Predicting the probability of occurrence of floral malformation in mango (Mangifera indica L) under climate change scenario

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Received 19 Feb 2022; Accepted 26 Mar 2022; Published 15 Apr 2022

Abstract

Malformation is a serious threat to mango cultivation in various Countries. The analysis of the potential impacts of climate change on mango malformation disease is essential for developing strategies to control malformation. The prediction of mango malformation occurrence was therefore undertaken by two approaches. In the first method, weather surfaces were generated using spatial interpolation technique (Kriging) for four weather s *viz.*, Tmax, Tmin, relative humidity and wind speed. The zonation was done using the threshold values conducive for *Fusarium mangiferae* growth and proliferation. The second method was statistical approach, using logistic quadratic model for predicting the probabilities of susceptible mango malformation areas in India. The results revealed that the spatial zonation of areas with mango malformation occurrence is higher for individual weather variable. However, when both temperature and relative humidity were used in combination, the area was considerably reduced. The study was also useful in classifying the area spatially using the threshold value for occurrence and non-occurrence of mango malformation. In case of logit model, the model was well fitted for predicting the probability of mango malformation occurrence. The model predicted high probability of mango malformation occurrence in Delhi, Uttar Pradesh and Haryana followed by Gujarat, Punjab and Jharkhand.

Keywords: weather surface, spatial interpolation, mapping malformation, climate change logistic quadratic model

Introduction

Mango malformation, a serious threat to mango cultivation causes gross deformation of vegetative and floral tissues (Aguilera *et al*. 2003, Chakrabarti 2011, Ploetz and Freeman 2009) [1, 11, 38]. It was first reported in India in 1891, but has been subsequently reported from Egypt, South Africa, Sudan, Swaziland, Brazil, Central America, Mexico, USA, Israel, Pakistan and Malaysia (Ploetz *et al*.2002, Zheng and Ploetz 2002) [39, 49]. Affected flowers are either sterile or abort shortly after fruits have been set; as a consequence, fruit yields are drastically reduced by 60 -90% in different commercial varieties of mango. The etiology of malformation has been a contentious issue, and a wide range of biotic and abiotic factors have been reported to cause the disease, including viruses, mites and nutritional deficiencies (Usha *et al*.1997, Gamliel-Atinsky *et al*. 2009, Otero-Colina *et al*. 2010, Chakrabarti, 2011, Lima *et al*.2012) [45, 17, 37, 11, 29]. Recently only *Fusarium mangiferae* was shown to cause mango malformation disease (Marasas *et al*, 2006, Zafar *et al*. 2006, Newman *et al*.2012, Freeman *et al*.2014) [30, 4, 35, 8]. It is now known that environment can influence host plant growth and susceptibility, pathogen reproduction, dispersal, survival and activity; as well as host-pathogen interaction (Lima *et al*. 2012) [29]. A change in temperature could directly affect the spread of infectious diseases and their survival between seasons. Most fungal pathogens require free water to infect their host plants. Rainfall is often required for dispersal of fungal spores, although some fungal spore types are wind-dispersed under dry conditions. The close relationship between the environment and diseases suggests that climate change will cause modifications in the current phytosanitary scenario. The impacts can be a decrease, an increase or no effect on the different pathosystems in each region. The documented evidence of recent climate changes supports that some eco-regions will be more affected by climate change than others, with the most bio diverse eco-regions particularly at risk (Gregory *et al*.2009, Beaumont *et al* 2011, Engler *et al*.2011, Heyder *et al*.2011, Milad *et al*.2011, Teixeira *et al*.2011) [21, 4, 14, 24, 32, 44]. It is expected that due to climate change there is a chance of an increase in temperature level, there by the favourable threshold value are exceeded leading to a reduction in the areas of disease occurrence (Ghini *et al*. 2008 and Landlearn 2012) [19, 28]. In Europe, southern regions are predicted to be more sensitive to climate change than northern ones, due to increases in summer drought (Kůdela 2009) [27]. In North America, the temperature increase is expected to be greater than the global average, particularly in boreal and mountainous regions (Bentz *et al*. 2010) [6].

