CHAPTER 1

GENERAL INTRODUCTION AND OBJECTIVES OF THIS THESIS

This introductory chapter provides a background to the major elements of the research, namely climate change, species distribution models (SDMs), date palms and the biology thereof, along with social, economic and ecological factors associated with the species. The chapter continues, outlining the general aims of our study and the modelling systems employed in our research.

1.1 CLIMATE CHANGE

Mankind's industrial development since the mid eighteenth century has led to a marked increase in global atmospheric concentrations of carbon dioxide, methane and nitrous oxide which now far exceed the values of the pre-industrial era, as determined from ice cores that span thousands of years (Meehl et al. 2007). The carbon dioxide concentration increases are predominantly due to the use of fossil fuels and changes in land-use, while agricultural development is the major factor in the case of methane and nitrous oxide. Thus, climate change is a reality (Adger et al. 2005) (Fig.1-1). The impact of climate change on our physical and ecological systems, as observed over the last century (McCarthy 2001; Parmesan & Yohe 2003) is a harbinger of more to come. Paralleling the changes in mean climatic conditions, our planet faces potentially irreversible catastrophic system feedbacks and associated consequences, an example being the melting of the Greenland ice sheet as a result of the collapse of thermohaline circulation (Alley et al. 2003; Gregory et al. 2004). However a large proportion of individuals in proactive organisations and representative nations have responded to past climatic changes by modifying lifestyles and behaviour, and many now contemplate further adaption to expected future climatic conditions. While this adaptation is primarily reactive, in that it is a response to past or current events, it is also anticipatory in terms of its predictive consideration of conditions of the future (Adger et al. 2005).

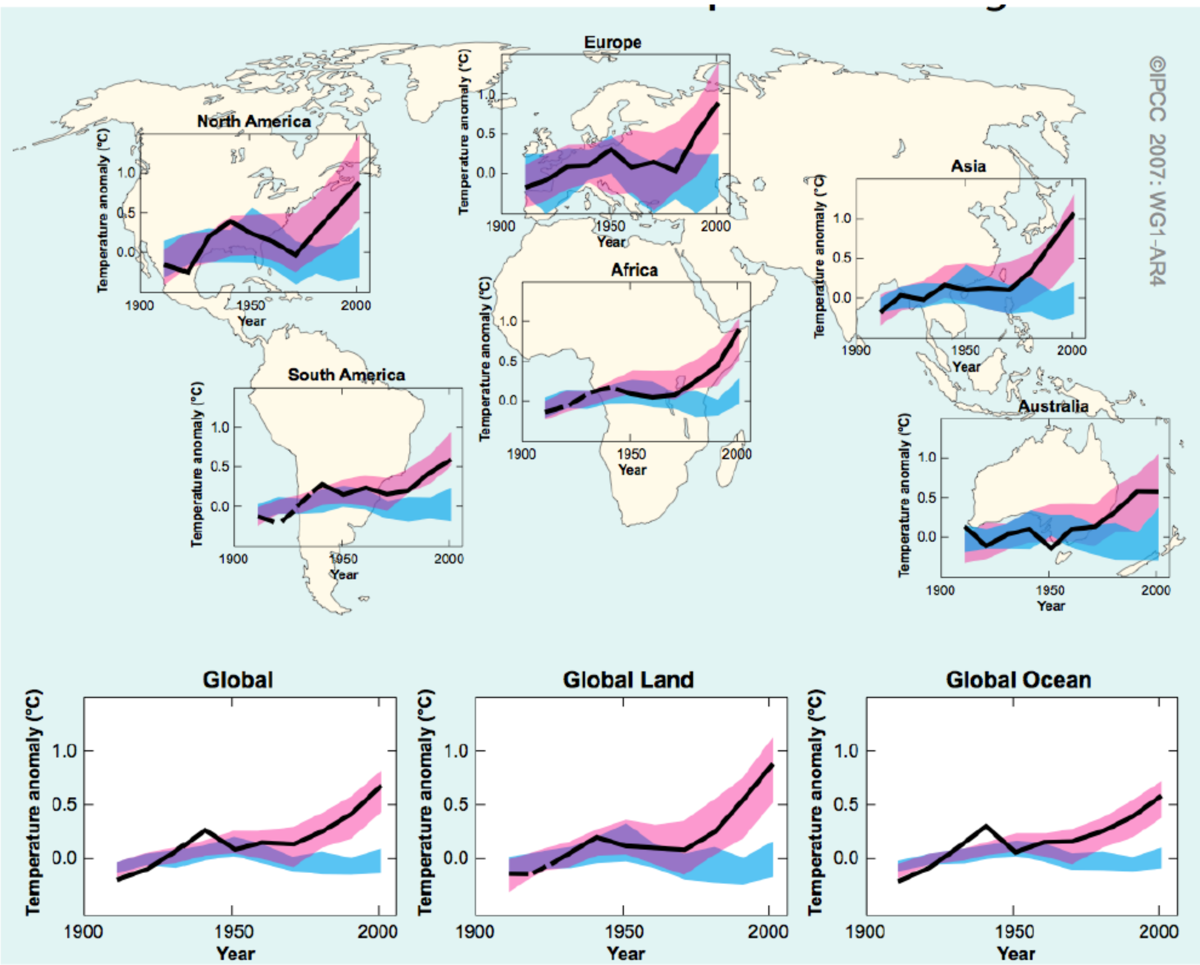

Figure 1-1 - Comparison of observed changes in continental and global-scale surface temperatures, with those simulated by models using natural and anthropogenic climatic change forcings (Meehl et al. 2007). The black line represents the decadal averages of observations for the period 1906–2005, plotted against the center of the decade and relative to the corresponding average for 1901–1950. Dashed lines depict spatial coverage lower than 50%. Blue bands represent the 5–95% range for 19 simulations from 5 climate models using only the natural solar activity and volcanic related forcings. Red bands show the 5–95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings.

The widespread impact of climate change on basic planetary existence is summarized in the following list: a) subsistence hunting cultures' difficulties in surviving; b) expansions in marine shipping; c) global food security declines; d) an increasing level of vector-borne diseases, asthma and other health concerns; e) changes in the migratory patterns of many species; f) increasing demands on offshore resources that includes both minerals and petroleum; g) declining ocean fish levels; h) declining levels of freshwater fish such as arctic char and salmon; i) lengthening of agricultural production periods; j) increased outbreaks of forest fires and insect infestations; k) disruptions in overland transportation from the thawing of permafrost and melting of ice roads; m) increased levels of coastal erosion and thawing permafrost causing damage to community infrastructures, as well as other serious impacts (Larsen et al. 2008).

