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Original article

Production suitability of date palm under changing climate in a semi-arid region predicted by CLIMEX model

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ABSTRACT

Objectives: Date palm (*Phoenix dactylifera* L.), a member of the Arecaceae family is grown on large areas in the world with varying climatic and soil conditions. However, date palm productivity is severely being affected by ongoing climate changes. Identifying suitable production areas for date palm under changing climatic conditions could help to sustain its production. The objective of the current study was to predict the range expansion/contraction in the production areas of date palm in a semi-arid region.
Methods: CLIMEX model was used to estimate the expected expansion/contraction in the potential distribution areas of date palm under current and future climatic conditions. Two climate change scenarios [(CCSs) i.e., A1B and A2] were used and production suitability was predicted for three timespans [i.e., 2030 (early-century), 2050 (mid-century) and 2100 (late century)].
Results: The model estimated significant suitable area (71.21%) for date palm cultivation under current climatic conditions. Climate change seemed to have no impact on production areas until early-century. However, range contraction (8 and 10% decline under A1B and A2 scenarios, respectively) in the suitable areas was predicted for mid-century. Nonetheless, severe range contraction (27.98 and 33% decline under A1B and A2 scenarios, respectively) was predicted in the production areas for late-century. Most of the climatically suitable areas during early-century became unsuitable during late-century. Moreover, the model predicted northward shift in the production areas for date palm. The range contraction was higher under A2 climate change scenario due to higher warming trend compared to A1B scenario.
Conclusion: The results of the current study indicate that plenty of areas are suitable for date palm cultivation. Thus, date palm cultivation could be increased in these areas for augmenting the production. Climate warming will result in the range shifts; thus, cultivation of future orchards should be planned in the most suitable areas in order to avoid the negative consequences of climate change on date palm production in the country.

1. Introduction

Global climate changes are affecting species' distribution at a massive pace, resulting in complex ecosystems and disturbance of the existing ones. Nonetheless, ongoing climate changes are affecting the distribution of plant species at different spatial scales (Ji et al., 2020; Kaky et al., 2020). Climate change is causing large-scale changes in the distribution of different plants species (Gebrewahid et al., 2020). Some recent studies have predicted that

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yield (Cammarano et al., 2019a; Schierhorn et al., 2020) and suitable production areas of different field crops (Chemura et al., 2020), fruit crops (Shabani et al., 2017) and other crops will be changed under changing climatic conditions (Chemura et al., 2020; Kogo et al., 2019).

Date palm (*Phoenix dactylifera* L.) is grown in warmer areas as it requires high temperature for its flowering and fruit development (Allbed et al., 2017). It is mostly grown in Middle East countries (Shabani et al., 2015). It is valuable source of food in the countries facing micronutrient deficiencies (Shabani et al., 2016b). Date palm is ideally cultivated in hot and dry regions (Allbed et al., 2017). Pakistan is an arid to semi-arid country with significant spatiotemporal climatic variations (Farooqi et al., 2005). The monsoon rains are important hydro-meteorological resource for the country, contributing 59% towards annual rainfall (Farooqi et al., 2005). Thus, climatic conditions of the country are ideal for date palm cultivation; however, it is grown on limited scale in the country. Furthermore, the domestic needs are fulfilled by import from neighboring countries such as Iran.

Species distribution models (SDMs) are important tools used to predict potential changes in species' distribution (Journé et al., 2020). These models integrate climate, land use, topography and soil-related data and correlate it with the current distribution of target species for estimating their future range expansion, contraction or niche shifts (Mateo et al., 2017; Sillero et al., 2021). Different correlative and mechanistic models are used to estimate climate and land use changes and their impact on species' distribution (Meineri et al., 2015; Shabani et al., 2017, 2016a). Numerous modelling exercise tended to choose the best model; however, combining the results of different models is concluded to be feasible to avoid over or underestimation in species' distribution (Fordham et al., 2018; Grimm et al., 2017). The CLIMEX model is considered as high performing mechanistic model for estimating species' distribution.

The CLIMEX is frequently used to estimate the impact of climate change on different species (Macfadyen and Kriticos, 2012). The CLIMEX model can estimate changes in the climatic suitability of species and animals under different climatic conditions at regional and global scales. It is a user friendly model frequently used to model range shifts of invasive plant species (Ramirez-Cabral et al., 2017; Shabani et al., 2016a). Although, climate is thought to be the sole driver of plant invasion, several other biotic and edaphic factors also limit the distribution of invasive plant species (Bullock et al., 2000). Numerous studies inferred the potential distribution of date palm at regional (Allbed et al., 2017; Shabani et al., 2014a) and global scales (Shabani et al., 2016a).