Understanding how climatic factors vary across the global landscape is hence necessary to determine the influence of climatic factors on plant disease. Based on information from numerous weather stations, various methods are available that spatially interpolate climate data on a landscape grid (Hijmans *et al*.2010, Butterworth 2010) [10]. Although extrapolating from individual studies to epidemics over entire regions is still a challenge, these studies show that impact assessments of climate change on future disease development are possible (Burdon *et al*.2006, Garrett *et al*.2005, Burdon and Thrall 2008) [8, 9]. Assessments are now often made on high resolution grids or at multiple sites across a region, where observed weather records are not available (Harrison *et al*.1995) [23]. Geographic Information System (GIS) helps to manage, analyse, and present spatially related information, combining multiple layers of environment and biological information related to a spatial location to gain a better understanding of a specific location (Englewood 1990) [13]. Recent studies reveal that the malformation occurrence is primarily influenced by weather conditions favourable for the growth and proliferation of casual organism (Reddy, 2007; Reddy *et al*.2008) [40, 41]. Due to lack of prerequisite information, it is challenging to develop approaches to accurately predict the spatial distribution of mango malformation disease occurrence throughout India. It is also difficult to predict *Fusarium mangiferae* distribution with high accuracy, because data sets confirming *Fusarium mangiferae* occurrence are quite limited in comparison with mango tree crop data sets. The analysis of the potential impacts of climate change on mango malformation disease occurrence under changing climate scenario are however essential for adopting timely disease management measures in order to avoid serious losses. The present study was therefore conducted to forecast the spatial distribution of mango malformation occurrence under the future climate change scenario using GIS and statistical methods.

Materials and methods

Study area

This study was undertaken in the experimental site at the Division of Fruits and Horticultural Technology, IARI, New Delhi. The entire geographical area of India was selected for mango malformation forecast, zonation and for prediction of future possible areas of occurrence and its intensity. The mango is cultivated throughout India and Mango growing zones were divided into different regions based on flowering period in India (Table 1).

Table 1: Mango growing zones with flowering period in India

Zone	Flowering period (months)
South India	November – December
North Eastern States	December – January
Central and East India	January – February
North and West India	February – March

Experimental Data

The weather data used for the study were Tmin and Tmax, relative humidity and wind speed for the period from November to March (flowering period) for last 50 years. The 50 years monthly average point weather data was collected from FULL IWMI, Sri Lanka for statistical analysis and FULL IPCC weather site (www.worldclim.org) in grid form for temperature (Tmax and Tmin). The Tmax collected from climate model (e.g. CCCMA), emission scenario (e.g. A2A), and IPCC (2007) [26] data and future climate scenario during 2020 were calibrated and statistically downscaled using the WorldClim data. The relative humidity and wind speed which were not available in future prediction models were considered as unchanged and used from IWMI, Srilanka. The collateral data for defining the threshold value of weather s were taken from our previous experiments and malformation occurrence areas from biennial reports of All India Co-ordinated Research Project (AICRP) on Tropical Fruits and published literature (Reddy, 2007; Reddy *et al*.2008) [40, 41] and from personal observations recorded from last 25 years. All the GIS works were carried out in ArcGIS (ESRI, USA) and SAS statistical package was used for the data analysis. The climate data of 1100 points were collected for all the four variables (Tmax, Tmin, relative humidity and wind speed) for whole India was developed using the Kriging techniques (Dille *et al*.2002) [12]. The grid size was defined at 1km^2. The wind speed and relative humidity were used for zonation. Maximum temperature was used for the year 2000, while maximum temperature predicted in climate scenario during the year 2020 was collected from projected future climate using climate model.

Zonation of mango malformation occurrence using threshold value

Zonation of possible mango malformation occurrence was developed using the threshold values of weather variables as defined in our earlier conducted experiment at Indian Agriculture Research Institute and available literature. The weather variables considered for zonation were temperature and relative humidity.