With an increased level of scientific certainty that man-made climate change is a reality (Solomon et al. 2007) the identification and assessment of potential impacts and key vulnerabilities and the need for adaptation becomes more urgent (Parry 2007). Such assessment by necessity must take place within the context of sustainable development and must address both the appropriate climate and non-climate drivers. For example, over the last decade, considerable attention has been given to defining and quantifying what may be described 'dangerous' climate change, in terms of the overriding objective of the United Nations Framework Convention on Climate Change to prevent the occurrence of such dangers (Barnett & Adger 2003; Dessai et al. 2004; Barnett 2011). In this regard, climate change is also likely to create climate conditions more favourable to the expansion of invasive species into new ranges (Bradley et al. 2010). Climate change and invasive species are two of the main factors driving overall global change (Jeffrey & Harold 1999) and thus species distribution models (SDMs) may be a valuable tool for obtaining data on potential future distributions under the impact of potential climate alteration.

1.2 SPECIES DISTRIBUTION MODELS (SDMs)

SDMs allow the incorporation of climate change scenarios into modelling, thus providing information on potential future species distributions. Such analyses can highlight specific new areas that may in the future be at risk of invasion, as well as identifying the important regions of biodiversity that may be affected. Mapping potential future distributions can inform the strategic planning of biosecurity agencies, prioritising areas that should be targeted for eradication and determining those areas' containment tactics would be more cost-effective. Biosecurity agencies undertaking the management or control of biotic invasions require, at the earliest, a synoptic view of these invasions, in order to assess risk and form their long-term management strategies (Kriticos et al. 2003b). For this purpose, SDM tools provide many advantages. Such models are alternatively described as bioclimatic or ecological niche models (ENMs) (Fitzpatrick et al. 2007). Species distribution and environmental data are used to create a profile, which describes how already known distributions relate to environmental variables, in practice called the 'environmental envelope approach' (Barry & Elith 2006). The fundamental principle of this approach is that climate is the primary determinant of the ranges of plants and other poikilotherms. The environmental envelope of a particular species is defined in terms of its upper and lower tolerances and a modelling technique is used for the creation of a habitat map that describes the environmental suitability for each location of the particular species (Barry & Elith 2006). A range of computer-based systems, all founded on this approach, have been developed, designed for the modelling of current or future distributions of the species. Examples of the most common of these systems are CLIMEX, HABITAT, MAXENT, BRT, RF and BIOCLIM (Peterson 2003; Taylor 2011; Shabani et al. 2012; Shabani et al. 2015a; Shabani et al. 2015b). In modelling invasive species distributions, the environmental conditions of known native locations of the species' distribution are used to project other potential regions and identify areas of potential suitability which could be colonised by non-native populations (Peterson 2003). Thus such modelling provides a practical tool for the identification of areas where an invasive species could establish itself and persist, as well as in the assessment of magnitude of the posed threat (Taylor 2011).

The CLIMEX modelling tool enables the modelling of an organism's potential distribution, employing a variety of data types, including direct experimental observations of the growth response of a species to temperature and soil moisture, its phenology and global data regarding its current distribution (Sutherst & Maywald 1985). CLIMEX has been used extensively in research on the potential distributions of invasive species, under current climatic conditions (Vera et al. 2002; Dunlop et al. 2006; Sutherst & Bourne 2009; Taylor & Kumar 2012; Taylor et al. 2012a; Taylor et al. 2012b) as well as in the projection of a variety of climate change scenarios (Watt et al. 2009; Chejara et al. 2010).

The basis of CLIMEX software is an eco-physiological model which incorporates the assumption that a favourable season leads to positive population growth of the species, while an unfavourable season will cause a decline at any given location (Sutherst et al. 2007b). The parameters used in CLIMEX to describe the species' response to climate are based on geographical range data or phenological observations (Sutherst et al. 2007b; Taylor 2011). The software may also be used deductively in applying observed parameters of climate response to climatic datasets. Both of these approaches are used in practice in the choice of the modelling parameter values which are then applied to novel climates to project potential ranges in new localities or under alternative climate scenarios (Webber et al. 2011b). The annual growth index (GIA) denotes the population growth potential under favourable climate conditions. The probability of population survival under unfavourable conditions is denoted by the four stress indices (cold, wet, hot and dry), and additionally by the inclusion of up to four interaction stresses (hot–dry, hot–wet, cold–dry and cold–wet). These growth and stress indices, calculated on a weekly basis, are incorporated into the Ecoclimatic Index (EI), an annual index of the climatic suitability, on a theoretical scale of 0-100. The establishment of a species is possible where EI > 0. EI values approaching the maximum are rare in practice, and usually only applicable to species with an equatorial range, implying ideal conditions all year round (Sutherst 2003).

While SDMs are used extensively, many challenges relating to parameter value uncertainties, data and calibration methods (Hanspach et al. 2011) may affect the accuracy of the output of the model. A reduction of the associated uncertainties and errors may be achieved by employing techniques such as sensitivity analysis (Burgman et al. 2005), which can identify parameters having the greatest influence on model output (Hamby 1994). Such analyses identify parameters which are functionally most important, thus providing an enhanced understanding of the climatic factors having the greatest impact on the distribution of the particular invasive species (Taylor 2011).

The major assumption inherent in CLIMEX is that the distribution of a species is determined primarily by climatic factors and that there is equilibrium between the species and the environment, in which it is being modelled. CLIMEX excludes alternative biophysical data derived from factors such as land-use, soil, disturbance levels and dispersal ability, although such non-climatic factors may be introduced to the model after the initial climate modelling has been completed. Inclusion of these other factors may help to further refine the distribution and improve the reliability of the modelling results. Issues regarding the scale on which non-climatic factors may be included into SDMs has recently received attention. There is widespread acceptance that the importance of climate is best expressed at macro-scales and therefore data with coarse spatial resolution may be most appropriate for projecting species distributions based on climate (Pearson et al. 2002a). In general, range limitations in terms of survival or reproduction are imposed by climate through direct physiological constraints (Gavin & Hu 2006). Alternatively, factors that influence the distribution within a particular climate envelope occur at differing spatial scales (Thomas et al. 2004). Thus, SDMs that provide assessment of risk on a continental scale may be refined for national or local-level assessment by the incorporation of factors such as soil nutrients, water holding capacity, existing land use and soil characteristics, appropriate to these scales (Kolomeitz & Van Klinken 2004; Rogers et al. 2007; Bradley 2010).

