

Climate change impacts on the future distribution of date palm in Oman



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Summary

As a consequence of climate change, the distribution of date palm will change. It is essential to identify which regions will benefit by having the potential opportunity of cultivating date palms in the future and which may be adversely affected. Governments and agricultural organizations can prepare for this situation in advance and thereby gain significant economic advantages which can enable them to improve their economies. Alternately, regions that could be adversely affected can become aware of the situation and transition their economies accordingly. This awareness provides an opportunity to plan for alternative sources of income. With this aim, this study made use of the CLIMEX software package in developing a global model of the climate response of *P. dactylifera* based on its native and cultivated distribution. This model was then used to illustrate date palm potential distribution using two global climate models (GCMs) including CSIRO-Mk3.0 and MIROC-H. These were run with the A2 SRES (Special Report on Emissions Scenarios) emission scenarios for 2030, 2050, 2070 and 2100. The A2 SERS was chosen with the assumption that, in the future, there would be high population growth coupled with slow economic growth and extensive technological change.

The CS GCM projected that the eastern and southern parts of the country will remain climatically suitable for *P. dactylifera* until 2030, however regions between 18°N to 22°N and 53°E to 56°E will become progressively less suitable by 2050, 2070 and 2100. Additionally, the CS GCM for Oman indicated that the western regions (21 to 24°N and 54 to 56°E) become totally unsuitable for date palm cultivation by 2100. A similar result was also obtained using the MR GCM, however the degree of unsuitability was slightly different to the CS GCM. While the MR model predicts lower declines in suitability, it does predict a higher decline in those areas that are highly conducive to date palm cultivation.

Overall there is a considerable reduction in climate suitability for date palm cultivation in Oman between 2070 and 2100.

It should be noted here that these results are preliminary and will be further refined as more field data becomes available during the course of this project.

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INTRODUCTION

DATE PALMS

Date palm (*Phoenix dactylifera* L.) (Fig. 1) 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. The species continues to provide a sustainable agro-ecosystem in harshly dry environments and provide the raw materials for housing, furnishings, and many handicrafts, over and above its delicious fruit, which 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- Date palm plantation

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.*, 2011b).

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. 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.*, 2011b).

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.*, 2011b).

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, 2007a; Al-Gboori & Krepl, 2010; Jain *et al.*, 2011b).

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.*, 2011b; 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 species distribution models (SDMs), global climate models (GCMs), disease and non-climatic parameters in terms of long-term strategies at global and country scales.

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. 2). 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).

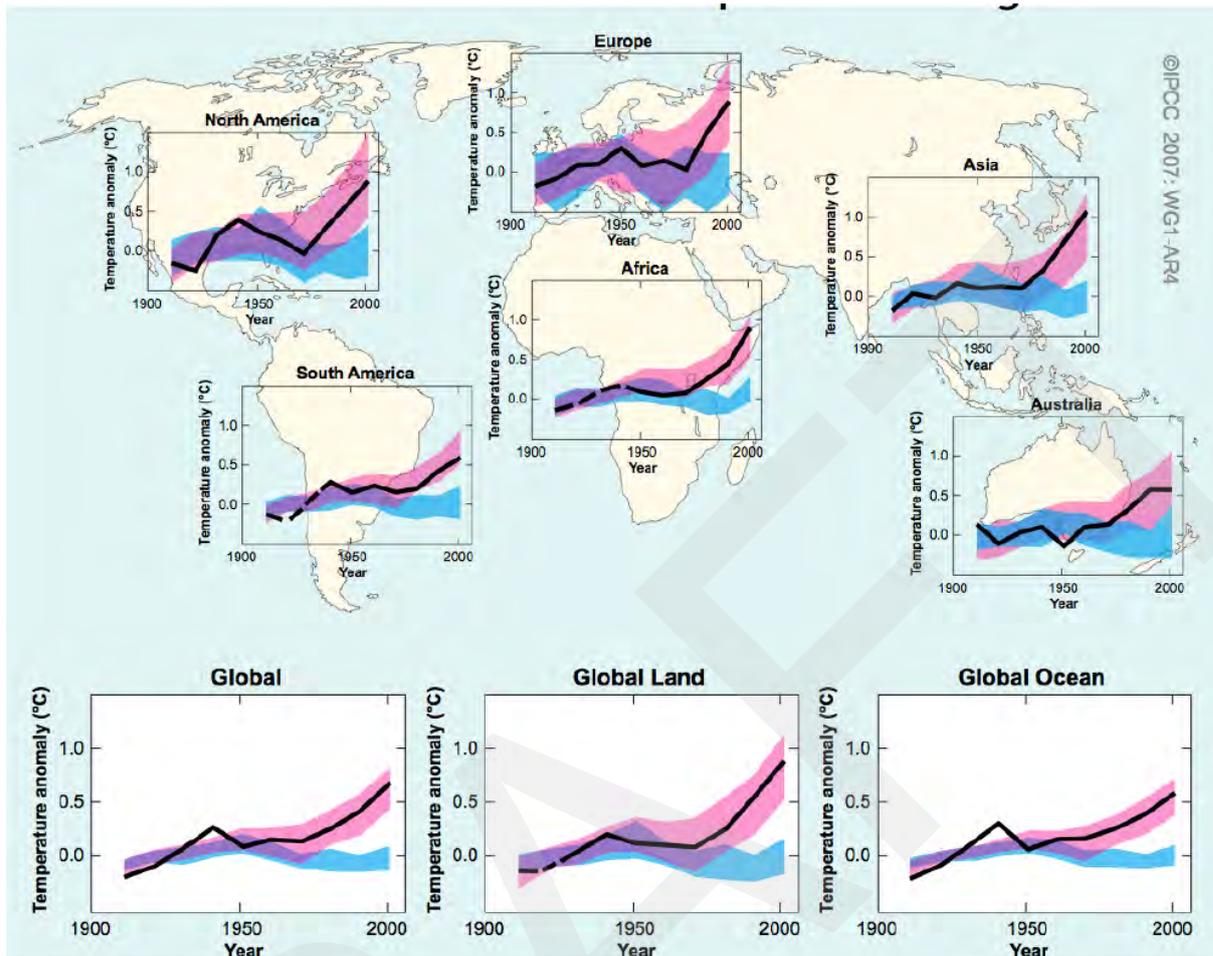


Figure 2- Comparison of observed changes in continental and global-scale surface temperatures, with those simulated by models using natural and anthropogenic climatic change forcings (Meehl *et al.*, 2007). The black line represents the decadal averages of observations for the period 1906–2005, plotted 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.

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, BOOSTED REGRESSION TREE, RANDOM FOREST and BIOCLIM. In modelling 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 a species could establish itself and persist, as well as in the assessment of magnitude of the establishment.

The CLIMEX modelling tool (Sutherst & Maywald, 1985) 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. 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.*, 2007). The parameters used in CLIMEX to describe the species' response to climate are based on geographical range data or phenological observations (Sutherst *et al.*, 2007; 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.*, 2011). 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.*, 2002). 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. It is founded on the theories of statistical mechanics (Jaynes, 1957), and continues to be an area of active research holding 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).

IMPACTS OF CLIMATE CHANGE ON DATE PALM IN OMAN

Climate is one of the principal aspects defining the potential range of plants and climate change directly affects the distribution of species (Andrewartha & Birch, 1954). Much evidence exists that the climate is changing globally, and land surface temperatures are expected to increase by 4°C between the present and 2100 (Jeffrey & Harold, 1999). Moreover, worldwide seasonal rainfall patterns are changing (Jeffrey & Harold, 1999). As a consequence, a number of serious issues arise. For example, the extent of pollution and aeroallergens will change (McMichael *et al.*, 2003). Changes in the expansion and transmission of some infectious diseases, famine, crop failure, water shortages and population displacement are some of the other issues involved with climate change. Climate change clearly threatens different areas, such as biodiversity, agricultural production, and human health. For example, it is expected that by 2030, the risk of diarrhea will increase by 10% in some specific regions due to climate change (McMichael *et al.*, 2003). Climate change can also have an impact on agricultural production by affecting the distribution of economically important crops.

Climate change can have a negative impact on economically important crops due to changes in their physiology. Altered climate can cause negative impacts on date palm production (Jain, 2011); for example, from 1990 to 2000, the annual income from date palms in the Middle Eastern countries decreased (Botes & Zaid, 2002). A number of factors could be involved in this reduction, and climate change could be one of them because significant losses in yield of some economically important crops have been attributed to plant diseases resulting from climate change. It has been reported that climate change has caused a \$438 million loss in wheat, \$116 million in grapes and \$67 million in sugar production in Australia and North America (Chakraborty *et al.*, 1998).