Logistic quadratic model

Logistic quadratic model (Anemiya 1981) [2] was used in the present study with the help of SAS software. The objective of the model was to find the influence of the independent on the binary dependent. The information on mango malformation occurrence was considered as either complete occurrence (or) non-occurrence and was used as the dependent s. The areas where malformation occurs were given a score of 1 and those areas, where malformation does not occur were given a score of 0. The independent s used in the model were Tmax, Tmin, relative humidity and wind speed. These were chosen based on the apriority knowledge and through detailed review on studies on mango malformation (Reddy, 2007; Reddy *et al*.2008; Chakrabarti, 2011) [40, 41, 11]. As these have an optimal point or range for occurrence of the disease the quadratic form of the model was considered most suitable. The present model consists of dichotomous dependent s (i.e., occurrence and non-occurrence) and eight explanatory s which were listed below. The quadratic form of logistic model was specified as forecasting mango malformation zonation and also predicting the future possible susceptible areas in year 2020.

$L = (P/1\text{-}P)$

$$Where\ L = \propto + \textstyle\sum_{i=1}^{8} \beta_i . X_i + U.$$

Where,

α = the constant of the equation

β = the coefficient of the predictor s

X_1 = reltive humidity (%)

X_2 = square of relative humidity

X_3 = temperature (Tmax)

X_4 = square of temperature (Tmax)

X_5 = temperature (Tmin)

X_6 = square of temperature (Tmin)

X_7 = wind speed
X_8 = square of wind speed and
U = random error

The logistic quadratic calculates the probability of success (p) over the probability of failure (q), the results of the analysis are in the form of an odds ratio (p/q).

The probability of occurrence of malformation was mapped in Arc-GIS software for 2000 and 2020 periods.

Results

The flowering period of mango in different zones of India were determined based on available literature and AICRP reports on mango and are given in Tables 1 and 2.

Threshold Approach

The comparison between the impacts of temperature on mango malformation occurrence is presented for the mango flowering period according to the classification given in Table 2. The results of favourable areas of mango malformation occurrence based upon relative humidity are presented for the mango flowering period as listed in the Table 1 for different zones of India. The results indicated that the regions found favourable for mango malformation are different with respect to the prevailing temperature and relative humidity. However, the real effect of occurrence will be only if both temperature and relative humidity reach optimum level. This was clearly indicated in forecasting of possible areas of mango malformation occurrence using temperature and relative humidity, which gave the output when both the threshold values are, fulfilled.

Logistic quadratic model approach

The probabilities of mango malformation occurrence in different states of India are predicted through logistic quadratic model for the years 2000 and 2020. Out of 1100 points, 300 points each for malformation occurrence and non-occurrence of malformation were considered for developing logistic quadratic model and rest points were used for validation. The model was fitted based on the available information on the malformation non-occurrence in states like Kerala, Tamil Nadu and Karnataka and malformation occurrence in states like Delhi and Uttar Pradesh. Using the estimated coefficients, the probability of malformation occurrence of unknown regions such as Punjab, Haryana, Chattgargh, Bihar, Maharastra Jammu and Orissa were predicted accurately. The results indicate that the southern and north eastern states were having very less or no chances of occurrence of mango malformation. In states like Bihar, West Bengal, Maharashtra and Madhya Pradesh, malformation was reported to occur in low to medium range, which indicates that these are the areas with likely probability of occurrence. The occurrence of mango malformation was observed in the medium to high range in states like Punjab and Gujarat. The states like Delhi, Uttar Pradesh and Haryana are the severely affected regions with high percent of malformation occurrence. This confirms that these states are having the highest probability of malformation occurrence. However, Gujarat which is predicted to possess a high probability of occurrence actually has a medium incidence of malformation.