The MaxEnt maximum entropy method is an all-purpose method facilitating the making predictions and inferences from data classified as incomplete (Phillips et al. 2006). It is founded on the theories of statistical mechanics (Jaynes 1957), and continues to be an area of active research holding an an annual conference and exploring Maximum Entropy and Bayesian

Statistical Methods, which have applications in a wide range of research in areas such as astronomy, statistical physics, signal processing, image reconstruction and portfolio optimization. It is applicable here as a general approach for the modelling of species distributions, involving presence-only datasets. The MaxEnt principle is to estimate a target probability distribution by calculating the maximum entropy or 'closest to uniform' probability distribution, by incorporation of a set of constraints which represent about the unknown data regarding the target distribution (Phillips et al. 2006).

There are many advantages, notwithstanding a few drawbacks, to the use of MaxEnt, and after a detailed description of the approach, a comparison with other modelling methods will be made in Section 2.1.4. MaxEnt advantages include: *a)* It requires only presence and environmental data representing the whole study area. *b)* It may include both continuous and categorical data, as well as the interactions of different variables. *c)* Efficient deterministic algorithms exist ensuring a convergence to the maximum entropy, or optimal, probability distribution. *d)* The calculated probability distribution has a concise mathematical definition, and is thus suitable for analysis (Phillips et al. 2006).

1.3 DATE PALMS

Date palm (*Phoenix dactylifera* L.) (Fig. 1-2) is a dioecious fruit tree, native to the hot arid regions, originally cultivated mainly in the Middle East and North Africa. Date palm agricultural production has gradually expanded to include Australia, Southern Africa, South America, Mexico and the USA, using germplasm exchange. This majestic plant has been termed the "tree of life" since ancient times due to its integration in human settlements, and consequent contribution to general wellbeing through food security, in hot and otherwise barren areas, where minimal plant species can flourish (Jain et al. 2011a). The species continues to provide a sustainable agro-ecosystem in harshly dry environments and provide the raw materials for housing, furnishings, and many handcrafts. Date palm may be eaten fresh or dried, and may be processed to provide a source of nutritious sugars, minerals and vitamins. Date palm is economically a major source of income for farmers and its associated industries in the communities where it is cultivated.

Figure 1-2 - Date palm plantation

1.4 DATE PALMS BIOLOGY

The date palm (*Phoenix dactylifera* L.) is one of fourteen species of the genus *Phoenix*, which is one of the 183 currently known palm genera. Taxonomically *Phoenix* is classified as being of the tribe Phoeniceae, subfamily Coryphoideae and family Arecaceae (Palmae) and has an extensive Old World natural distribution. *Phoenix* sizes range from stemless to tall, with the date palm being the tallest at over 30 metres. The leaves of the date palm are 3–6 metres in length and in form, pinnate, induplicate (V-shaped) and erect, with basal leaf spines. The fruit is ovoid to oblong and smooth with a fleshy mesocarp (Jain et al. 2011a).

Historically it is one of the oldest cultivated fruit trees on earth. Along with the olive and fig, date palm forms an ancient group of fruit trees closely associated with the beginnings of agriculture and was domesticated in Mesopotamia (modern-day Iraq) more than 5,000 years ago (Jain et al.

2011a). While it was previously thought that the date palm had no wild ancestors, in recent archaeological research, together with contemporary botanical field and laboratory studies, has revealed that the cultivated date is related to feral populations in North Africa and the Middle and Near East. Wild dates, now considered to be of the same species, can hybridize with the named cultivars and are morphologically similar to the domesticated form, their most prominent differentiating feature being their much smaller fruits (Jain et al. 2011a).

The value of the species within both subsistence and market economies is far greater than merely a nutritious high-energy fresh fruit which can be eaten, as it can easily be stored by a natural sun drying process, to be used as a supplementary food substance throughout the year. It may be pressed into an easily-transportable date cake or transformed into syrup that can be fermented into date wine or vinegar. Additionally it is used as a source of bioethanol which also produces a by-product as a feedstock. The heart of a felled tree is also edible and the pits (seeds) can be eaten by livestock. The fruit is an important source of raw materials for related agrofood industries, as well as for secondary metabolites important in the human diet. In an oasis environment, date palm trees create a microenvironment suitable for the development of other forms of agriculture and raising livestock, as well as providing much-needed shade. Tree stems provide wood for construction, the midribs of the leaves fencing material and the leaves themselves may be woven into baskets, mats, hats and similar products. Thus date palm is truly an age-old multipurpose species (Jain et al. 2011a).

Typical desert date palms flower once a year in spring in the Northern Hemisphere. This appears to be governed by climate and in periods of exceptionally high desert rainfall, a second annual flowering may occur. In their native, wild environment, trees are pollinated by wind or insects, while in extreme northern Chile, where date palms are grown in an ideal stress-free environment with ample irrigation water and high temperatures with minimal fluctuation, the date palm flowers and fruits continuously like coconuts. While the fact that the species has the genetic capacity for continuous flowering and fruiting, this is unlikely to result in an increased annual productivity per tree than normally occurs in a single annual flowering season. However, this potential may be worth exploiting, where similar ideal environments exist, for off-season marketing purposes (Al-Shahib & Marshall 2003; Hasan et al. 2006; Chao & Krueger 2007b; Al-Gboori & Krepl 2010; Jain et al. 2011a).

Pests and diseases are, to varying degrees, dependent on locality, perpetual threats to date cultivation, and in certain cases to the continued life of the trees. Bayoud disease, a fatal vascular wilt caused by the soil-borne fungal disease *Fusarium oxysporum,* is a prominent threat. The disease first made an appearance in the late nineteenth century in Morocco and has spread extensively in that country and neighbouring Algeria. It attacks the prized Moroccan Medjool cultivar in particular and is dispersed mainly by offshoots transfer. After the onset of initial leaf withering symptoms, the death of the tree follows within months. No known chemical or biological antagonist exists and the only current solution appears to lie in selecting cultivars that are resistant (Armstrong & Armstrong 1981; Botes & Zaid 2002; Jain et al. 2011a; Sutherland et al. 2013).

To this end, the general aim of this research is about quantifying the impact of climate change on future distribution of date palm, a cash crop of major world importance, as well as identifying suitable areas for sustainable date palm cultivation based on various SDMs, Global Climate Models (GCMs), disease and non-climatic parameters in terms of long-term strategies at global and country scales.