Future climate projections show that countries like Pakistan will get drier and hotter (Farooqi et al., 2005). The expected climate changes would exert rapid shifts in climatically suitable production areas of different crops (Chemura et al., 2020). Predicting these changes timely would help scientists, policy makers, government institutes and stakeholders to devise suitable management strategies. Ecological niche modeling or so-called species distribution modeling approach is a viable tool for assessing the range shifts of plant species under current and future climatic conditions (Journé et al., 2020). These models provide novel insights for future; thus, can be used for the quantification of climate change impacts on different species, including plants and field crops (Journé et al., 2020). Several global studies have predicted rapid changes in climatically suitable production areas of different crops; however, no study has been conducted in Pakistan in this regard. Global studies have indicated that Pakistan has a suitable climate for the date palm cultivation; however, no regional study has been conducted yet to infer the potential distribution of date palm in the country. Thus, current study inferred the potential distribution of date palm in Pakistan under current and future climatic conditions of the country. The result of the study will help to identify the potential suitable areas for date palm cultivation in the country, which could help to increase the date palm production of the country.

2. Materials and methods

2.1. Study species

Date palm (*Phoenix dactylifera* L.) is grown in warmer areas as it requires high temperature for its flowering and fruit development (Allbed et al., 2017). It is ideally cultivated in hot and dry regions having a prolonged hot weather, dry summer and humid weather during fruit ripening stage (Allbed et al., 2017). It contains at least six vitamins; thus, offer a valuable source of food in the countries facing micronutrient deficiencies (Shabani et al., 2016b). However, climate change is expected to decrease its suitable production areas at regional and landscape scales. Several regional (Allbed et al., 2017; Shabani et al., 2014a) and global studies (Shabani et al., 2016a) have concluded that production areas will suffer a contraction. However, the fate of production areas in semi-arid country like Pakistan have never been estimated by ecological niche models. Therefore, the species was selected for the current modeling study.

2.2. CLIMEX software

The CLIMEX model integrates generalized eco-physiological parameters and weekly responses of the species to climate, and generates series of annual indices. CLIMEX model assumes that distribution of species is increased and decreased under favorable and unfavorable climatic conditions, respectively. The weekly growth of the species is calculated on the basis of temperature index (TI) and moisture index (MI) as annual growth rate (GA). The GA is influenced by four types of stresses including cold, dry, hot and wet, which cumulatively contribute towards stress indices (SI). Based on these indices CLIMEX calculates an Ecoclimatic Index (EI), ranging from 0 to 100. A value of 0 represents no possible growth, while 100 represents optimum growth. Thus, CLIMEX uses all these indices and calculates EI for a specific geographic location whose data is available in the meteorological database of the model. The species' occurrence is only possible when EI > 0 (Park et al., 2014; Sutherst et al., 2007).

The EI describes the habitat suitability of the species (Sutherst et al., 2007; Taylor and Kumar, 2013). Based on EI, distribution maps are created under current and future climate scenarios and for different time periods.

The CLIMEX requires a series of parameters to calculate the EI for a particular species (Shabani et al., 2017). These parameters are based on temperature and moisture requirements, and sensitivity of the species to different types of stresses described above. The values of these parameters could be experimentally determined or estimated form the current distribution range. Thus, parameter fitting exercise requires sound knowledge of species biology and current distribution range. The parameters are needed to change until a good-fit is obtained. Afterwards a baseline model (good-fitted model according to the current distribution of species) is fitted and prediction can be made for the future climatic conditions under different climate change scenarios (Kriticos et al., 2011; Ramirez-Cabral et al., 2017; Shabani et al., 2016a, 2012). The values of these parameters in the current study were derived from the published studies on date palm at regional and global scales (Allbed et al., 2017; Shabani et al., 2015; 2014b; 2012).

2.3. Historical and future climate data

The CLIMEX requires current and future climatic data in met-manager application. CliMond (https://www.climond.org/ Kriticos et al., 2012) provides the required data at two different spatial scales [10′ (18.55 km) and 30′ (55 km)].