Date palm (*Phoenix dactylifera* L.) is a valuable plant that provides a significant source of income for both local farmers and governments in arid and semi-arid regions of the world (Jain *et al.*, 2011a). A number of reports document the cultivation of date palms back to the 5th millennium BC. Since ancient times, the majority of date palms have continued to be grown in the hot deserts of North Africa and the Middle East, including Syria, the Persian Gulf region and north Yemen (Tengberg, 2011). The native range of this species is from the south-eastern Azores to Pakistan, and its cultivation stems from the 4th millennium BC in Mesopotamia and Palestine (Agroforestry Tree Database, 2013). The genus *Phoenix* includes up to 400 species (Elshibli *et al.*, 2009b; Bokhary, 2010; Ahmed *et al.*, 2011) within the Arecaceae family. To mature, the fruit requires prolonged summer heat. Rain or high humidity during fruiting increases the risk of the fruit cracking and the onset of fungal diseases (Burt, 2005b). Long summers with high day and night temperatures, and mild, sunny, dry winters without prolonged frost are the ideal climatic conditions for this species (Jain *et al.*, 2011b). Dates (*Phoenix dactylifera* L.) are fruit trees which belong to the family Arecaceae which comprises almost 400 species, and is a crop of economic importance for many countries (Jain *et al.*, 2011b). The plant has achieved its relative importance mainly because of its great nutritional value (carbohydrate, fat, salts, minerals, protein, vitamins and dietary fiber), productivity and long yield life of approximately one hundred years (Botes & Zaid, 2002; Al-Shahib & Marshall, 2003; Eshraghi *et al.*, 2005; Chao & Krueger, 2007b; Khayyat *et al.*, 2007; Mahmoudi & Hosseininia, 2008; Tengberg, 2011; Kassem, 2012; Reilly & Reilly, 2012). Date palm is adapted to both arid and semi-arid conditions and needs distinct climatic conditions, including prolonged summer heat without rain or humid weather, to produce commercially viable fruit (Jain *et al.*, 2011b). For instance, the overall heat necessity scales from 4000 to over 4500 degree-days, a calculation based on the summation of the number of degrees of daily mean temperature above 18 degrees Celsius (Rahnema, 2013). Dates require deep soils since 85

percent of their roots are distributed within a 2m depth and 25m distance from tree trunk in loamy soil (Zaid & De Wet, 1999). Depending on growth circumstances, yield per palm, amount of spikelets per bunch and number of fruits per spikelet are approximately 100, 30 and 7 kilograms respectively.

Long-term management strategies to sustain economically important crops require information about the expected potential distribution and relative abundance of this plant under current and future climate scenarios. There are several distribution models that can provide information in this area, including species distribution models (SDMs), bioclimatic models and ecological niche models (ENMs). However, it has been reported that niche models only enable estimates of a species' fundamental niche (Soberon & Peterson, 2005) while other reports show that it provides a spatial image of the realized niche (Guisan & Zimmerman, 2000; Pearson & Dawson, 2003).

CLIMEX has been widely used in many different applications (Kriticos & Randall, 2001). Taylor *et al.* (2012a) used CLIMEX for illustrating the potential distribution of *Lantana camara L.* by 2070. Yonow and Sutherst (1998) employed CLIMEX for mapping the distribution of the Queensland fruit fly. Sutherst and Floyd (1999) applied the same software for modular modeling of pests. The susceptibility of both animal and human health to parasites under future climates has also been studied using CLIMEX (Sutherst, 2001).

As a consequence of climate change, the distribution of species like date palm will change (McMichael *et al.*, 2003). It is essential to identify which regions will benefit by having the potential opportunity of cultivating date palms in the future and which may be adversely affected. Governments and agricultural organizations can prepare for this situation in advance and thereby gain significant economic advantages which can enable them to improve their economies. Alternately, regions that could be adversely affected can become aware of the

situation and transition their economies. This awareness provides an opportunity to plan for alternative sources of income. With this aim, this study made use of the CLIMEX software package in developing a global model of the climate response of *P. dactylifera* based on its native and cultivated distribution. This model was then used to illustrate date palm potential distribution using two global climate models (GCM) including CSIRO-Mk3.0 and MIROC-H. These were run with the A2 SRES (Special Report on Emissions Scenarios) emission scenarios for 2030, 2050, 2070 and 2100. The A2 SERS was chosen with the assumption that, in the future, there would be high population growth coupled with slow economic growth and extensive technological change.

PROCEDURE

CLIMEX SOFTWARE

CLIMEX is a modeling software package that basically operates on an eco-physiological growth model that assumes that species encounter favorable and unfavorable seasons. Growth is maximized during favorable seasons and minimized during unfavorable seasons (Sutherst & Maywald, 1985; Sutherst *et al.*, 2007). CLIMEX enables the user to deduce different parameters that illustrate the species' geographic reaction to climatic factors (Sutherst & Maywald, 2005). A major criticism of CLIMEX is that it does not include biotic interactions and dispersal in the modeling process. However, other factors may be incorporated after the CLIMEX modeling has been performed using GIS and RS software (Davis *et al.*, 1998). The key assumption behind CLIMEX is that climate is the main determinant of the distribution of plants and poikilothermal animals (Kriticos *et al.*, 2007). CLIMEX enables the user to infer parameters that describe the species' response to climate based on its geographic range or phenological observations (Sutherst *et al.*, 2007). The Ecoclimatic Index (EI) is a general annual index of climatic suitability based on weekly calculations of growth and stress indexes.

It is scaled from 0 to 100, and theoretically, species can establish if $EI > 0$. In CLIMEX, the annual growth index (GI_A) describes the potential for population growth during favorable climate conditions. The GI_A index is determined from the temperature index (TI) and moisture index (MI) which represent the species' temperature and moisture requirements for growth. The user can describe the probability of survival of the species during unfavorable conditions using four stresses: cold, heat, dry and wet. Therefore, based on available data, this software was used to develop a model of the potential distribution of *P. dactylifera* under current and different future climate scenarios.

DISTRIBUTION OF DATE PALMS (*P. DACTYLIFERA*)

The Global Biodiversity Information Facility (GBIF) (2015b) was used to gather information on *P. dactylifera* distribution and this information was supplemented by other date palm literature (Auda & Khalaf, 1979; Heakal & Al-Awajy, 1989; Abbas *et al.*, 1991; Elhoumaizi *et al.*, 2001; Eshraghi *et al.*, 2005; Hasan *et al.*, 2006; Saadi *et al.*, 2006; Mahmoudi & Hosseininia, 2008; Bokhary, 2010; Markhand, 2010a; Shayesteh & Marouf, 2010; Al-Senaidy *et al.*, 2011; Jain *et al.*, 2011b; Marqués *et al.*, 2011; Tengberg, 2011; Global Biodiversity Information Facility, 2015a). Records were geographically representative of the known distribution of date palms in Oman as shown in Figure 3.