1.5 GENERAL AIMS

This study constitutes studies based on different modelling techniques to project future distribution of date palm in an era of climate change. The overall purpose of this study was to model the impact of climate change on the Middle Eastern and global potential geographic distributions of date palm using CLIMEX (Chapter 2) and then to determine potential distributions of *P. dactylifera* under future climates and soil types and their physicochemical properties, in order to assess the sensitivity of these distributions to climate change, and evaluate concurrent implications for cultivation of the species in Iran (Chapter 3). Next we refined those areas projected to become suitable for cultivation under climate change using four non-climatic parameters: *a)* areas with physicochemical soil property suitability, *b)* areas with soil taxonomy suitability, *c)* slopes with a gradient below 10°, and *d)* land use suitability for cultivation in Iran for the study projection years 2030, 2050, 2070, and 2100 (Chapter 4). Thereafter a sensitivity analysis identifying climatic parameters of major functional importance in projecting date palm distribution in CLIMEX was conducted (Chapter 5). Our research then modelled future distributions of *Fusarium oxysporum* f. spp., a fungal disease of date palm, under climate changes (Chapter 6). The next step was to determine risk levels of *Fusarium oxysporum f.* spp. invasion in areas of suitability for date palm cultivation under different scenarios of climate change (Chapter 7). Then followed the construction of a deterministic model which identified localities where a positive Net Present Values (*NPV*) could be obtained from date palm in those regions projected to become suitable, by using CLIMEX in conjunction with a number of non-climatic parameters. Evaluations were undertaken for the specific study projection years, as defined above, in Iran (Chapter 8). A determination of the potential distributions of *P. dactylifera* under future climates and assessment of this distribution in terms of climate change, progressed to a consideration of the possible long-term use of dates as an ideal food commodity to tackle malnutrition in developing countries (Chapter 9). Secondary investigation was made into the value of the use of *a)* native range data only; *b)* exotic range data only; and *c)* both; to model species distributions of date palm (Chapter 10). A comparison follows of the performance of CLIMEX as a mechanistic bioclimatic modelling methodology, used in conjunction with MaxEnt, Boosted Regression Trees and Random Forests as correlative bioclimatic modelling techniques, in projecting current and future distributions of *P. dactylifera* (date palm) (Chapter 11). Finally, Chapter 12 summarises the main findings of the research and discusses future research directions.

CHAPTER 2

CLIMATE CHANGE IMPACTS ON THE FUTURE DISTRIBUTION OF DATE PALMS: A MODELING EXERCISE USING CLIMEX

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1) SHABANI, F. KUMAR, L. & TAYLOR, S. (2012). Climate change impacts on the future distribution of date palms: a modeling exercise using CLIMEX. *PLoS ONE* 7(10), e48021.
2) SHABANI, F. KUMAR, L. & TAYLOR, S. (2015). Distribution of date palms in the Middle East based on future climate scenarios. *Experimental Agriculture*, 244-263. doi:10.1017/S001447971400026X

CHAPTER 3

SUITABLE REGIONS FOR DATE PALM CULTIVATION IN IRAN ARE PREDICTED TO INCREASE SUBSTANTIALLY UNDER FUTURE CLIMATE CHANGE SCENARIOS

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SHABANI, F. KUMAR, L. & TAYLOR, S. (2014). Suitable regions for date palm cultivation in Iran are predicted to increase substantially under future climate change scenarios. *Journal of Agricultural Science*, 152(4), 543-557. doi:10.1017/S0021859613000816

CHAPTER 4

PROJECTING DATE PALM DISTRIBUTION IN IRAN UNDER CLIMATE CHANGE USING TOPOGRAPHY, PHYSICOCHEMICAL SOIL PROPERTIES, SOIL TAXONOMY, LAND USE AND CLIMATE DATA

This chapter has been published as:

SHABANI, F. KUMAR, L. & TAYLOR, S. (2014). Projecting date palm distribution in Iran under climate change using topography, physicochemical soil properties, soil taxonomy, land use and climate data. *Theoretical and Applied Climatology* 118(3), 553–567. doi: 10.1007/s00704-013-1064-0

CHAPTER 5

SENSITIVITY ANALYSIS OF CLIMEX PARAMETERS IN MODELING POTENTIAL DISTRIBUTION OF *PHOENIX DACTYLIFERA* L.

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SHABANI, F. & KUMAR, L. (2014). Sensitivity Analysis of CLIMEX Parameters in Modeling Potential Distribution of *Phoenix dactylifera* L. *PLoS ONE* **9**(4), e94867.

CHAPTER 6

FUTURE DISTRIBUTIONS OF *FUSARIUM OXYSPORUM* F. SPP. IN EUROPEAN, MIDDLE EASTERN AND NORTH AFRICAN AGRICULTURAL REGIONS UNDER CLIMATE CHANGE

This chapter has been published as:

SHABANI, F. KUMAR, L. & ESMAEILI, A. (2014). Future Distributions of *Fusarium oxysporum* f. spp. in European, Middle Eastern and North African Agricultural Regions under Climate Change. *Agriculture, Ecosystems and Environment* **197**, 96-105. http://dx.doi.org/10.1016/j.agee.2014.08.005

CHAPTER 7

RISK LEVELS OF INVASIVE *FUSARIUM OXYSPORUM* F. SPP. IN AREAS SUITABLE FOR DATE PALM (*PHOENIX DACTYLIFERA*) CULTIVATION UNDER VARIOUS CLIMATE CHANGE PROJECTIONS

This chapter has been published as:

SHABANI, F. & KUMAR, L. (2013). Risk levels of Invasive *Fusarium oxysporum* f. spp. in Areas Suitable for Date Palm (*Phoenix dactylifera*) Cultivation Under Various Climate Change Projections. *PLoS ONE* **8**(12), e83404.

