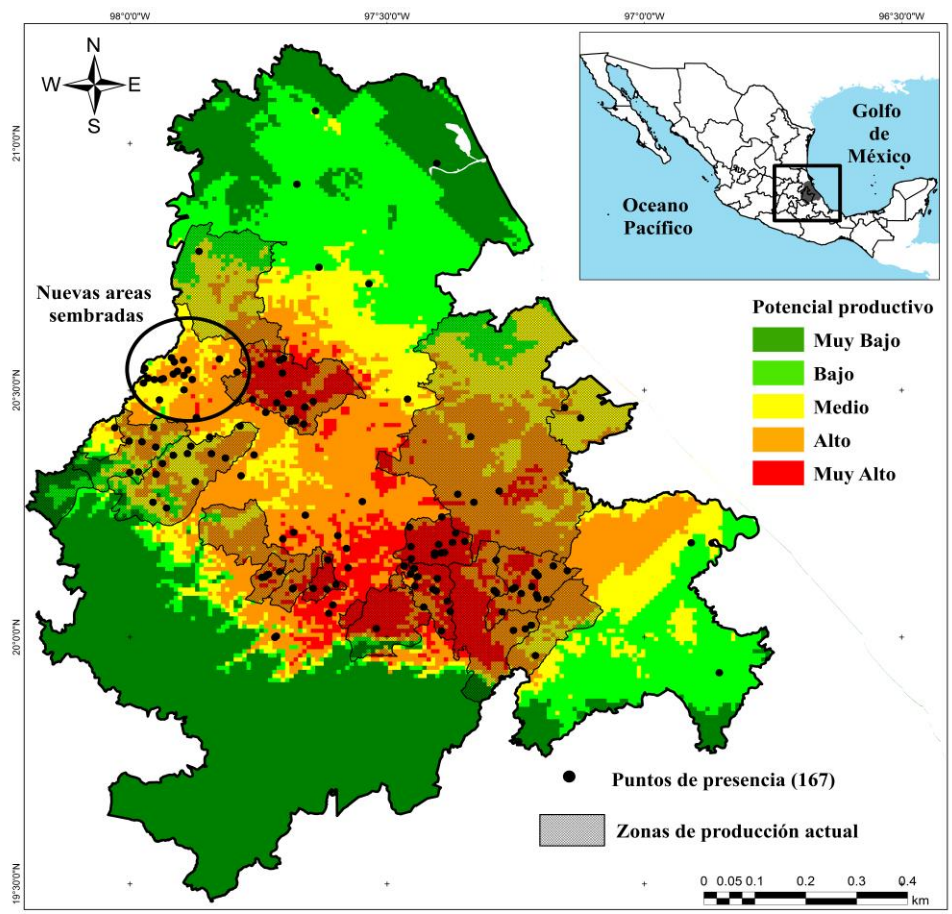

Figure 2. Spatial representation of the estimation of the productive potential for vanilla in the Totonacapan region obtained by means of the maximum entropy algorithm.

For the MCE an evaluation scale of five classes was built, with areas of potential i) very low; ii) low; iii) medium; iv) high; and v) very high (Table 2). The MCE turned out to be a more robust methodology, which considers larger areas compared to MaxEnt.

Table 2. Criteria for evaluating climatic and edaphic variables to establish the productive potential of vanilla in the Totonacapan region, built from field trips and expert opinion.

Variable	Levels of the productive potential of vanilla				
	Very low	Low	Medium	High	Very high
Altitude (masl)	>1 000	800-1 000	400-800	200-400	0-200
Annual rainfall (mm)	<800 ó >2 500	800-1 200	1 200-1 500	1 500-2 000	2 000-2 500
Annual temperatura (°C)	<18 ó >26	18 - 20	20 - 22	22 - 24	24 - 26
pH	<4 ó >8	4 - 5.5	5.5	5.6 - 6.7	6.7 - 7.9
Soil*	Soils different from Feozem and Cambisol	Soils different from Feozem and Cambisol	Different types of Feozem and Cambisol	Feozem haplico and Cambisol eutrico	Feozem haplico and Cambisol eutrico
Organic material (%)	<1	<1	1 - 2	2 - 3.5	≥3.5
Pending (%)	>40	35-40	30-35	20-30	0-20

*= FAO classification system (1999).

Figure 3 shows those areas in the Totonacapan region that meet the agroclimatic conditions of the crop, specific areas with medium, high and very high aptitude for the establishment of the vanilla, where to improve the management of the crop with aspects such as control phytosanitary, irrigation and fertilization, it is expected to obtain the best yields in the field of the region. The results were taken as a reference by the Association of Vanilla Producers of the State of Puebla AC, to manage the sowing of 100 ha with vanilla between May and June 2017.

When considering edaphoclimatic factors (annual precipitation, annual temperature, pH, type of soil and organic matter) and physiographic factors (altitude and slope) in the MCE, a greater area with medium to very high productive potential was delimited with respect to the results obtained with the MaxEnt algorithm, which did not include physiographic variables. However, both methods agree that the greatest productive potential is located northwest of the Totonacapan region, in the border areas of Puebla and Veracruz, which is where the current producing areas are located, with medium to very high productive potential.