The climatology of 10′ gridded spatial resolution was used in the current. The 10′ gridded data had 565,801 location for the whole world and monthly averaged data on maximum and minimum temperature, rainfall and relative humidity and 9:00 and 15:00 h for each of these locations is available. Historical climatology is averaged from 1961 to 1990 and finally averaged on 1975 (Kriticos et al., 2012).

The future climatic data for all of the locations is available based on two different global circulation models (GCMs) and two different climate change scenarios. These two GCMs had been selected for data generation due to their superior performance than rest of the available GCMs (Kriticos et al., 2012). The data is available for different decades. Thus, data [for current, 2030 (early-century), 2050 (mid-century) and 2100 (late-century)] were downloaded from CliMond website and used. We only used MIROC-H data of A1B and A2 SRES scenarios (IPCC, 2007). Therefore, we used A1B and A2 SRES scenarios as data for RCPs is not available for CLIMEX. We assumed A1B equivalent to RCP2.6 and A2 to RCP8.5. Firstly, a baseline model was fitted to infer the potential distribution of date palm globally, and then potential distribution of date palm was estimated for Pakistan. However, use of A1B and A2 climate change scenarios must be taken as a limitation of the current study. Future studies must be conducted with RCP scenarios once the climate data for these scenarios is available.

3. Results

The baseline model indicated that global and regional areas reported to be suitable were estimated as suitable in the current study (Fig. 1). Thus, the results present the model as good-fitted. The date palm occurrences available from Global Biodiversity Information Facility (GBIF) were included in the baseline model and visually inspected. The optimum predicted area in the baseline model hosted >95% occurrence records of date palm at global level. Nonetheless, output of baseline model was compared with the published studies at regional scales, which were in agreement with the results of baseline model. Thus, multi method testing revealed that the fitted parameters resulted in a good-fitted model (Fig. 1).

The model predicted 71.21, 3.42 and 25.37% of the total surface area of Pakistan as optimum, suitable and unsuitable for date palm under current climatic conditions (Table 1, Fig. 2). The areas in the extreme north, having high altitude and low temperature were predicted as unsuitable under current climatic conditions of the country.

The model predicted a slight increase in the suitable production areas for early-century (Table 1). Similarly, the percentage of unsuitable areas was also decreased compared to current climatic conditions. The optimum and suitable areas for date palm production increased to 74.56 and 4.21%, respectively, while the unsuitable area decreased to 21.23% for early-century under A1B CCS. Similarly, optimum and suitable areas increased to 73.45 and 4.78% respectively under A2 CCS, while unsuitable area declined to 21.28% compared to the areas predicted for current climatic conditions of the country (Table 1, Fig. 3).

The model predicted slight contraction in optimum date palm production areas for mid-century compared to current climatic conditions, whereas suitable and unsuitable areas increased compared to current climate under both CCSs. The higher contraction in the optimum production areas was noted under A2 climate change scenario compared to A1B. The optimum area contracted to 63.21 and 61.12% under A1B and A2 CCSs, respectively for mid-century (Table 1, Fig. 4). Similarly, suitable areas increased to 8.78 and 8.21% under A1B and A2 CCSs, respectively. Likewise, unsuitable areas were expanded to 28.01 and 30.67% under A1B and A2 CCSs, respectively (Table 1, Fig. 4).

The model predicted a severe contraction in optimum areas, where less than half of the country's area was predicted optimum, whereas >50% of country's area became unsuitable during late-century under both CCSs (Table 1, Fig. 5). Higher range contraction was predicted under A2 CCS than A1B. The optimum area for date palm production contracted to 43.23 and 38.21% under A1B and A2