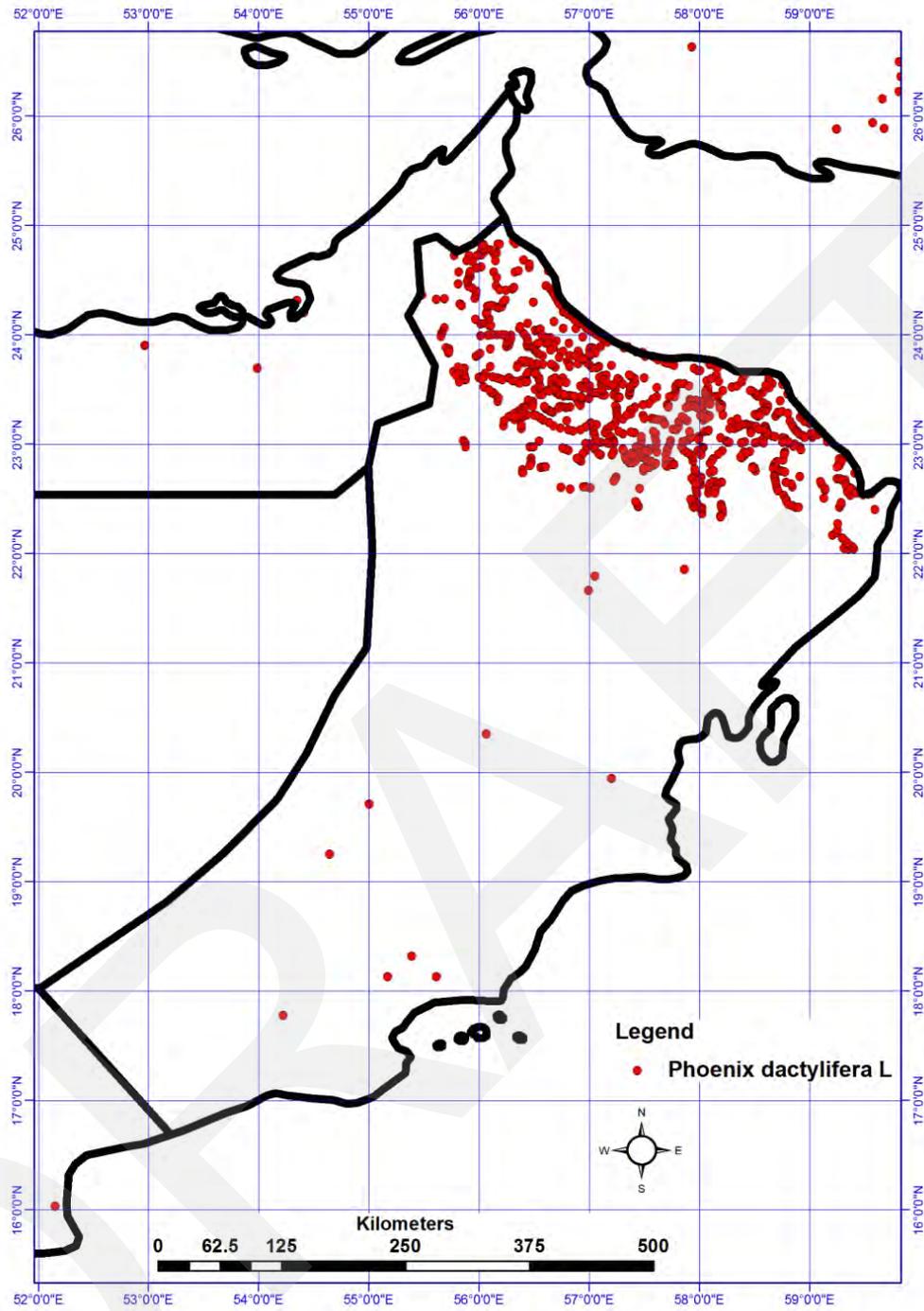


Figure 3- The current distribution of *P. dactylifera* in Oman based on GBIF and other sources

CLIMATE DATA, CLIMATE MODELS AND CLIMATE SCENARIOS

A set of forty emissions scenarios for future global emissions of greenhouse gases and sulphate aerosols, the so-called SRES scenarios was established by the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic *et al.*, 2000). Each of these scenarios depicts a ‘storyline’ created from a set of arguable assumptions about global demographic, economic and technological factors, which are considered as having impact on future emissions. The IPCC chose a representative sub-set of six illustrative marker scenarios, ranging from the B1 scenario based on rapidly diminishing greenhouse gas emissions, to the A1FI scenario, in which fossil fuels continue to be used at an intensive level. Rahmstorf *et al.* (2007) have shown since then that projections from GCMs generally underestimated more recent global temperature and sea level trends. Manning *et al.* (2010) have illustrated even more recently, that since 2000, fossil fuel carbon dioxide emissions match the most extreme of the SRES scenarios. Combining such observations, with the continued failure to achieve agreement on legally binding global reductions in greenhouse gas emissions suggests that these conservative emissions scenarios have no further validity. In this light, only ‘A’ family SRES emissions scenarios in the CliMond dataset have been included (Kriticos *et al.*, 2012). We chose the A2 SRES scenario on the basis that it includes relevant demographic variables, as well as financial and technological factors, relating to greenhouse gas (GHG) emissions. Its assumptions include both demographic and regional economic development data drawn from independent and self-reliant nations (Intergovernmental Panel on Climate Change, 2007). The predictions of A2 scenario depict a relatively moderate increase in GHG, clustered around the midpoint of extreme low and high projections. In this study, the CliMond 10’ gridded climate data were used for modeling (Kriticos *et al.*, 2011). Five climatic variables were utilized to represent historical climate (averaging period 1950–2000). These were average minimum monthly temperature (Tmin), average maximum monthly temperature (Tmax), average monthly precipitation (Ptotal) and

relative humidity at 09:00 h (RH09:00) and 15:00 h (RH15:00). These variables were also used to typify potential future climate in 2030, 2050, 2070 and 2100. The potential distribution of date palms under future climate was modeled using two Global Climate Models (GCMs), CSIRO-Mk3.0 (Kriticos *et al.*, 2011) and MIROC-H (Center for Climate Research, Japan), with the A2 SRES scenario (Gordon *et al.*, 2002; Kriticos *et al.*, 2011; Intergovernmental Panel on Climate Change, 2014). These two GCMs were part of the CliMond dataset and were selected from 23 GCMs based on the following criteria:

- All required variables, including temperature, precipitation, sea level pressure and humidity for CLIMEX were available
- Small horizontal grid spacing in both GCMs
- Better representation of observed climate at local scales, compared to the other GCMs (Hennessy & Colman, 2007).

In the remainder of this paper, MR and CS are used as the abbreviation of MIROC-H and CSIRO-Mk3.0, respectively.

The MR model predicts that temperature will increase by approximately 4.31°C, while the CS model predicts a rise of 2.11°C by 2100. There are also differences in rainfall patterns for CS and MR models. For example, the CS model predicts a 14% decrease in future mean annual rainfall, whereas the MR model predicts a 1% decrease (Suppiah & Hennessy, 2007; Chiew *et al.*, 2009).

The A2 scenario was selected to characterize one of the possible climate scenarios during 2030, 2050, 2070 and 2100. The A2 scenario covers different factors including demographic, economic and technological forces driving GHG emissions; this scenario assumes neither very high nor low global GHG emissions compared to the other scenarios, such as A1F1, A1B, B2, A1T, B1 by 2100 (Suppiah & Hennessy, 2007).

No scenarios from the B family of SRES scenarios were included in this paper, mainly because of the observation that some parameters such as global temperature and sea level rise are presently increasing at a much greater rate than predicted by the hottest SRES scenarios (Rahmstorf *et al.*, 2007).

FITTING CLIMEX PARAMETERS

Using both native habitat range and agricultural distribution data in parameter fitting is highly recommended because it produces a model that approximates the potential distribution of the taxa being modeled (Kriticos & Leriche, 2010). This is because the limitations imposed by biotic influences in the species' native range may be absent in non-native locations, thus allowing it to expand its range beyond its realized Hutchinsonian niche (Sutherst, 2003; Kriticos & Leriche, 2010). In this study, parameters were fitted using the native range and the global agricultural distribution of date palms. However, the distribution data of *P. dactylifera* from North America, Mexico, and the Caribbean were not used in parameter fitting as this was set aside for model validation. The parameters were iteratively adjusted depending on satisfactory agreement between the potential and known worldwide distribution of *P. dactylifera*. The parameters were subsequently verified to ensure that they were biologically reasonable. Model validation was conducted using North American, Mexican, and Caribbean distribution data. It should be highlighted that the threshold parameters do not have a unit, while the accumulation rates use the week⁻¹ unit.

COLD STRESS

The cold stress temperature threshold (TTCS) mechanism was used to describe the species' response to frost. Generally, the minimum winter temperature that can be tolerated by *P. dactylifera* is 10°C (Elshibli *et al.*, 2009a). However, date palms have been recorded in locations as low as 4°C (Global Biodiversity Information Facility, 2015b). Therefore,

intolerance to frost was incorporated by accumulating stress when the average monthly minimum temperature fell below 4°C, with the frost stress accumulation rate (THCS) set at – 0.01 week⁻¹. This cold-stress mechanism allowed the species to survive in Spain (39° 635' N and 2° 523' W) (Global Biodiversity Information Facility, 2015a). Additionally, this value provided an appropriate fit to the observed distribution in South America, South Africa and Asia.

HEAT STRESS

The heat stress parameter (TTHS) was set at 46°C because it was reported that *P. dactylifera* is able to persist up to this temperature in eastern Pakistan (Global Biodiversity Information Facility, 2015a). The heat stress accumulation rate (THHS) was set at 0.9 week⁻¹, which allowed *P. dactylifera* to persist along eastern Pakistan (Hasan *et al.*, 2006; Markhand, 2010b; Kriticos *et al.*, 2011) and southern Iran (Shayesteh & Marouf, 2010; Tengberg, 2011; Global Biodiversity Information Facility, 2015a).