The index s do not explain the variation in the model or the fit of the model is not good. In selected regions, the Chi square based test such as Wald has revealed that the s chosen for the study sufficiently explained the variation in the model (Table 3). The analysis of maximum likelihood estimates show whether the particular index has an influence over the dependent dummy s or not. The results of maximum likelihood estimates were significant for s such as relative humidity, maximum and minimum temperatures, but not significant for wind speed. When the quadratic linear model was fitted, quadratic term for relative humidity, Tmax and Tmin was found significant. However, the quadratic term for wind speed was not significant. The relative humidity, Tmin had positive coefficient and Tmax had negative coefficient (Table 4). The results confirm that most of the predicted probable areas of mango malformation were having the optimum favourable weather variables during the flowering period. Hence the chances of very high probability were in the states of Delhi, Uttar Pradesh and Haryana. The results confirm that the three s (Tmax, Tmin and relative humidity) are important for ascertaining the probability of occurrence of mango malformation. The odds ratio was calculated to facilitate interpretation of the coefficient of logistic model. The result of odds ratio is presented in Table 5. It showed that relative humidity and Tmin have more influence on the occurrence of mango malformation followed by Tmax. In our previous study, 25-28ºC and relative humidy >65% favoured growth of *F.mangiferae*. No macro and micro conidia of *F.mangiferea* developed at temperatures below 25ºC and above 28ºC (Nagaraja *et al.*2011) [34]. However, the interpretation is that, one unit increase in Tmin will increase the probability of mango malformation occurrence by 66 % and in similar way if there is a one unit increase in relative humidity there will be 62 % chances of increasing the probability of occurrence. An increase in Tmax by one unit, the chance of probability of occurrence of malformation will be reduced by 99%. Results of association of predicted probabilities and observed responses are presented in Table 6. Normally, the four measures vary from 0 to 1; with large values correspond to stronger association between the predicted and observed values. The Somers' D-gamma and c are found to be close to one. This indicates that the model is very fit and accurate. The prediction using logistic quadratic model and by using threshold value of temperature and relative humidity for the probable areas of occurrence of mango malformation were more or less similar. The results of estimated probability of mango malformation occurrence in different states using quadratic logistic model during 2000 and 2020 are presented in Table 7. In the year 2000, the states which had the probability of 40 and 47 per cent were Maharashtra and Madhya Pradesh respectively. The states like Jharkhand, Punjab, Gujarat, Chhattisgarh, Delhi, Uttar Pradesh and Haryana had highest probabilities of occurrence. The rest of the states had probability less than 40%. Whereas in the year 2020, the states with above 50 per cent are West Bengal, Bihar, Jharkhand, Gujarat, Uttar Pradesh, Madhya Pradesh, Chhattisgarh, Delhi and Haryana in increasing order of chances of probability for occurrence. The trend of probability areas of non-occurrence in the year 2000 and 2020 were observed to remain the same and in case of Andhra Pradesh and also in other states where there is no possibility of having the mango malformation. However, the north eastern states like Tripura, Arunachal Pradesh, Nagaland and Mizoram an increase in probability of occurrence in 2020 was observed when compared with the year 2000. While in case of Orissa and Maharashtra, there is a likely decrease in probability of occurrence. All other states were observed to have an increase in probability of occurrence of malformation. The above results indicate that the southern states either have very less or are free from mango malformation malady. These results confirm the ground truth on mango malformation occurrence in these states. The states like Bihar, West Bengal, Maharashtra and Madhya Pradesh are also reported to have low to medium range occurrence, which indicates that these are the areas having likely probability of occurrence. Similarly, the incidence of mango malformation is reported to occur in the medium to high range in states like Punjab and Gujarat. The states like Delhi, Uttar Pradesh and Haryana are severely affected states with high per cent of malformation occurrence. This confirms that the above states possess the highest probability of occurrence. However, the Gujarat state which is having high probability of occurrence is reported to have medium incidence of malformation. The above results confirm that most of the predicted probable areas of mango malformation were having the optimum weather variabless favourable for disease development during the flowering period. Hence, the chances of very high probability were in the states of Delhi, Uttar Pradesh and Haryana. The predicted possibility of mango malformation occurrence was more or less equal to the method mapped using the threshold value conducted in laboratory. In the current study, logistic quadratic equation was developed and fitted into weather surfaces for the s like Tmax and Tmin, relative humidity and wind speed for the year 2000 and 2020. Mango malformation occurrence areas were predicted in spatial scale and are depicted in Figure (1). The probability value less than 0.4 was considered as non-favourable areas, 0.4-0.7 was grouped in the range of low to medium and above 0.7-1.0 was considered as high zones of mango malformation. The comparison of favourable areas of mango malformation occurrence between the year 2000 and 2020 are presented based upon Logit value. The results are presented for the mango flowering period according to the Table 2. The results show that during month of November none of the states in either year have the probability of occurrence of malformation. In the rest of India flowering period of mango does not coincide with this month even though they are indicated to have high probability of occurrence. However, the results for December month showed an increase in the probabilities of occurrence compared to November month in case of Andhra Pradesh and small pockets in Karnataka, Tamil Nadu and Kerala while north eastern states showed complete freedom from malformation during this period.In the remaining part of India the flowering period of mango does not coincide with this month even though they show chances of higher probability of occurrence of malformation. The results for January month depict negligible risks for the North eastern states, while states like Chhattisgarh, part of Madhya Pradesh, Jharkhand and west Bengal showed chances of medium to high probability of occurrence of malformation. While the results for the February month showed possible chance of mango malformation occurrence in few pockets in Uttarakhand, northern Rajasthan, north eastern part of Madhya Pradesh, southern part of Chhattisgarh, western Gujarat, few pockets of north eastern parts of west Bengal, Himachal Pradesh, Jammu and Kashmir and southern part of Punjab and Bihar, three states *viz.*, Uttar Pradesh, Delhi and Haryana were predicted to have high probability of malformation occurrence. The results for March month show that few pockets in Gujarat, North Western Uttar Pradesh, and Rajasthan, Jammu and Kashmir, Himachal Pradesh, part of Haryana and whole state of Punjab are predicted to have mango malformation occurrence. The rest of India like north eastern regions showed probability for mango malformation occurrence but flowering period in these areas does not coincide with March period.