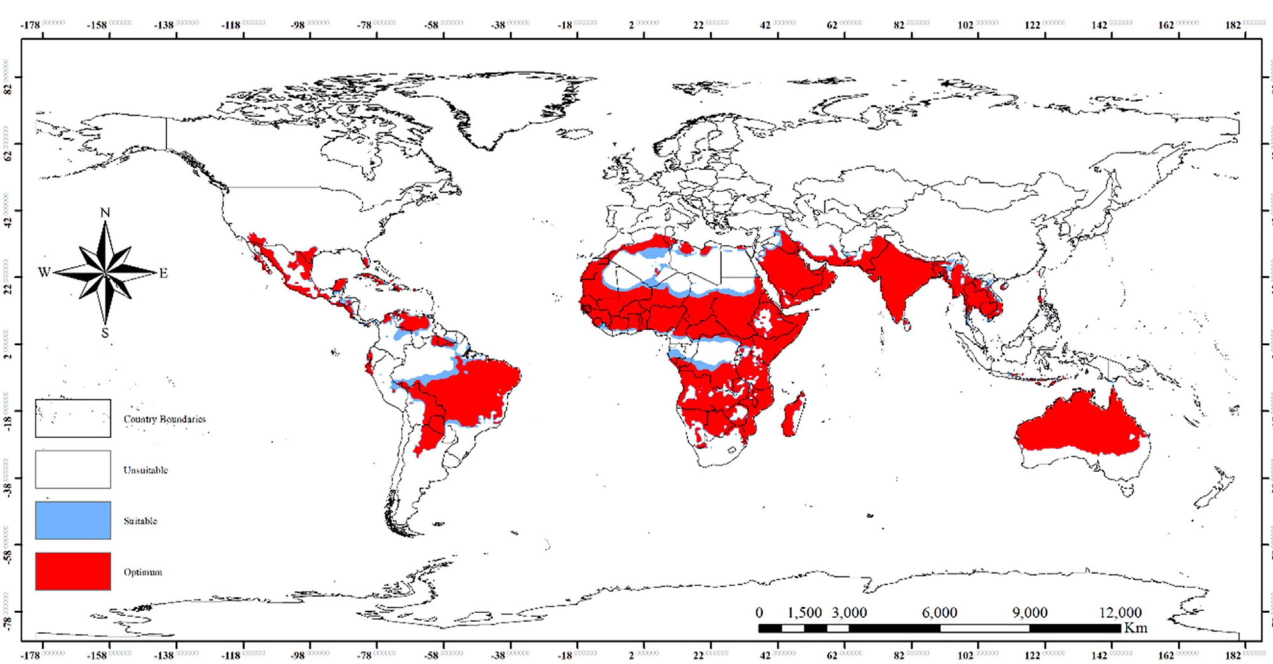

Fig. 1. Baseline model for habitat suitability of date palm in the world under current climatic conditions.

Table 1
The impact of different climate change scenarios on production area suitability of date palm for different time periods modeled by CLIMEX model.

Year	Climate Change Scenario	Optimum area (% area of country)	Suitable area (% area of country)	Unsuitable area (% area of country)
Current		71.21	3.42	25.37
2030 (early-century)	A1B	74.56	4.21	21.23
	A2	73.45	4.78	21.77
2050 (mid-century)	A1B	63.21	8.78	28.01
	A2	61.12	8.21	30.67
2100 (endlate-century)	A1B	43.23	6.56	50.21
	A2	38.21	6.34	55.45