CHAPTER 8

EFFECTS OF CLIMATE CHANGE ON ECONOMIC FEASIBILITY OF FUTURE DATE PALM PRODUCTION: AN INTEGRATED ASSESSMENT IN IRAN

This chapter is under review with the *Journal of Agricultural Economics*

Shabani, F. Cacho, O. Kumar, L. Effects of climate change on economic feasibility of future date palm production: an integrated assessment in Iran

CHAPTER 9

PROJECTED FUTURE DISTRIBUTION OF DATE PALM AND ITS POTENTIAL USE IN ALLEVIATING MICRONUTRIENT DEFICIENCY

This chapter has been published as:

SHABANI, F. KUMAR, L. NOJOUMIAN, A. H. ESMAEILI, A. & TOGHYANI, M. (2015). Projected future distribution of date palms and its potential use in alleviating micronutrient deficiency. *Journal of the Science of Food and Agriculture*. doi: 10.1002/jsfa.7195

CHAPTER 10

CLIMATE MODELING OUTPUTS GET SKEWED BASED ON CORRELATIVE AND MECHANISTIC MODELS

This chapter is under review with *International Journal of Biometeorology*

Shabani, F. Kumar, L. Solhjouy-fard, S. Climate modeling outputs get skewed based on correlative and mechanistic models.

CHAPTER 11

SHOULD SPECIES DISTRIBUTION MODELS USE ONLY NATIVE OR EXOTIC RECORDS OF EXISTENCE OR BOTH?

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CHAPTER 12

SYNTHESIS AND GENERAL CONCLUSIONS

12.1 INTRODUCTION

The study of how current climatic change influences crop production yields is not only vital in establishing a baseline for estimating the impact of climate change, but also can provide insight into the effective prediction methods applicable to future agricultural productivity. Climate factors represent the major determinant of plant growth and impact on a number of plant physiological processes, such as the commencement and duration of phenological stages. In recent decades, global temperatures have increased, leading to earlier onset of cultivation stages, as well as altering the duration of these stages in certain species, in certain areas. This affects farmers and producers in their choice of suitable crop varieties for a specific location. Varieties developed for or adapted to a certain region over the past 30 years may not be the best for the future. The incorporation of crop models into climate change scenarios can support information on whether farmers need to replace current crops or crop varieties with alternatives from other regions, and whether more research is necessary to develop new varieties. A further important area of study is the impact of climate change on crop pests and diseases.

Climatic factors alter soil processes such as the organic balance, nutrient cycle, erosion, leaching and salinity, leading to soil condition changes that alter the long-term potential yield of crops. Finally, extreme climate and weather conditions may damage crop yields potential and significantly increase agricultural production risks. The addition of these aspects to crop-modelling demands higher resolution data in both spatial and temporal spheres.

In constructing our profile of climate change vulnerability, we made the assumption that exposure to climate change will affect current sensitivity, whether positively or negatively, and that farmers will respond to altered sensitivity levels, if they have sufficient capacity to adapt. Thus, the vulnerability profile is built-up by combining the indices for adaptive capacity and sensitivity indices, taking into account climate change exposure. This study's outcome gives an indicator of the ability of district farmers to embrace alternative economic activities to offset reduced agricultural income arising from negative climatic factors such as drought. Districts with better irrigation rates and/or better infrastructures are more equipped to cope with climate fluctuations and alternative economic shocks.

In a line with this matter, species distribution models provide valuable information on potential future species distribution. For example, CLIMEX, HABITAT, MAXENT, BRT, RF and BIOCLIM are some of the computer-based programs that are designed to model species' current or future distributions.

The overall purpose of our research was to assess the impact of climate change on potential date palm distribution by means of various GCMs, mechanistic and correlative modelling techniques, in conjunction with an array of non-climatic parameters.

12.2 SUMMARY OF MAIN FINDINGS

The research has highlighted some broad-scale shifts in locations of suitability for the cultivation of date palm and how certain regions may be affected due to broad regional-scale changes over the next century, through the use of coarse scale climate data. Such modelling facilitates the planning of strategies to minimize economic consequences in regions that may be adversely affected, as well as using it to economic advantage for regions that may be positively affected. For example, in the Middle East, results indicate that sizeable areas of Iraq and Saudi Arabia will become unsuitable for date palm cultivation due to a westward increment of heat stress in the region. Thus, it is projected that these countries will not be able to cultivate date palm to the same extent that they have previously. On the national scale however, the results in Iran show an increase in areas of suitability for the future cultivation of date palm.

In refining of areas becoming suitable for date palm cultivation based on projected climate change and soil type suitability, our study shows that 0.52% of CLIMEX outputs using CS and MR GCMs with the A2 scenario in Iran are suitable for date cultivation in terms of consideration of soil type, compared with the current date palm plantation areas covering 4.8 million ha. In addition, this result highlights that the incremental addition of new parameters of soil type, soil physicochemical properties, slope and use of suitable land increases the accordance between the GCMs. Thus the greater the number of non-climatic parameters incorporated, the greater the accuracy of the output. Further, the results show that the minimum disagreement between GCMs, in terms of where date palm can grow, was achieved when the localities of suitable soil physicochemical properties and taxonomy were introduced as refinement tools. This result indicates that the soil factors have a greater effect than land use and slope, in terms of the suitability of locations for the cultivation of date palm.

The Taguchi method formed the basis of the sensitivity analysis used in this research and was performed for the identification of the parameters of greatest functional importance, in order to enhance the understanding of the climatic factors that most affect date palm projection scenarios in CLIMEX. Results show that eight of fourteen tested parameters had an influencing effect on potential distribution, these being the DV1, DV2, DV3 and SM0, SM1, SM2, SM3 and SMWS parameters. Thus, particularly where there are limitations to resources, studies should utilize more extensive sources of data, with the purpose of fitting these eight parameters with greater accuracy. It may be concluded that parameters more sensitive to change have greater impact on the output compared to those relatively less sensitive.

The study also indicates notable shifts in areas of suitability for *Fusarium oxysporum* f. spp. and the effects of climate change in regions of Europe, the Middle East and North Africa. The distribution maps included provide information suitable for the long-term agricultural management of production in areas projected as becoming unsuitable or marginally suitable for *Fusarium oxysporum* f. spp..

In modelling the risk of *Fusarium oxysporum* f. spp. in date palm cultivation for the study projection years 2030, 2050, 2070 and 2100, results show that greater areas of low risk of invasion are projected to become highly suitable for the cultivation of date palm until 2070. However, there a trend of reduction was projected in areas of high suitability to both date palm and *Fusarium oxysporum* f. spp. during the forthcoming ninety years. In agreement with this trend, the results of the study showed that 40%, 37%, 33% and 28% of regions projected to become highly suitable to date palm face a high risk of *Fusarium oxysporum* f. spp), in comparison with 37%, 39%, 43% and 42% under low risk, for the years of study projection, respectively. It is also indicated that marginal risk areas will be restricted to 231, 212, 186 and 172 million hectares for those years.