Table 2: States grouped on the basis of the flowering month

Month of flowering in mango	States
November	Andhra Pradesh, Tamil Nadu, Kerala and Karnataka
December	Andhra Pradesh, Tamil Nadu, Kerala, Karnataka and North Eastern States
January	North Eastern States, Chhattisgarh, Goa, Madhya Pradesh, Maharashtra, Orissa and West Bengal
February	Chhattisgarh, Goa, Madhya Pradesh, Maharashtra, Orissa, West Bengal, Bihar, Jharkhand, Chandigarh, Uttar Pradesh, Delhi, Gujarat, Haryana, Himachal Pradesh, Jammu and Kashmir, Punjab, Uttarakhand and Rajasthan
March	Bihar, Jharkhand, Chandigarh, Delhi, Uttar Pradesh, Gujarat, Haryana, Himachal Pradesh, Jammu and Kashmir, Punjab, Uttarakhand and Rajasthan

Table 3: Testing Global Null Hypothesis: BETA=0

Test	Chi-square	Df	Pr > Chi-sq
Likelihood ratio	358.0884	8	<.0001
Score	145.8840	8	<.0001
Wald	61.2086	8	<.0001

Table 4: Analysis of Maximum likelihood estimates

Parameter	df	Estimate	Standard error	Wald Chi-square	Pr > Chi-sq
Intercept	1	-103.7	22.2327	21.7687	<.0001
RH1	1	4.1395	0.8065	26.3415	<.0001
RH1SQ	1	-0.0340	0.00702	23.4220	<.0001
TMX1	1	-4.7838	0.7887	36.7899	<.0001
TMX1SQ	1	0.1189	0.0195	37.3286	<.0001
TMN1	1	4.1921	0.7284	33.1242	<.0001
TMN1SQ	1	-0.2392	0.0371	41.6245	<.0001
WS1	1	8.0757	11.4562	0.4969	0.4809
WS1SQ	1	-1.7079	4.0152	0.1809	0.6706