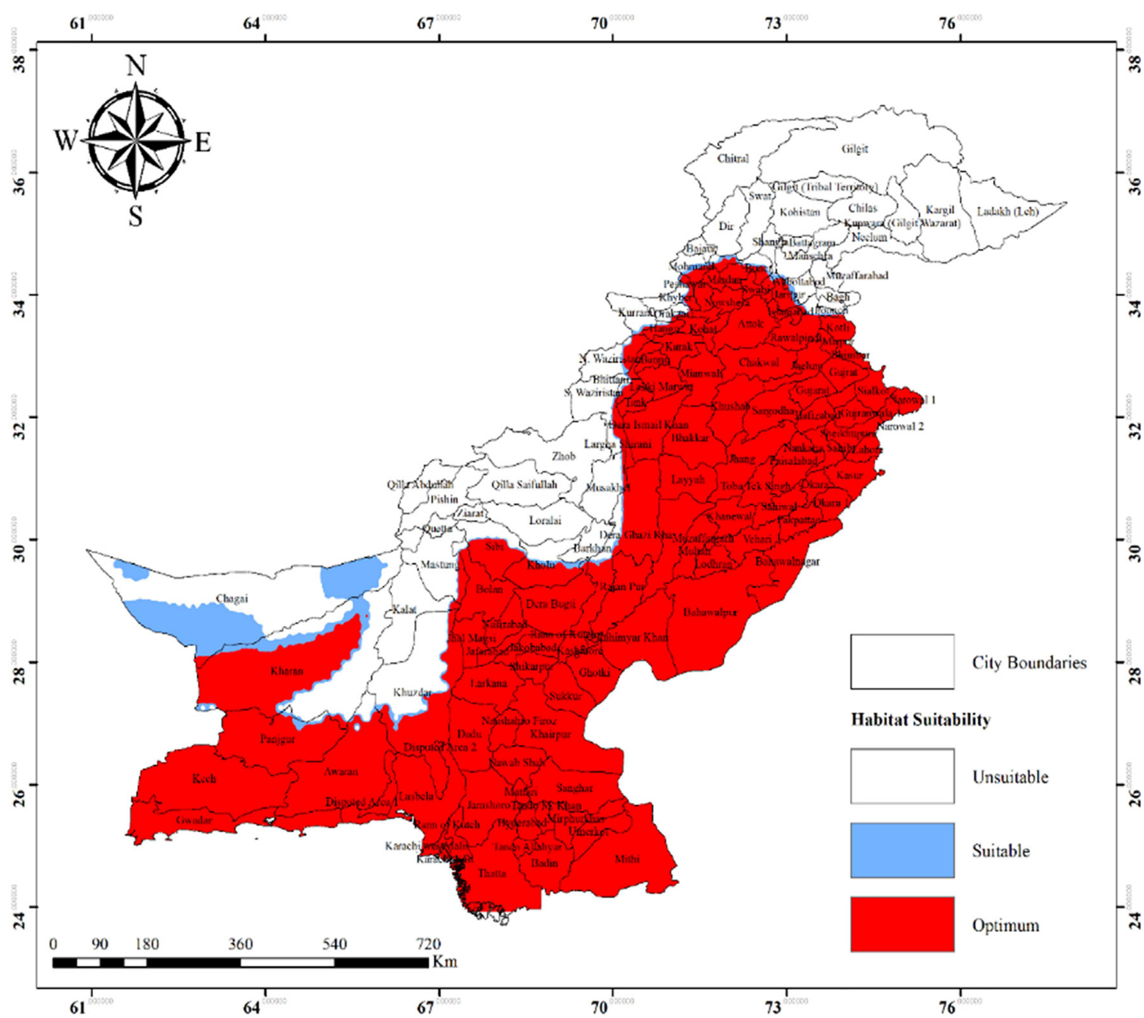

Fig. 2. Habitat suitability of date palm in Pakistan under current climate predicted with CLIMEX model.

CCSs, respectively during late-century. Likewise, unsuitable areas were expanded to 50.21 and 55.45% under A1B and A2 CCSs, respectively (Table 1, Fig. 5).

Regarding area changes under future climatic conditions, optimum area for date palm cultivation increased to 3.35 and 2.24% during early-century under A1B and A2 CCSs, respectively (Table 2). Similarly, area suitable for date palm cultivation increased to 0.79 and 1.36% under A1B and A2 CCSs, respectively. Nonetheless, unsuitable areas recorded a decline of 4.14 and 3.60% under A1B and A2 CCSs, respectively for near-century. Optimum area for date palm cultivation decreased by 8.00 and 10.9% during mid-century under A1B and A2 CCSs, respectively. In contrast optimum and unsuitable areas witness significant increase. The highest decline in the optimum production areas was noted during late century. The decline in optimum areas was 27.98 and 33%, respectively under A1B and A2 CCSs (Table 2).

4. Discussion

The predictions indicated that climate change will have no or little effect on the suitable areas for date palm cultivation in the country until mid-century. However, severe range contraction was predicted during late-century under both CCSs. Most of the areas predicted as suitable during early and mid-century became unsuitable during late-century. The higher range contraction was estimated under A2 CCS compared to A1B. A slight shift was also recorded in the potential distribution range, where some areas in