The results of our model identifying areas where a positive *NPV* could be obtained from date palm (*P. dactylifera*) in regions that have been projected to become suitable using CLIMEX (610000 km^2), show that only about 0.01% of the CLIMEX projections in Iran are likely to become highly economically viable for cultivation of date palm over the next ninety years.

In regard to the positive impacts of future distributions of date palm on the alleviation of malnutrition and micronutrient deficiency in an era of climate change, our study focussed on the potential long term use of dates as an ideal food commodity to tackle malnutrition in developing countries, where reports consistently highlight the destitute conditions and morbidity of children as a consequence of malnutrition. The modelling outputs indicated large shifts in areas suitable to date palm cultivation, based on global scale climate change over the next sixty years. Most of the regions, which manifest suffering from micronutrient deficiencies, were projected to become highly conducive for date palm cultivation. These results could thus be of positive value in strategic planning by government agencies and agricultural organizations, by identifying future areas in which to cultivate this nutritionally important crop to alleviate micronutrient deficiencies.

Our comparative research into differences in climate modelling outputs between correlative and mechanistic models showed that the different modelling approaches predicted fairly different distributions both globally and for Middle Eastern countries. While the co-areas of both predictions are similar, MaxEnt picks out other areas not in the native distribution range, while CLIMEX generally picks those areas which are more in the native regions. In contrast, Boosted Regression Trees (BRT) and Random Forests (RF) methods were much more conservative than MaxEnt and CLIMEX in projections of date palm for the present. In this regard, we recommend that results of single high or low end scenarios and single GCMs should be combined with other scenarios and GCMs, using software such as CLIMEX, MaxEnt, BRT and RF. This method will decrease the amount of uncertainty in projecting future distributions of species.

12.3 IMPLICATIONS OF THE STUDY

This study showed how CLIMEX and MaxEnt software could be used to provide and formulate effective strategies for managing the date palm industry at the global, national and local levels. Some divergence was noted in projecting suitable areas for date palms between the results of the CS and MR GCMs and demonstrated that incorporating non-climatic factors, such as soil types, biotic interactions, diseases and land use can effectively refine projections and reduce variance in modelled outputs. Refining CLIMEX outputs with non-climatic parameters, such as suitability in soil physicochemical properties and taxonomy, slope and land use, enhances output accuracy and robustness, since the results need to reflect additional requirements. In this regard, both models showed that approximately 56.5 million ha of Iran may become conducive to date palm cultivation by 2030, while 34.25 million ha of these projections are invalid due to soil physicochemical properties, soil taxonomy, slope or land use variables. Similar trends for both GCMs were projected for the years 2050, 2070 and 2100. Therefore, our results indicate that the incremental addition of each new parameter reduces disagreement between GCMs.

Additionally using Taguchi method proved a useful technique in the streamlining of data collection requirements for modelling potential distribution.

Our research highlights significant shifts in regions classified as conducive to *Fusarium oxysporum* f. spp. and the impacts of climate change in parts of Europe, the Middle East and North Africa. The distribution maps used to illustrate this study may be invaluable in the design and execution of cost-effective agricultural production methods of the future.

While the study projected a downward trend in terms of regions that will become highly suitable for the growth of date palm, with high risk of *Fusarium oxysporum* f. spp. invasion, it projected an upward trend for areas with low risk until 2070, followed by a slight decline to 2100. Thus, relevant authorities and organisations in countries projected to become highly conducive to date palm with marginal or low risk of *Fusarium oxysporum* f. spp., should consider these projections in the implementation of appropriate policies and programs, ensuring the date palm industry's safety and the development of a date palm biosecurity system.

The study considered the impact of climate change on the economics of date palm production in the future, through an integrated assessment of projections for Iran. Although approximately 610000 km^2 of Iran was projected to become highly conducive for date palm, merely 0.01% of these areas will actually be highly economically viable for date palm cultivation. Therefore, our methodology of integrated assessment of date palm may be useful for other agricultural crops in different countries to minimize economic consequences in regions that may be adversely affected through climate alteration.

Based on projections for future date palm distribution, the study also proposed the potential to use dates as an ideal food commodity to tackle malnutrition in developing countries where reports continually highlight destitute conditions and morbidity among children as a consequence of malnutrition. Therefore, our climatic modeling procedure of future distribution of date palm could be utilized for other nutritious agricultural productions in different countries. This will maximize advantages of climate change on yield and productions in regions that may be positively affected through climate alteration.

This study indicated how climate modelling outputs get skewed based on correlative and mechanistic models. Our research suggested some improvements to enhance bioclimatic modelling capability to project future distribution of different species.

A further aspect of the study demonstrated how modelling outputs may be skewed according to the input proportions of native and exotic data, and included suggestions towards a methodology for improving projections on this basis.

Finally, the study demonstrated the necessity of caution in using global and regional climate change models on projected date palm distribution, in terms of the high level of sensitivity of distributions to the upper and lower temperature tolerance limits. SDM results also vary depending on the emissions scenario used. Thus, management decisions should be based on outputs of a number of scenarios.

12.4 LIMITATIONS AND RECOMMENDATIONS

This study utilised two modelling software programs (CLIMEX and MaxEnt) to determine potential distributions of date palm. It would be useful to conduct a comparative study with other SDM software packages. In general, species distribution modelling methods use gridded climate datasets of moderate spatial resolution. The impact of varying the spatial resolution of climatic datasets on the potential distribution of date palm is another issue that requires further exploration. Furthermore, the study enhanced the accuracy of projections by finding the common projected areas of two GCMs for date palm and only *Fusarium oxysporum* f. spp. as a destructive invasive species. The projection of other date palm diseases should also enhance accuracy. A lack of occurrence records in some regions surely affected our projections. Therefore, it should be kept in mind that all projections of this study are based on available data. The occurrence records in species distribution databases, such as Global Biodiversity Information Facility and Missouri Botanical Gardens' database, should be maximized and updated. In line with this issue, it is highly recommended that occurrence database organizations keep sending request of species occurrences to the related universities or organizations across the globe, specially Middle Eastern and African countries. Next, this type of projection exercise can be used in projection of future land use patterns at different scales. However, for downscaling studies, the need of fine scale data, such as soil physicochemical properties, soil taxonomy, land use and water sources, are vital. It should be mentioned that the presented methodology in integrated assessment of date palm have some limitations due to other important parameters that have not been investigated. However, our methodology can provide useful insights in terms of agricultural economics and long-term strategies in response to climate change and suitable production. To this end, our presented results are indicative because a certain level of uncertainty is associated with future levels of greenhouse gas emissions and climate projections.