Table 5: Odds ratio estimates

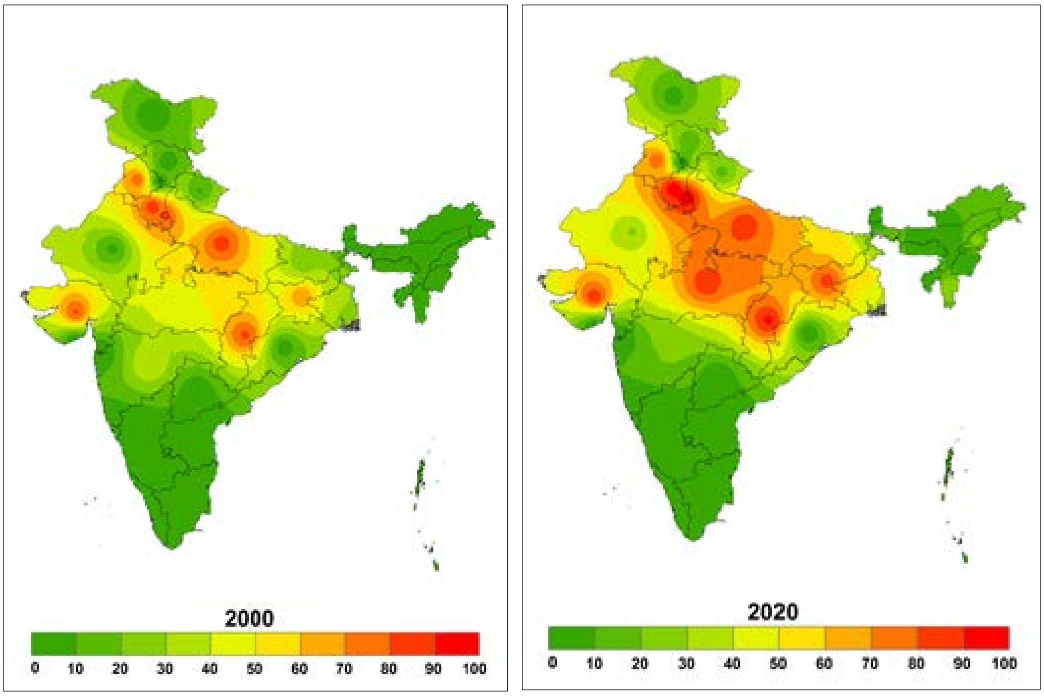
Effect	Point estimate	95%Wald Confidence limits	
RH1	62.770	12.919	304.984
RH1SQ	0.967	0.953	0.980
TMX1	0.008	0.002	0.039
TMXISQ	1.126	1.084	1.170
TMN1	66.164	15.871	275.818
TMN1SQ	0.787	0.732	0.847
WS1	>999.999	<0.001	>999.999
WS1SQ	0.181	<0.001	474.190

Table 6: Association of predicted probabilities and observed responses

Statistical indicator	Value
Percent concordant	95.0
Percent discordant	0.5
Percent tied	4.5
Pairs	40107
Somers'D	0.945
Gamma	0.990
Tau-a	0.253
C	0.972

Table 7: Estimated probability of occurrence of mango malformation in India

Sl. No.	State	Malformation occurrence (%)	
		2000	2020
1	Tamil Nadu	00	00
2	Kerala	00	00
3	Karnataka	00	00
4	Assam	00	00
5	Manipur	00	00
6	Meghalaya	00	00
7	Sikkim	00	00
8	Goa	00	00
9	Himachal Pradesh	01	12
10	Jammu and Kashmir	01	06
11	Tripura	01	05
12	Nagaland	01	22
13	Andhra Pradesh	03	03
14	Mizoram	05	27
15	Arunachal Pradesh	05	12
16	Orissa	05	03
17	Rajasthan	08	29
18	Uttarakhand	09	17
19	Bihar	25	60
20	West Bengal	32	52
21	Maharashtra	40	21
22	Madhya Pradesh	47	86
23	Jharkhand	69	84
24	Punjab	77	78
25	Gujarat	81	86
26	Chhattisgarh	82	92
27	Delhi	83	99
28	Uttar Pradesh	84	86
29	Haryana	88	99