DRY STRESS

The term 'drought' refers to a period of time without significant rainfall (Jain *et al.*, 2011b). Water stress occurs as a consequence of water loss through transpiration or evaporation during a period of time when there is a lack of available water in the soil (Jain *et al.*, 2011b). Different degrees of water stress can be seen in a plant. When water loss is prolonged, a significant disruption in the metabolism of the plant occurs (Jain *et al.*, 2011b). However, the date palm has developed a number of strategies to prevent dry stress. These include maintaining a high level of hydration, the ability to function while dehydrated, increasing the amount of water absorption (i.e., keeping a high level of osmotic pressure) by using abscisic acid, and by the development of an extensive root system (Jain *et al.*, 2011b). Dry stress was not used in this study for the above reasons.

WET STRESS

August to October are the critical months when rain damage can inflict serious economic damage to the date crop (Elshibli *et al.*, 2009a). A recent study observed that a total of 78.74 mm of rainfall during an 8-day period caused a greater than 50% loss in date palm yields while 86.36 mm of rainfall in 10 days led to 15% losses in date palm farms in some countries (Elshibli *et al.*, 2009a). Date palms are known to suffer wet stress easily. The wet stress threshold (SMWS) was set to 0.9 and the accumulation rate (HWS) set at 0.022 week⁻¹ to allow the species to grow well in arid and semi-arid regions such as Algeria, Morocco, and southern Iran.

TEMPERATURE INDEX

P. dactylifera has been cultivated in areas with a mean annual surface temperature greater than 16°C, such as southern Iran (Tengberg, 2011; Global Biodiversity Information Facility, 2015a), south-eastern Iraq, eastern Pakistan (Hasan *et al.*, 2006; Elshibli *et al.*, 2009a), and northern and central Algeria (Saadi *et al.*, 2006; Elshibli *et al.*, 2009a). Western Pakistan's climatic parameters are comparable to other places suitable for date palm cultivation with the exception of its annual surface temperature, which is 13°C. Thus, the limiting low temperature (DV0) should be between 13°C and 16°C. Fourteen degrees Celsius was selected due to providing the best fit to the observed distribution of date palms in North Africa and Asia. Summer temperatures in locations which are highly climatically suitable for this species rarely exceed 46°C, thus the limiting high temperature DV3 was set at 46°C (Burt, 2005a). The lower (DV1) and upper (DV2) optimal temperatures were set at 20°C and 39°C, respectively, because temperatures between 20°C and 39°C are cited as favorable temperatures for date palm, depending on the varieties (Jain *et al.*, 2011b). These numbers also provided the best fit to the observed distribution in South America, Asia, South Africa and Australia (Elshibli *et al.*, 2009a).

MOISTURE INDEX

In terms of soil moisture, the lower moisture threshold (SM0) was set at 0.007, to represent the permanent wilting point (Kriticos *et al.*, 2007). Furthermore, this number provided a good fit to the observed distribution of date palms in South America, Asia and the Middle East. The lower (SM1) and upper (SM2) optimum moisture thresholds were set at 0.013 and 0.81, respectively, to improve species growth in Cuba, Egypt, Saudi Arabia, Iran, India, and some countries in Africa (Elshibli *et al.*, 2009a). The upper soil moisture threshold (SM3) was set at 0.9 because this species and its fruit can be negatively affected by high soil moisture (Elshibli *et al.*, 2009a). Additionally, this value provided an appropriate fit to the observed distribution. All CLIMEX parameters are summarized in table 1.

Table 1- CLIMEX parameter values used for *L. dactylifera* modeling

Parameter	Mnemonic	Values
Limiting low temperature	DV0	14°C
Lower optimal temperature	DV1	20°C
Upper optimal temperature	DV2	39°C
Limiting high temperature	DV3	46°C
Limiting low soil moisture	SM0	0.007
Lower optimal soil moisture	SM1	0.013
Upper optimal soil moisture	SM2	0.81
Limiting high soil moisture	SM3	0.9
Cold stress temperature threshold	TTCS	4°C
Cold stress temperature rate	THCS	-0.01 week ⁻¹
Heat stress temperature threshold	TTHS	46°C
Wet stress threshold	SMWS	0.9
Wet stress rate	HWS	0.022 week ⁻¹
Heat stress accumulation rate	THHS	0.9 week ⁻¹

OUTCOMES

CURRENT CLIMATE

The present distribution of native and cultivated *P. dactylifera* is illustrated in Figure 3. A comparison between the modeled climate appropriateness (Figure 4) with the recognized

distribution of this species showed that there was a good match between the Ecoclimatic Index resulting from the CLIMEX model and the current distribution of *P. dactylifera*. The modeled results indicated that the Oman has suitable climatic conditions for *P. dactylifera* and there was a reasonably good fit between the model predictions and the actual recorded distribution data.

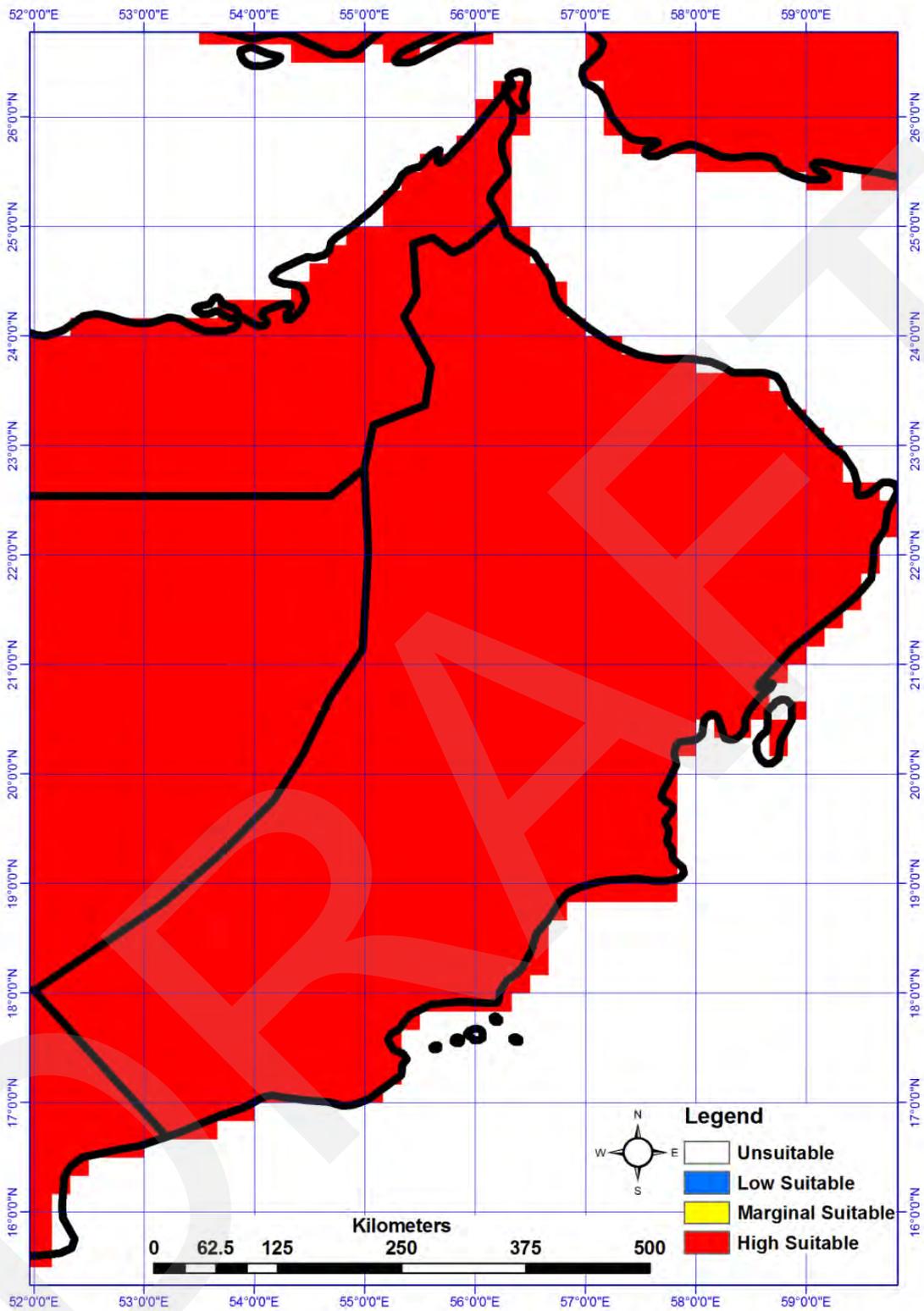


Figure 4- The Ecoclimatic Index for *P. dactylifera*, modeled using CLIMEX for current climate.