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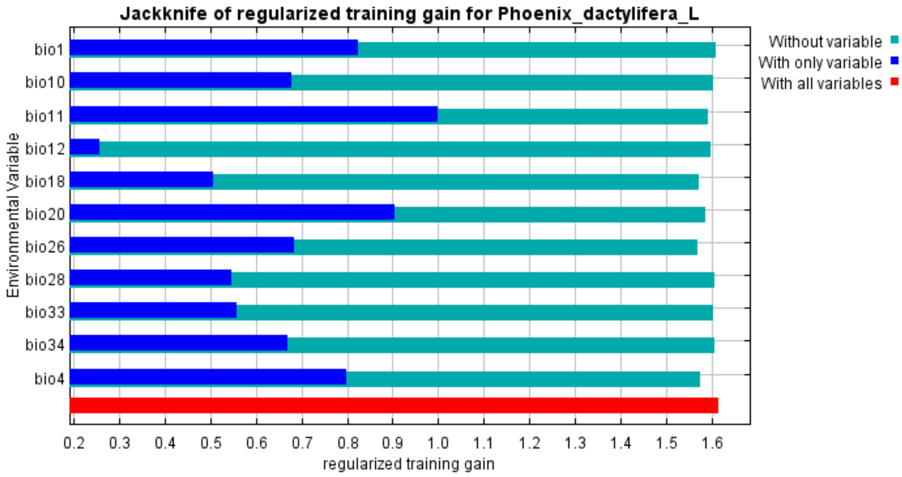
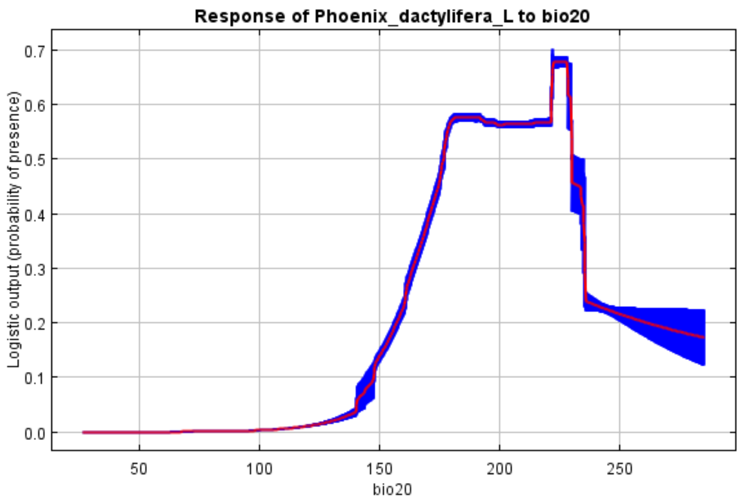
APPENDIX

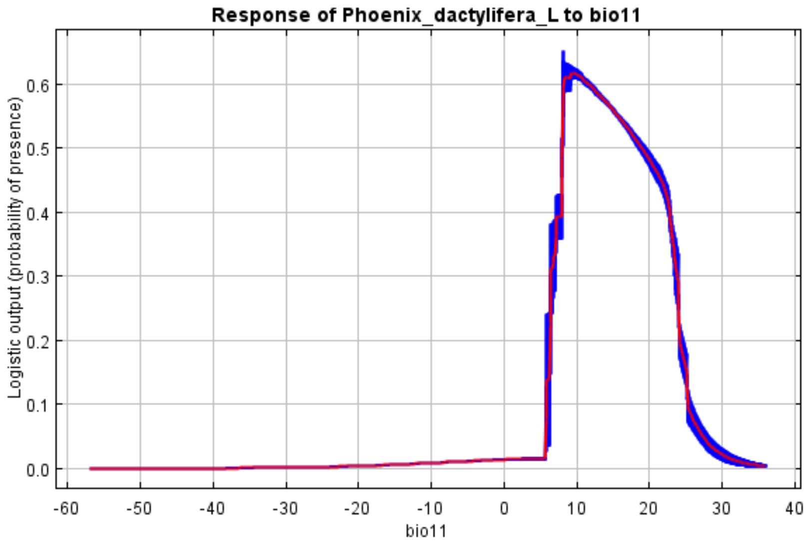
a)



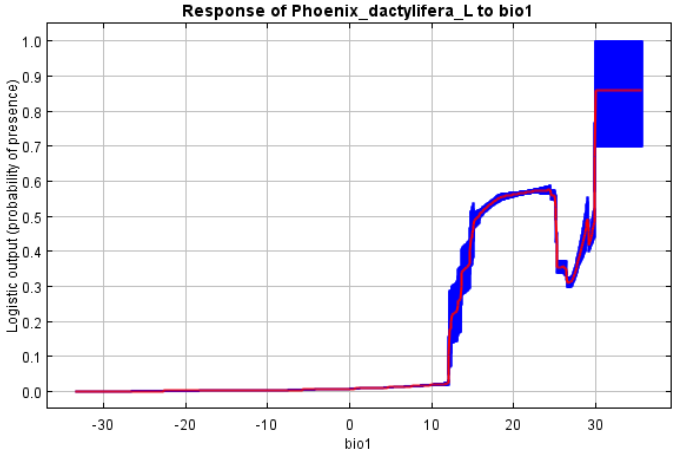
b)



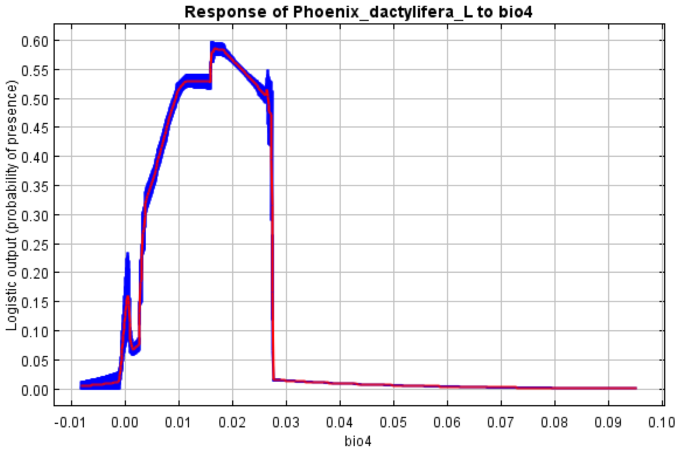
c)