🟩 Not susceptible 🟨 Less susceptible 🟥 Highly susceptible

Fig 1: Predicted probability of mango malformation occurrence for the year 2000 and 2020 using logistic approach (Color gradient from green to red represent regions showing very low to very high incidence of malformation disease

Discussion

The establishment and severity of disease depends on many interacting factors, including: seasonal or annual weather, microclimatic factors, age and vigour of mango trees, pathogen inoculums potential, mango tree density, and tree stand history, past management practices, localized populations of mango resistant or susceptible varieties and pathogens, occurrence of pathogen vectors, biological control agents, and several other factors. Based on defined weather conditions, threshold of weather surface was generated and mapping of possible mango malformation occurrence areas for different months was prepared. The most important weather variables are maximum temperature (23 to 28ºC) and relative humidity (55 to 65 %) for spread and growth of *Fusarium mangiferae* (determined through a separate laboratory experiment). Based on this range, malformation forecasting was done. Similar weather-based infection risk models were developed earlier (Mina and Sinha 2008, Beresford *et al*.2011, Mboup *et al*.2012) [33, 5, 31]. Since mango is a perennial tree crop, and when once planted will remain at same place for several years, predictions of potential distribution of pathogen *Fusarium mangiferae* under current and changing climate will provide valuable insights about where mango malformation disease might occur. It is important to note, however, that the co-occurrence of suitable climate space for the pathogens and mango crop, their host does not necessarily result in disease. The distribution of mango malformation in India observed over the past several years suggests a relationship between disease severity and local climate. Temperature apparently appears to play a key role in disease development (Ploetz *et al*.2002, Atinsky *et al*.2009) [39, 3]. What is widely accepted regarding epidemiology of the pathogen *Fusarium mangiferae* is that prior bud colonization is a prerequisite for infection (Youssef *et al*.2006, Zafar *et al*.2006, Teixeira *et al*.2012) [47, 48, 44]. One pre-condition for mango malformation occurrence is the favourable weather conditions for the growth of *Fusarium mangiferae* that range from 23-28ºC temperature and relative humidity of 55-65 % during mango flowering period. Identifying flowering period of different zones of India is must for finding out possible occurrence of mango malformation. Interpolation by Kriging was a geostatistical method based on statistical models that predict spatial autocorrelation of sampled data points (Dille *et al*.2002) [12]. The weather data of India collected over 1100 points were hence interpolated using the Kriging methods to generate climate surface of mango growing regions.