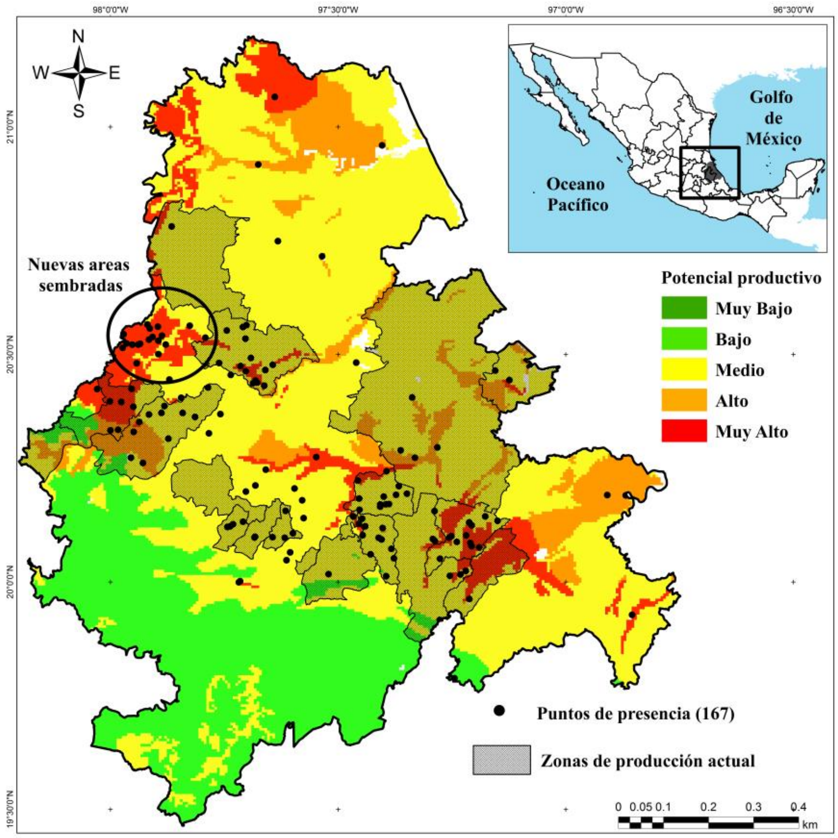

Figure 3. Spatial representation of the estimation of the productive potential for vanilla in the Totonacapan region obtained through multicriteria evaluation.

Discrimination of the productive potential by land use and current vegetation

By using land use and vegetation cartography (INEGI, 2016), it was possible to identify the current land use of the areas with productive potential for the cultivation of vanilla obtained by the MaxEnt and MCE algorithms (Table 3). Coverages where the expansion of the crop can be potentiated are located in those areas where the continuity of an ecosystem is not put at risk; therefore, agriculture and grassland areas are the most optimal, as long as socioeconomic factors manage to reconvert them.

Table 3. Coverage for use of soil and vegetation of the productive potential of vanilla in the Totonacapan region.

Use of soil and vegetation	Maximum entropy (%)					Multi-criteria evaluation (%)					Total	
	MA	A	M	B	MB	MA	A	M	B	MB	(%)	ha
Jungle	3	4	4	1	1	5	3	5	0	0	13	197 276
Forest	0	5	5	1	30	0	1	10	10	20	41	622 178
Farming	1	2	3	3	5	1	2	5	3	3	14	212 451
Urban zone	0	0	6	1	4	0	0	8	2	1	11	166 926

Use of soil and vegetation	Maximum entropy (%)					Multi-criteria evaluation (%)					Total	
	MA	A	M	B	MB	MA	A	M	B	MB	(%)	ha
Pasture and scrub	4	5	5	3	2	3	3	9	2	2	19	288 326
Others*	0	0	0.5	0.5	1	0	1	1	0	0	2	30 350
Total (%)	8	16	23.5	9.5	43	9	10	38	17	26	100	1 517 507

*= includes mangrove, aquatic vegetation and halophyte. MA= very high; A= high; M= medium; B= low; MB= very low.

The results obtained by MaxEnt and MCE indicate that the areas with the greatest productive potential are located within the grassland areas that are destined for livestock, this information was validated through on-site tours with directors of the Association of Vanilla Producers of the State of Puebla AC and served as the basis so that between May and June 2017, vanilla is planted 100 ha to the northwest of the Totonacapan region, considering that in these areas with greater productive potential (high to very high) the probability of adaptation is increased, development and growth of vanilla.

Both methodologies agree that the areas with the greatest productive potential are located on agricultural, pasture and forest areas. It is proposed the cultivation of vanilla in those areas whose current use is destined to livestock (pasture) and to the agriculture of corn, beans, squash and pepper mainly. Barrera-Rodríguez *et al.* (2011); Jaramillo *et al.* (2012 and 2013) establish that to increase the areas planted with vanilla in the Totonacapan region, the profitability of the crop must be improved in the face of other activities, giving an added value to the product that is marketed in green through the beneficiation process.

Conclusions

The production of vanilla in the Totonacapan region is a secondary activity, among producers of advanced age (>55 years), low level of studies (<8 years) and in a smallholding (<0.5 ha). In addition to these factors, phytosanitary problems, fertilization, access to credit and market, have also contributed to a decline in the productivity of vanilla in the region, marked by the reduction in the area sown.

The highest productive potential for the cultivation of vanilla is found in the northwest of the Totonacapan region, in areas that are mostly destined for cattle raising and agriculture with more profitable cyclical crops, between the limits of Puebla and Veracruz. The productive potential is conditioned by the increase in rainfall in the driest month (April: <60 mm year^{-1}) and temperatures no higher than 30 °C in the warmest quarter (June-July-August), so that the irrigation can substantially help improve yields in the field and consequently productivity in the region.

The productive potential for the sowing of new areas with vanilla in the Totonacapan region, obtained by means of geographic techniques, helped to make decisions in relation to the expansion of this crop, towards those surfaces with greater probability of adaptation for the development and optimal growth of the vanilla, with what is expected to increase the productivity of the national vanilla producer sector and therefore its international competitiveness. Both methods should not be considered different but complementary; however, the limitation of these techniques to socioeconomic, market and crop management factors should be considered, in virtue of which it is necessary to complement them with fieldwork.

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