FUTURE CLIMATE

The results of the two global climate change models (GCMs) including CSIRO-Mk3.0 (CS) and MIROC-H (MR) with the A2 emission scenarios for the potential distribution of *P. dactylifera* for 2030, 2050, 2070 and 2100 are illustrated in Figures 5 to 12.

RESULTS FROM CS MODEL

In Oman (Figure 5), the CS GCM projected eastern and southern country will remain climatically suitable for *P. dactylifera* by 2030. However, the CS model predicted that regions between 18°N to 22°N and 53°E to 56°E become progressively less suitable by 2030, 2050, 2070 and 2100 (Figures 6-8). It should be mentioned that the CS GCM for Oman indicated that western regions (21 to 24°N and 54 to 56°E) are totally unsuitable by 2100 (Figure 8). Thus, this model projected that there was a considerable reduction in climate suitability for date palms between 2070 and 2100.

RESULTS FROM MR MODEL

From the MR GCM (Figures 9-12), it can be seen that the Oman is projected to become climatically less suitable for date palms between 2050 and 2100 (Figure 10-12). It should be mentioned that the MR GCM projected that by 2100, regions between 18°N to 23°N and 53°E to 57°E would become climatically unsuitable for date palm cultivation (Figure 12).

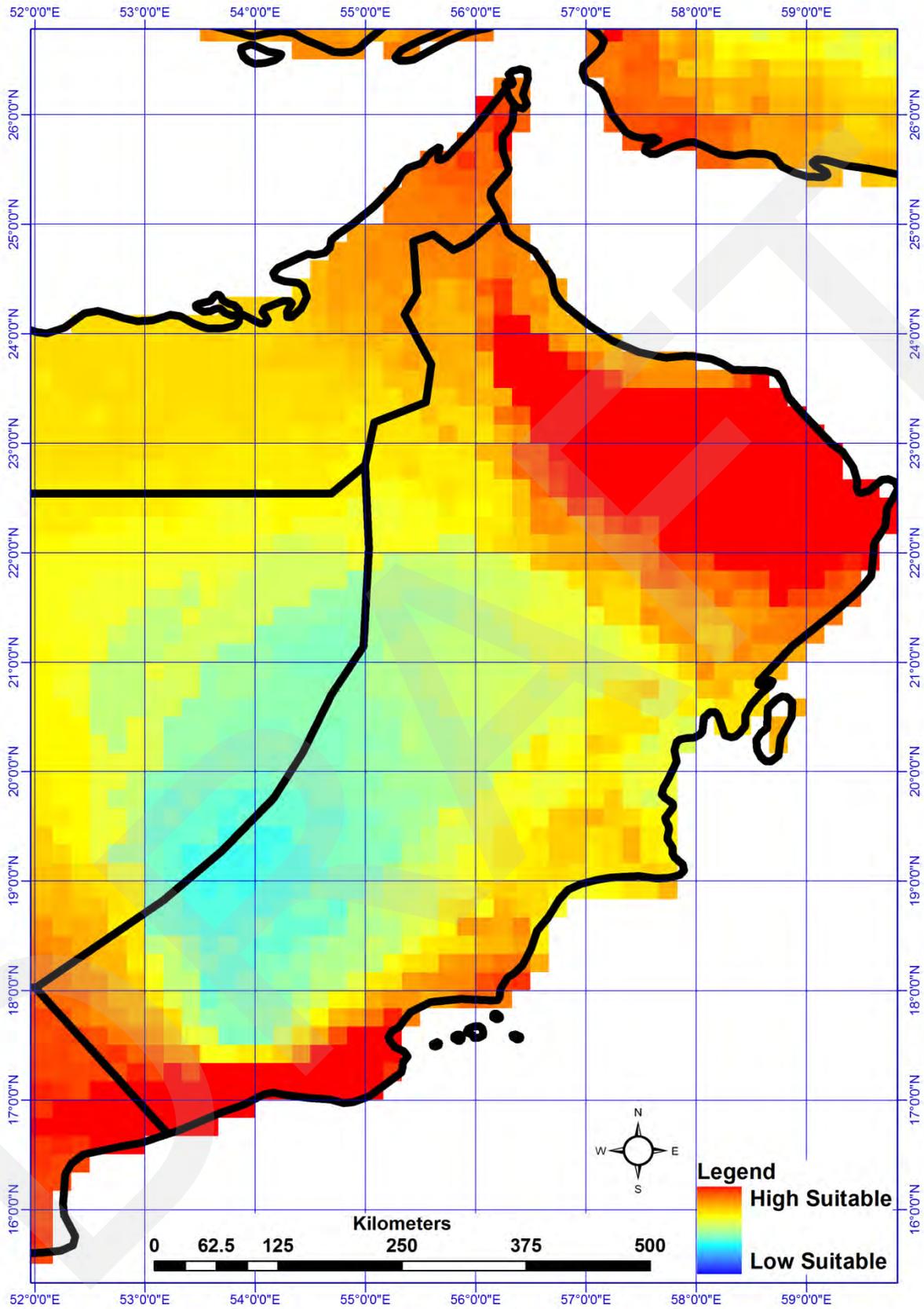


Figure 5- The stretched climate suitability (EI) for *P. dactylifera* under the CSIRO-Mk3.0 GCM running the SRES A2 scenario and for 2030.