In the current study, the forecast of mango malformation was done by two approaches that is (i) threshold method and (ii) logistic quadratic approach. In the thresholding approach, weather variables favourable for growth of *Fusarium mangiferae*, the major causal factors for mango malformation occurrence were defined on the basis of current condition and accordingly forecasting was done using the predicted climate surface. In case of logistic quadratic approach, some of the observed points having mango malformation were considered and weather variables for corresponding observed points were used to define the probability of occurrence of malformation based on the current scenario. Both the logistic quadratic model and mapping with threshold value for mango malformation were found suitable for zonation of mango malformation occurrence spatially and logistic quadratic model predicted the probability of occurrence of mango malformation accurately as evident from partial ground truth data. The logistic quadratic model was found best suited for predicting and mapping the probability using the logistic equation which was useful in proving the spatial information on the possible occurrence of mango malformation in different regions of India in different flowering months. The study also attempted to forecast the potential regions of mango malformation occurrence in India in future climate conditions (2020) using the predicted temperature (CCCMA) model due to climate change scenario using weather surface available in grid form with threshold value for mango malformation from laboratory study. A comparison of the possible areas of occurrence of mango malformation according to the threshold value and zonation using logistic equation showed a reduction in the areas of mango malformation occurrence in southern states and a decrease in the area of Uttar Pradesh towards eastern regions and in Bihar states, and an increase in area of occurrence could be predicted in Punjab, Jammu and Kashmir, Himachal Pradesh and Uttarakand. The study also concluded that the chances of malformation occurrence are highly influenced by the weather s *viz*. relative humidity, Tmax and Tmin and the biology of mango flowering period which must coincide with the favourable weather attributes. The areas which are showing conducive factors for temperature and relative humidity and their combinations other than their flowering period in other zones are not likely to happen, since floral mango malformation occurrence is based on the conditions that should be favourable during the flowering period. Thus, from our results it is clear that the regions of western and north India during the month of February-March have optimal level of (Tmax and Tmin and relative humidity) all three favourable variables and the incidence was found to be severe in northern India as compared to southern India. The regions of central India Maharashtra were observed to show the occurrence of malformation which confirms the results in literature. Madhya Pradesh and Chhattisgarh have more favourable areas for malformation; however, the mango growing areas in these states are base minimum. The above results confirms with the finding of non-spatial data (Marasas *et al*.2006) [30] that reported the correlation between weather s and disease intensity and showed that an increase in relative humidity increased the disease intensity. These results are incongruent with non-spatial data reported by several other workers (Aguilera *et al*. 2003, Wingfield *et al*.2010) [1, 46]. During the flowering stage higher temperatures with higher amount of rainfall and lower RH favours the disease development. These conditions might favour high moisture formation on panicle surfaces. Similar models using the effect of environmental conditions on disease development were developed earlier in other crops (Broome *et al*.1995, Usha *et al*.1997, Siebold and von Tiedemann 2012, González-Domínguez *et al*. 2015) [7, 45, 42, 20]. In future (2020) due to increasing global temperatures, the area which is going to be directly affected by the disease is likely to decrease. However new areas suitable for mango cultivation and mango malformation occurrence can crop up. Our studies revealed that as the maximum temperature increases, the occurrence of mango malformation decreases and that maximum temperature has a negative influence on the occurrence of malformation. The above results are in agreement with the findings of Noriega–Cantu *et al*.(1999) [36] who reported that mango malformation prone areas at flowering stage had temperatures below 29 ºC while malformation free areas had temperatures greater than 29 ºC. The spatial prediction was at par with the finding of Reddy (2007) [40] for Uttar Pradesh in India. Similar spatial distribution maps associated to climate change effects in Brazil were developed for coffee leaf miner (*Leucoptera coffeella*) by Hamada and his co-workers (1999). The climate change risk analysis for the Black sigatoka of banana (caused by *Mycosphaerella fijiensis*) was studied by Ghini *et al*. (2008) [19], elaborating disease distribution maps assembled from scenarios and General Circulation Models (GCM) data provided by the Intergovernmental Panel on Climate Change (2007). The maps revealed that there will be a reduction in the favourable area for the disease in Brazil. In Scotland, models predict in the mid-term a lower impact of oilseed rape diseases such as *Leptosphaeria maculans* and *Pyrenopeziza brassicae* (Fitt *et al*.2011) [15]. In Northern Germany, however, oil seed rape pathogens such as *Alternaria brassicae*, *Sclerotinia sclerotiorum*, and *Verticillium longisporum* are predicted to be favoured by average warmer temperatures (Siebold and Tiedemann 2012) [42].The approach we used for simulating future climatic conditions for 2020 by modifying current weather datasets had the advantage of providing variability in future weather to enable statistical comparison of mango malformation disease risk between current and future climates to provide immediate help to mango growers. However, it is likely weather variability will increase in the future with global warming and shift mango growing regions to new areas. Our results emphasise the importance of including long term impact assessments of climate change on mango malformation disease intensity and its effect on mango crop productivity in different areas of the world.

Author Contributions

Conceived and designed the experiments: UK, NKS, SRN, and BS; performed the experiments: NKS, NA, UK; Analysed the data: NKS, NA, SRN; Wrote the paper: KU, BS.

Acknowledgement

The financial assistance provided by Director, ICAR-IARI, New Delhi, India for conducting the studies is gratefully acknowledged.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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