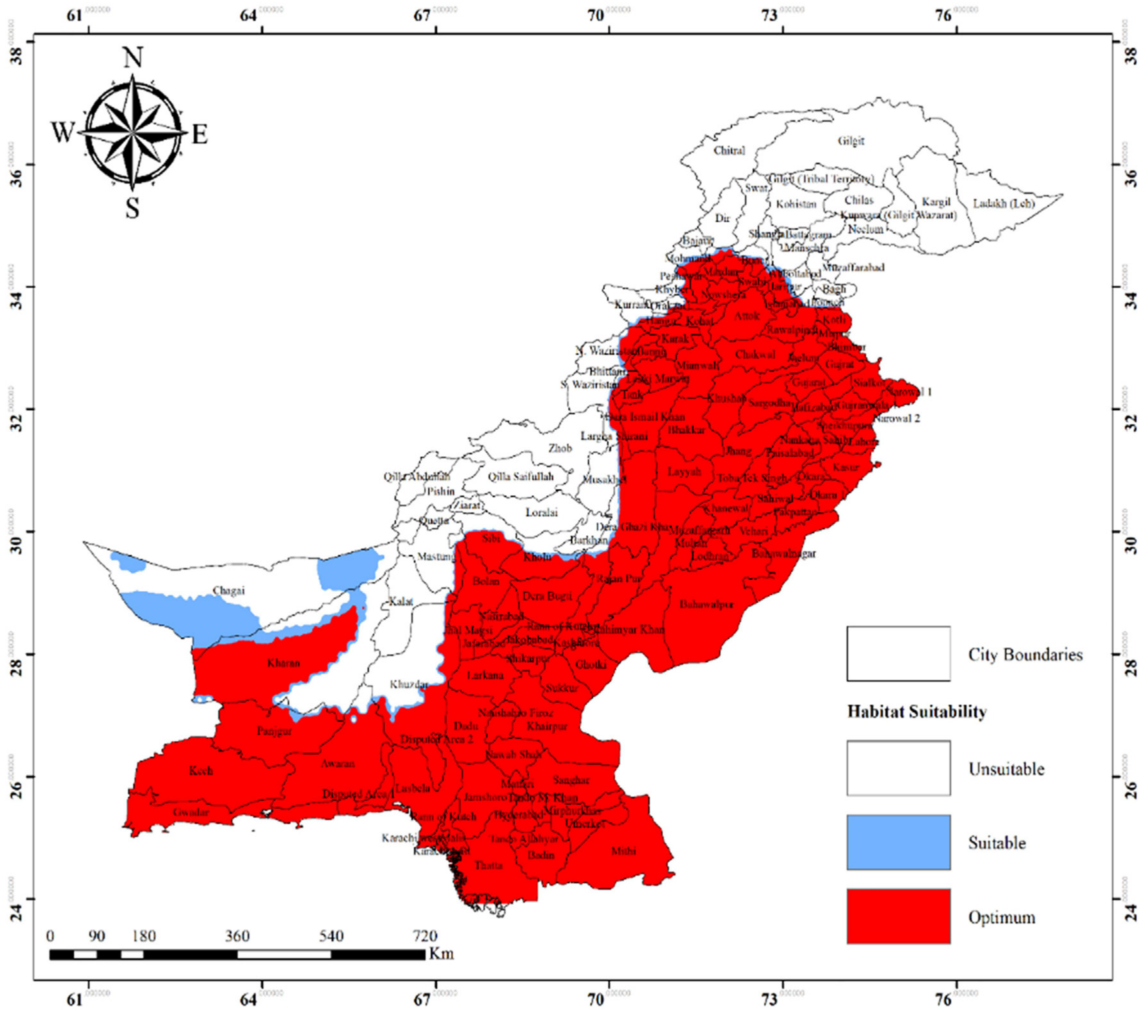

Fig. 3. Potential distribution of date palm in Pakistan for 2030 (early-century) predicted with CLIMEX model.