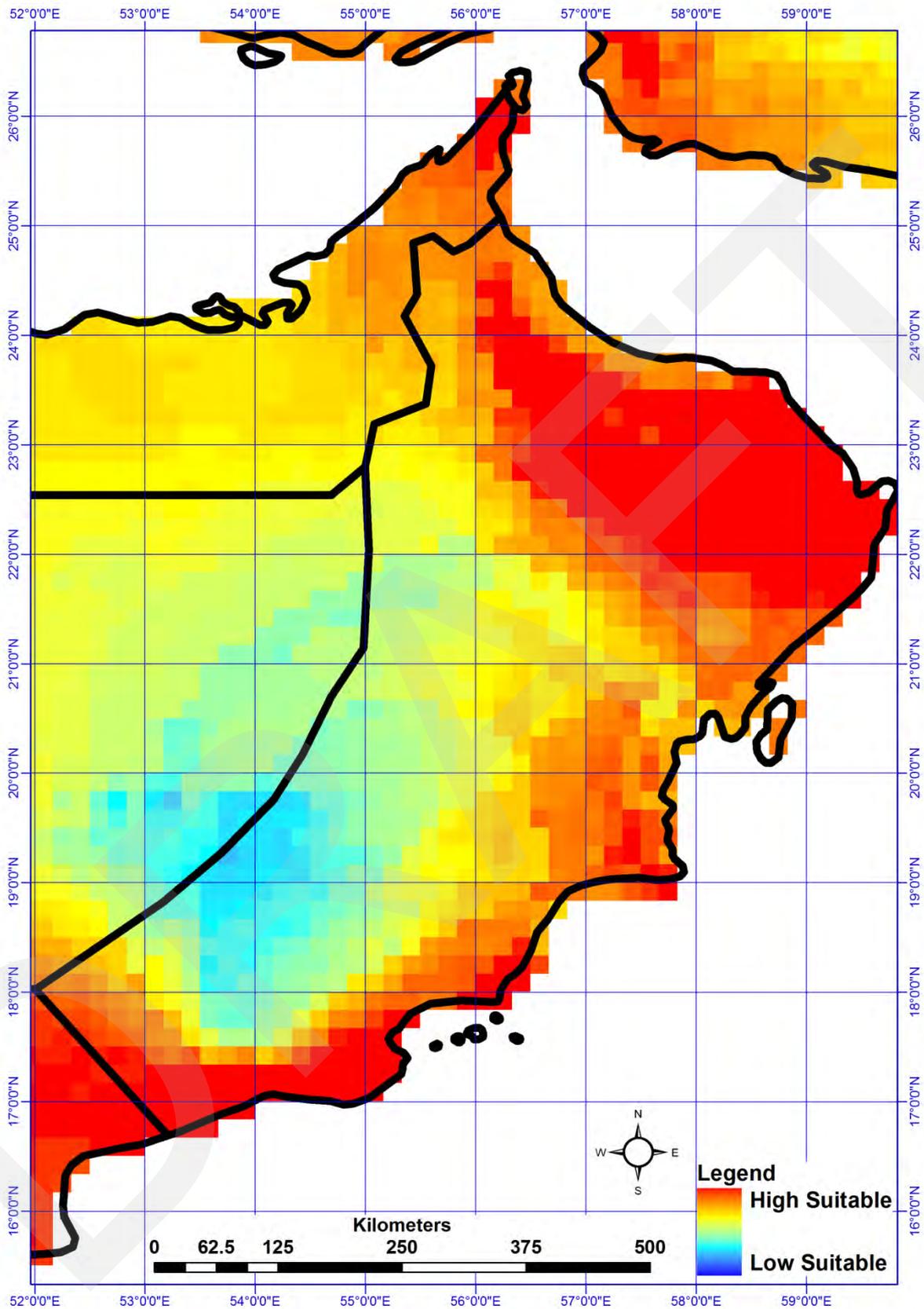


Figure 6- The stretched climate suitability (EI) for *P. dactylifera* under the CSIRO-Mk3.0 GCM running the SRES A2 scenario and for 2050.

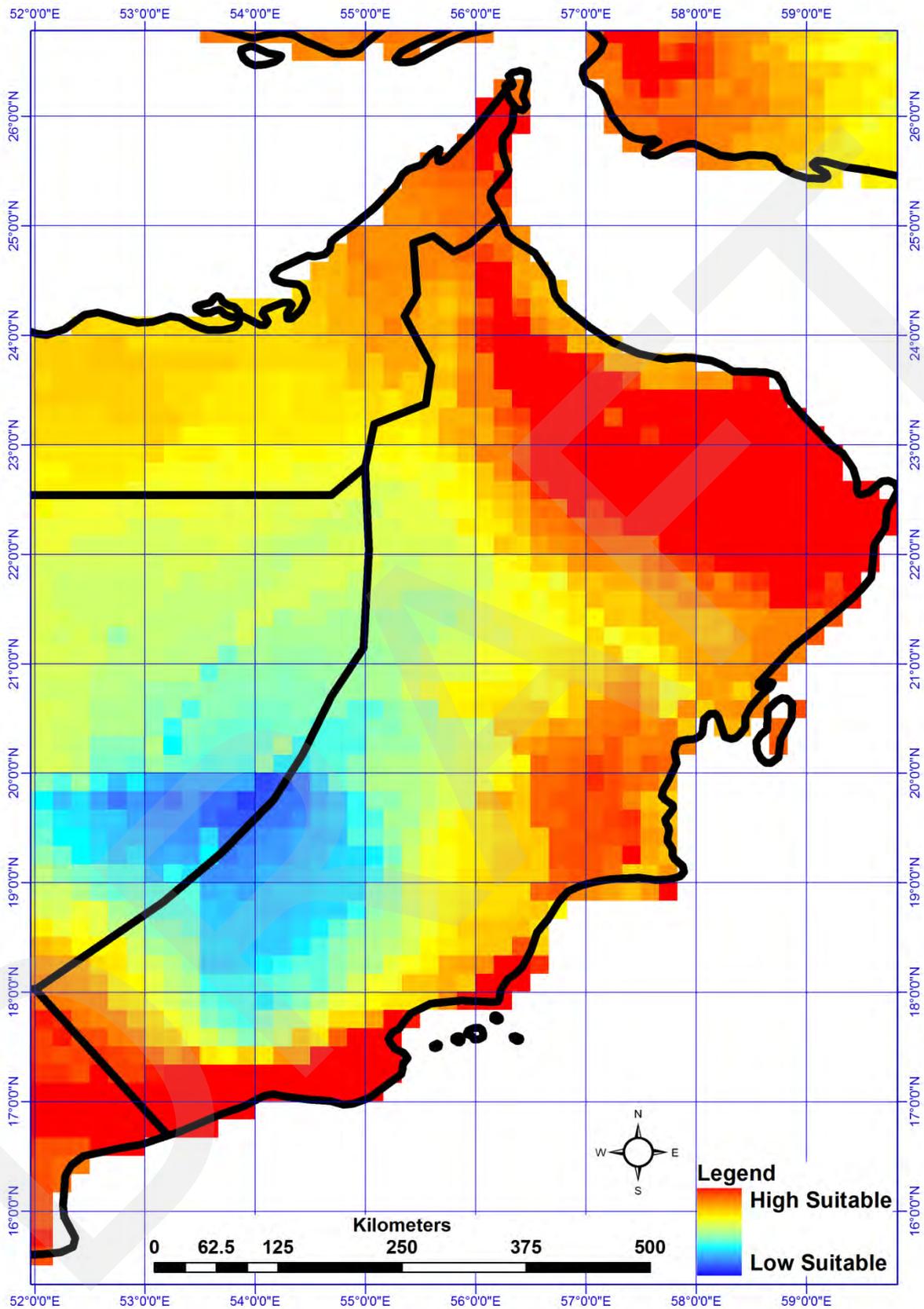


Figure 7- The stretched climate suitability (EI) for *P. dactylifera* under the CSIRO-Mk3.0 GCM running the SRES A2 scenario and for 2070.

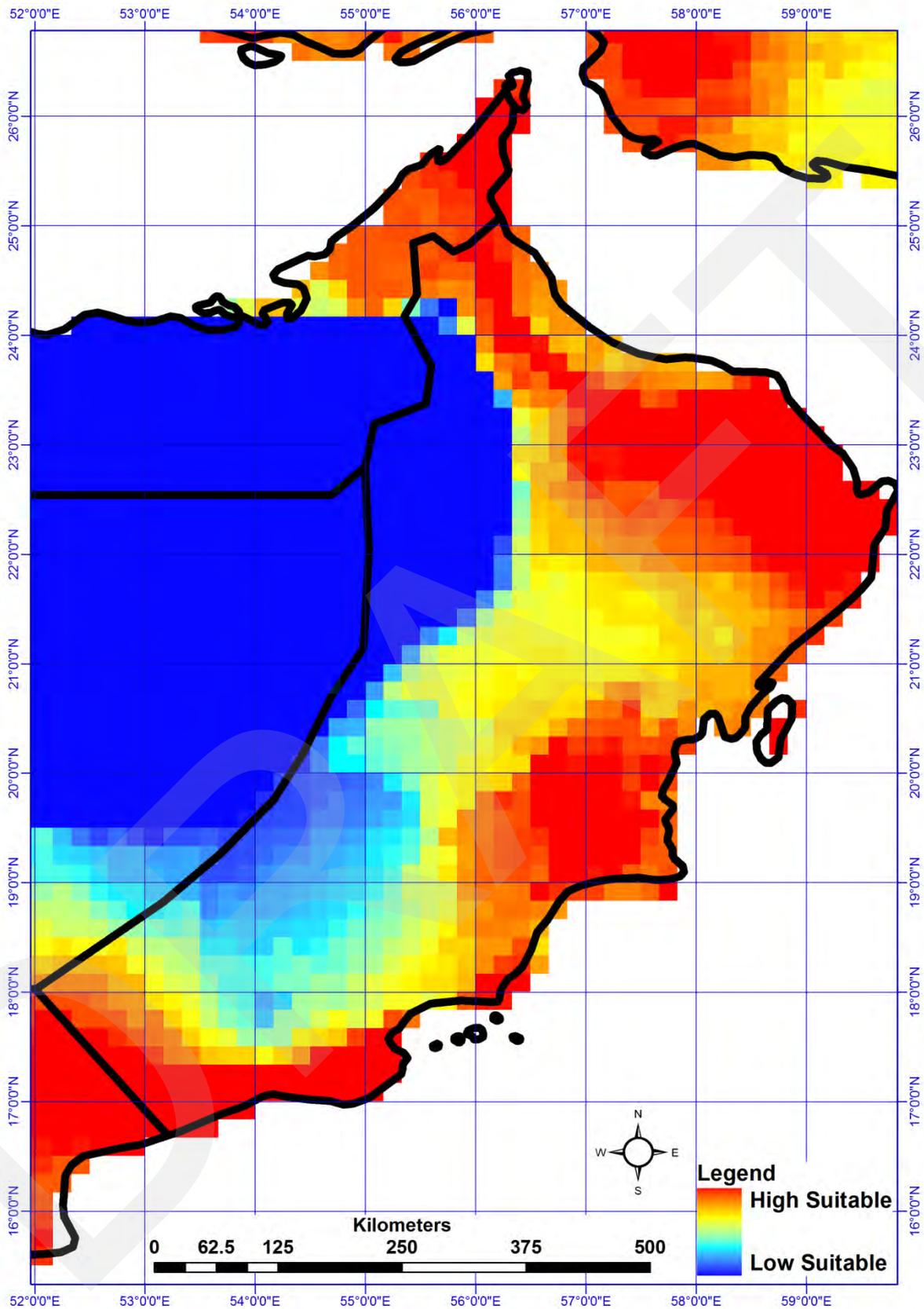


Figure 8- The stretched climate suitability (EI) for *P. dactylifera* under the CSIRO-Mk3.0 GCM running the SRES A2 scenario and for 2100.