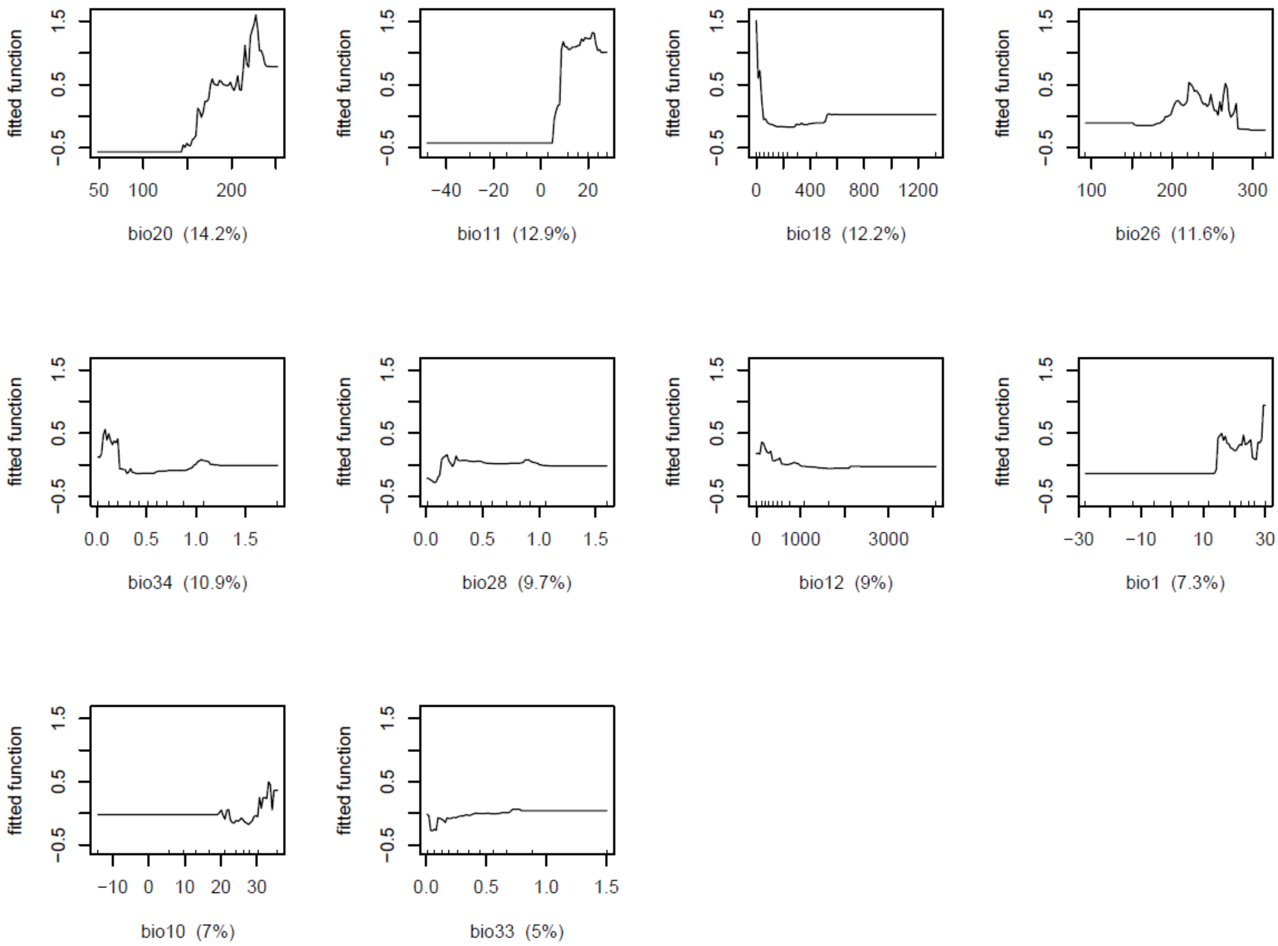
d)



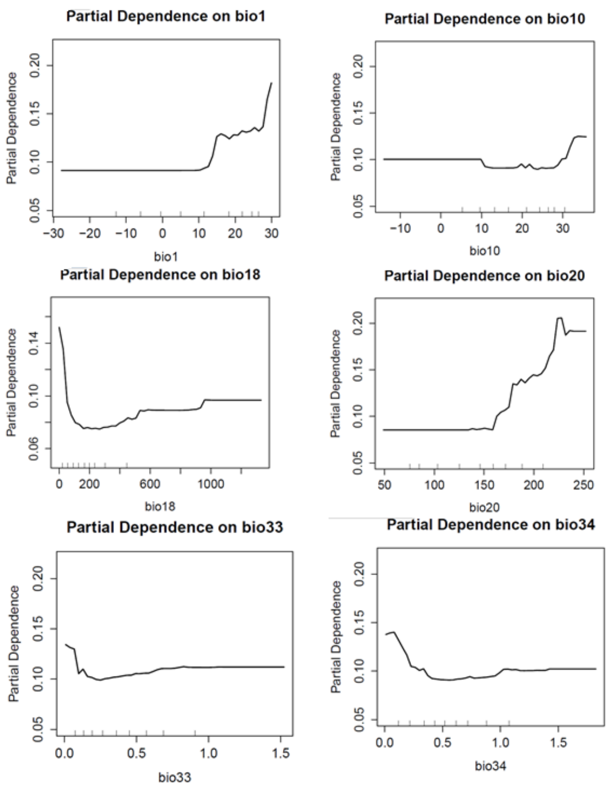
e)



Appendix 10-1 - *a)* MaxEnt Jackknife tests of the environmental variable importance and the contribution variables to predict presence probability of *Phoenix dactylifera* L. based on full dataset (exotic + native). *b,c,d & e)* MaxEnt response curves of the contribution variables to predict presence probability of *P. dactylifera* L. to bio20, bio11, bio1 and bio4.



Appendix 10-2 - Response curves of the contribution variables to predict presence probability of *Phoenix dactylifera* L. resulting from correlative bioclimatic models.



Appendix 10-3 - Response curves of the contribution variables to predict presence probability of *Phoenix dactylifera* L. resulting from RF as a correlative bioclimatic model.

	MaxEnt	BRT	RF
AUC-Training	0.944	0.993	1
AUC-Test	0.918	0.954	0.977

Appendix 10- 4 - Statistical evaluations of MaxEnt, BRT and RF.