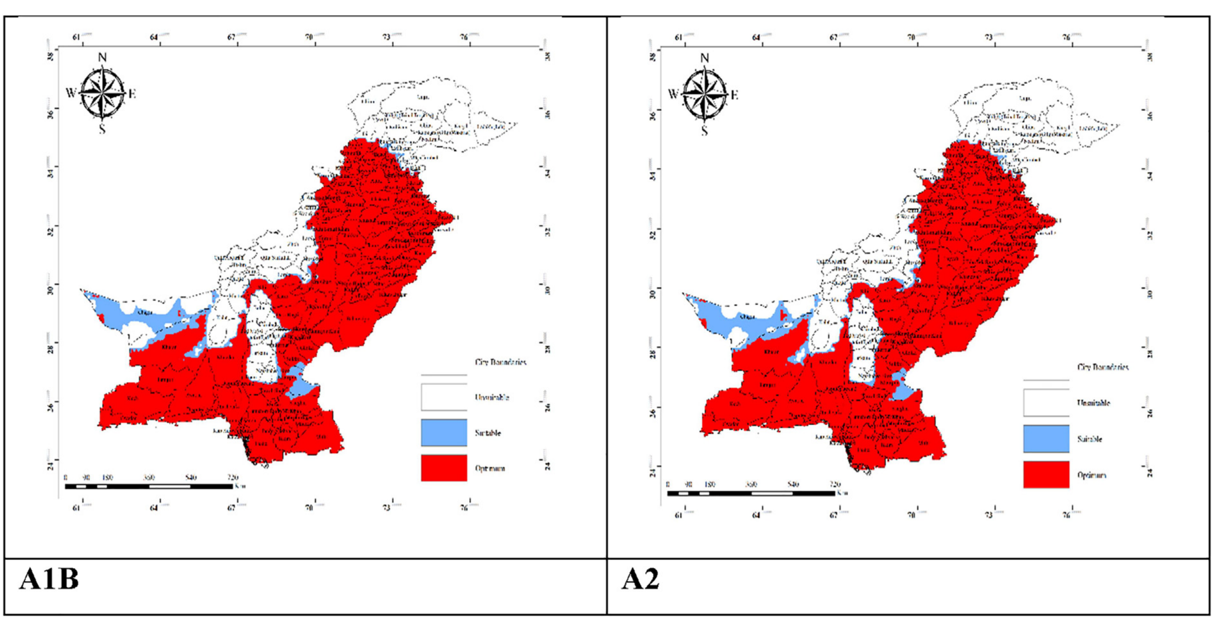

Fig. 4. Potential distribution of date palm in Pakistan for 2050 predicted with Climex model.

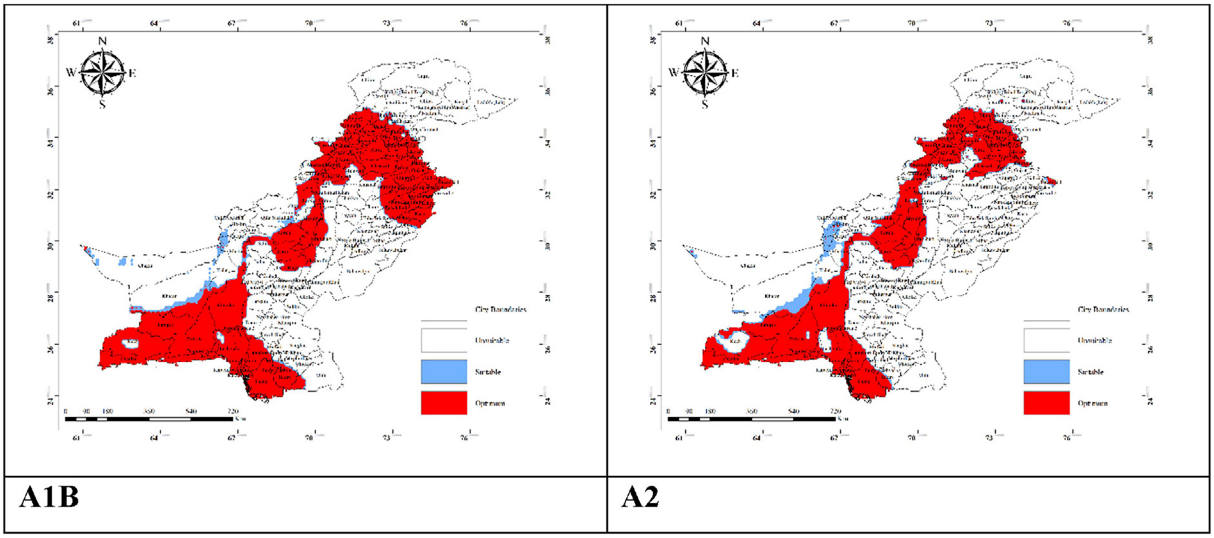

Fig. 5. Potential distribution of date palm in Pakistan for 2100 (late-century) predicted with CLIMEX model.

Table 2
Percentage change in production area suitability of date palm for different time periods modeled by CLIMEX model.