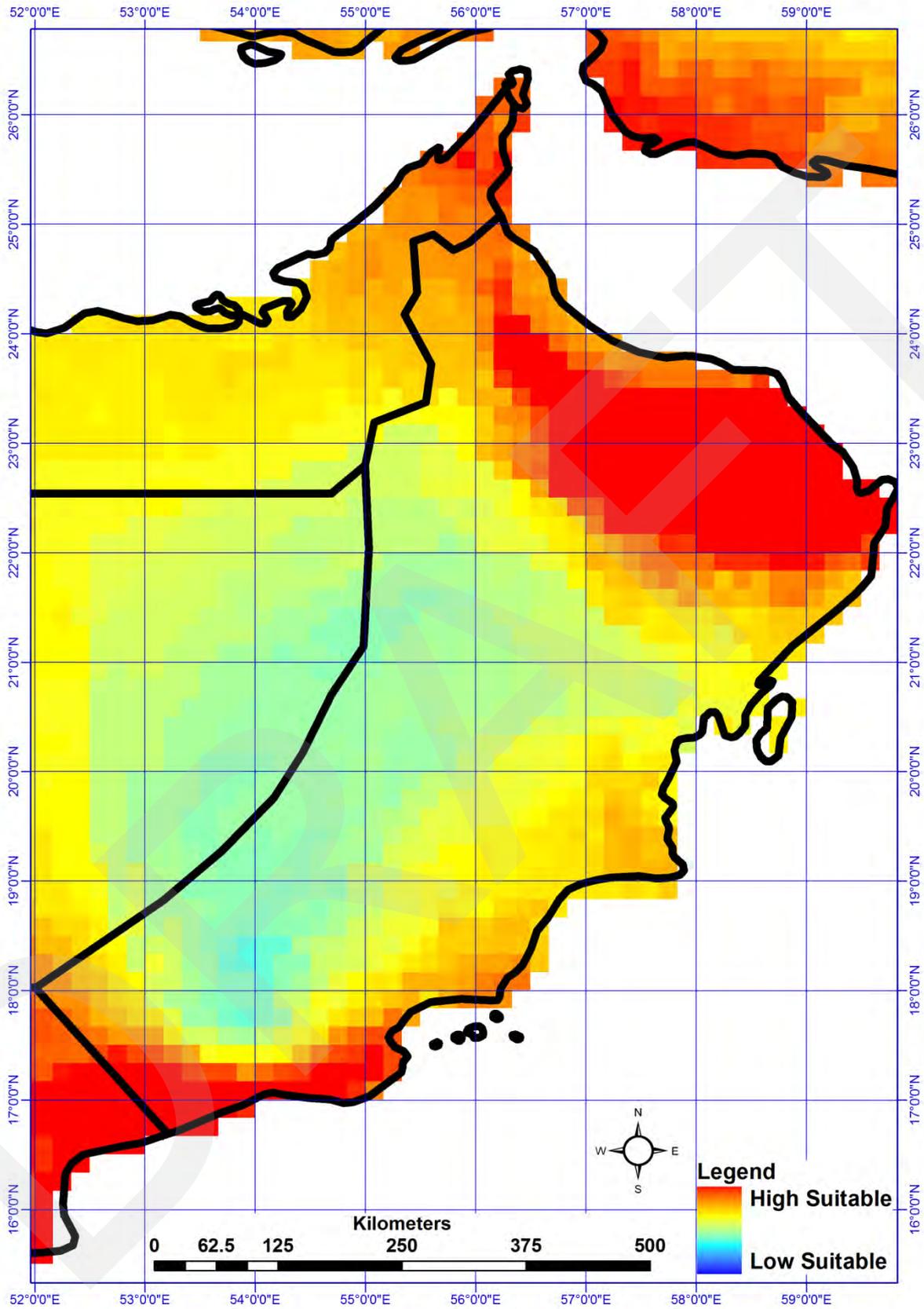


Figure 9- The stretched climate suitability (EI) for *P. dactylifera* under the MIROC-H GCM running the SRES A2 scenario and for 2030.

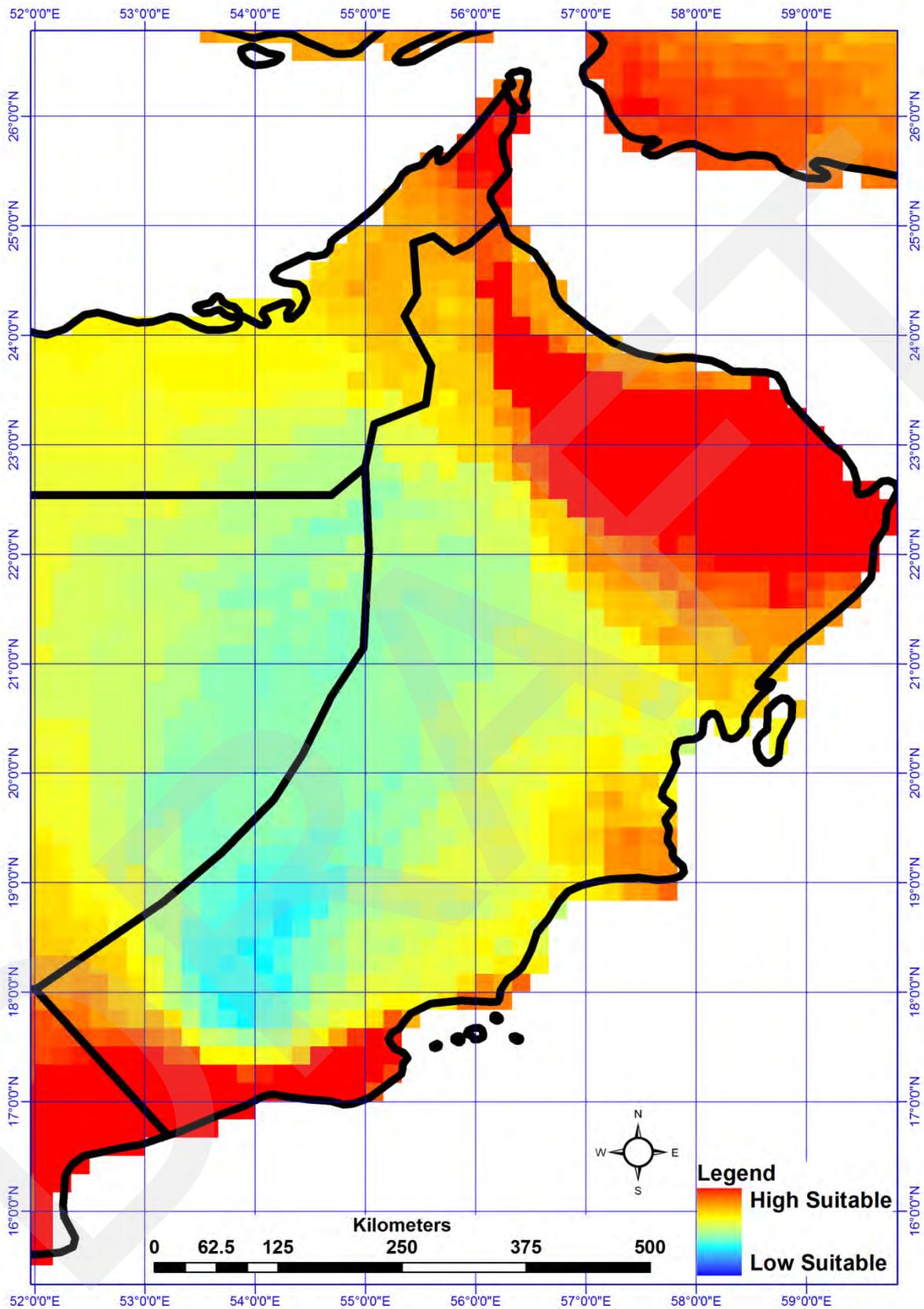


Figure 10- The stretched climate suitability (EI) for *P. dactylifera* under the MIROC-H GCM running the SRES A2 scenario and for 2050.