Year	Climate Change Scenario	Optimum area (% area of country)	Suitable area (% area of country)	Unsuitable area (% area of country)
2030 (early-century)	A1B	3.35	0.79	−4.14
	A2	2.24	1.36	−3.60
2050 (mid-century)	A1B	−8.00	5.36	2.64
	A2	−10.09	4.79	5.30
2100 (endlate-century)	A1B	−27.98	3.14	24.84
	A2	−33.00	2.92	30.08

the extreme north became suitable during late century. Thus, the results indicate that climate change will have no impact on the date palm distribution in Pakistan until mid-century; however, severe range contraction is expected during late century.

The results of the climate change modelling provide an indication of the changes in the potential distribution of date palm in Pakistan under current and future climatic conditions of the country. Some areas currently suitable for date palm cultivation may become climatically unsuitable in future, which indicate severe consequences of climate change. Although climate change will result in range contraction, date palm is not cultivated in the country in its climatically suitable range. Thus, the current study identified the climatically suitable areas, where date palm could be cultivated to augment the domestic production.

Predicting species' distribution under changing climate is a challenging task and requires critical thinking (Araujo and New, 2007; Morán-Ordóñez et al., 2017), quality data and choose careful model selection (Araújo and Guisan, 2006). Plant species did not cover the full spatial range having suitable climatic conditions; thus, are in non-equilibrium state. This non-equilibrium state of plant species create hurdles in successful predictions due to incomplete occurrence data (Mateo et al., 2017; Sutherst and Bourne, 2009). Nonetheless, using data of global occurrences of the species could improve the output of species distribution models (Broennimann and Guisan, 2008; Farooq and Onen, 2017). Furthermore, species settling under climatic conditions not present in native range due to phenotypic plasticity further makes modelling exercise a difficult task (Csergő et al., 2017). Population biology of the species is strongly affected by shifts in the ecological niches under changing climate (Atwater et al., 2018; Petitpierre et al., 2012). Although modelling species' distribution is a challenging task, it generates interesting data that can be utilized to manage the impacts of climate change on plant species (Gallien et al., 2012; Mateo et al., 2017; Sutherst and Bourne, 2009). Interestingly, recent study have reported that earlier climate models predicted climate change impacts very accurately, strengthening the belief of using these models to predict changes in species' distribution (Kay, 2020).

Climate alone was considered for estimating the potential distribution of the date palm in the country, which indicated that most of the suitable areas lie in southeastern side of the country, which are hot having dry summers. The date palm is currently being cultivated in a small portion of these areas, which need to be considered for increasing the cultivation and substantially, production of the date palm in the country. The suitable areas were predicted to become unsuitable in 2100 with some differences in climate change scenarios. The differences in the predicted areas by the differences in their GHG emission scenarios. A number of studies have indicated that climate warming will negatively impact the potential distribution of the date palm (Allbed et al., 2017; Shabani et al., 2014b, 2012).

Crop yields and production areas of different crop are expected to be altered by climate change at global scale (Chemura et al., 2020; Ray et al., 2019). The expected climate changes would make new areas suitable for cultivation of field crops (Shabani et al., 2017), whereas yield increases are expected in few locations with rising temperature (Cammarano et al., 2019b; Schierhorn et al., 2020). However, a certain increase in temperature will benefit the crops, whereas further increase would exert negative impacts on crop yields. The current study indicated that date palm would benefit from climate change till mid-century, whereas experience negative consequences during late century.

The integration of soil properties, disturbance and land use changes has recently been started (Seebens et al., 2017) in ecological niche models. In fact these data are not available on global scales, thus models calibrated on global scales are unable to integrate these sorts of data. However, some studies indicated that if regional soil data are available, these are useful for improving the predictions (Buri et al., 2017; Walker et al., 2017). Nonetheless, the correlative models are unable to integrate experimental data. Rapid development of ecological modelling has necessitated that integration of traits data through experimentation is necessary to have a clear picture of range expansion in different species (Grimm et al., 2017; Kattenborn et al., 2017). Although these data were not incorporated in the current study, still the study provides valuable insights on the climatically suitable areas of date palm in Pakistan.

5. Conclusion

The results of the current modelling exercise indicate that plenty of areas are climatically suitable for date palm cultivation in the country. The date palm cultivation could be increased in these areas for augmenting the domestic production. Climate warming will result in the range shift, thus cultivation should be planned accordingly to avoid the negative consequences of climate change in the country. The estimation of yield changes is needed for the country to strengthen these results. Climate warming will result in the range shifts; thus, cultivation of future orchards should be planned in the most suitable areas in order to avoid the negative consequences of climate change on date palm production in the country.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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