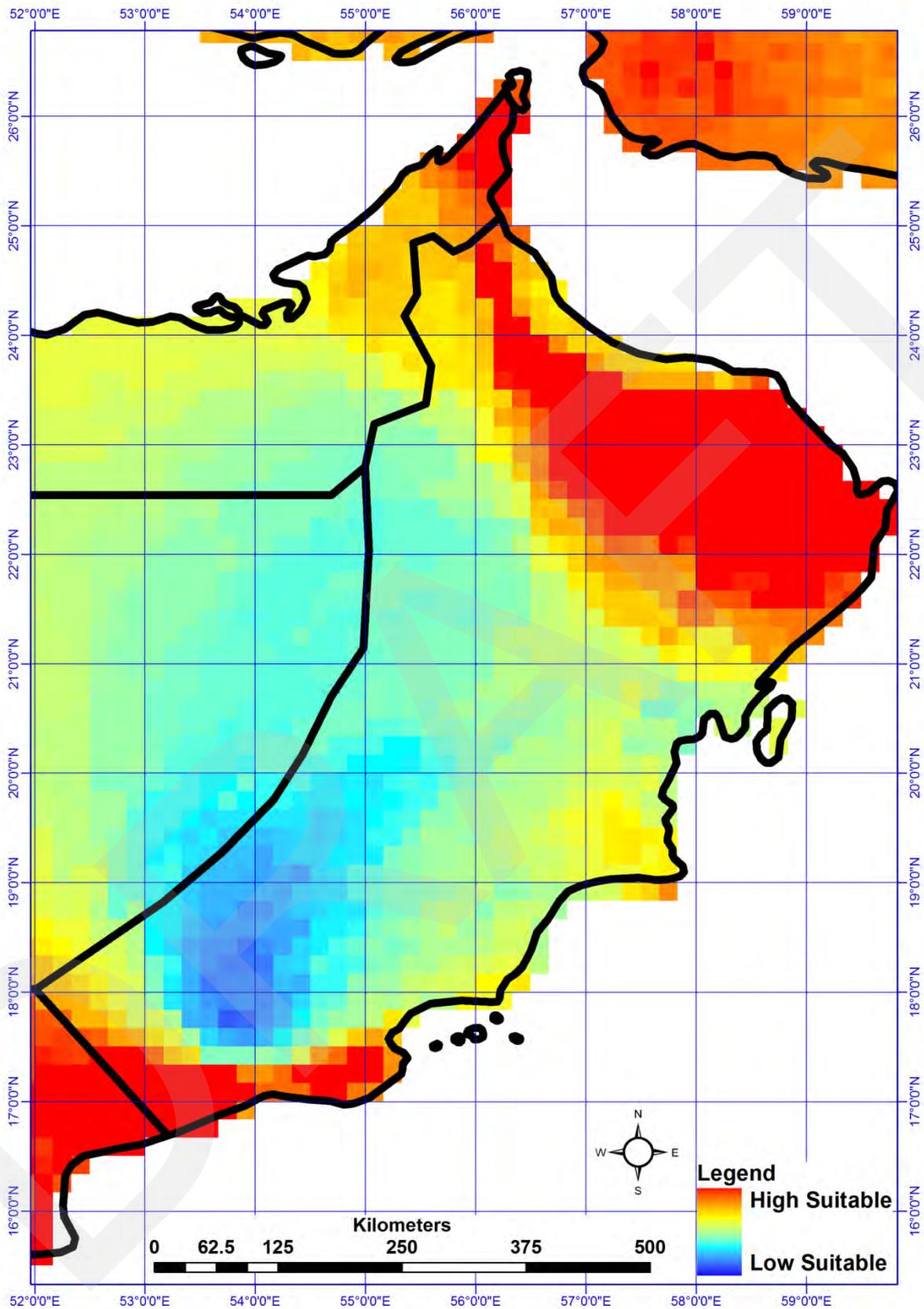


Figure 11- The stretched climate suitability (EI) for *P. dactylifera* under the MIROC-H GCM running the SRES A2 scenario and for 2070.

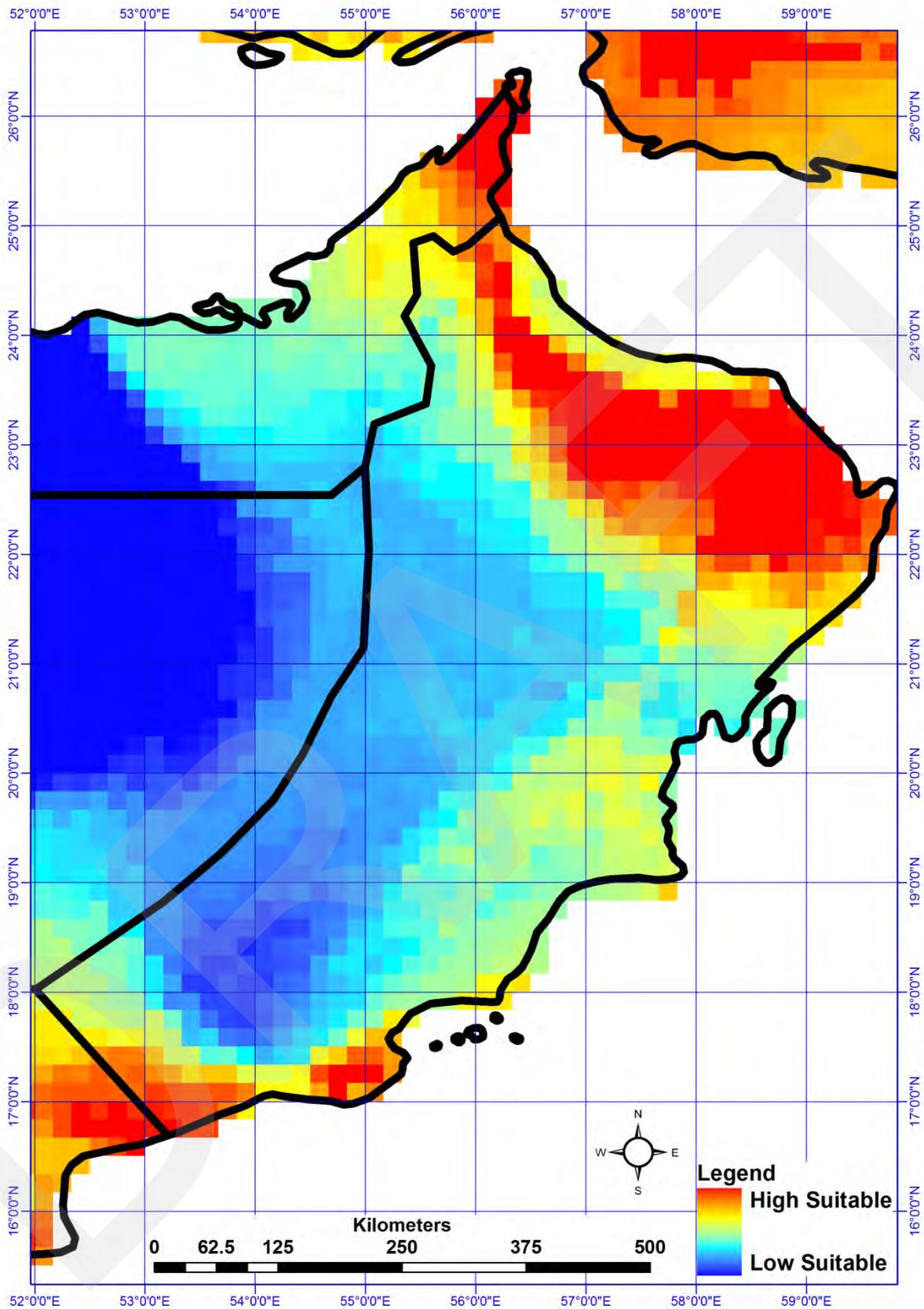


Figure 12- The stretched climate suitability (EI) for *P. dactylifera* under the MIROC-H GCM running the SRES A2 scenario and for 2100.

DISCUSSION

Suitable climatic areas for *P. dactylifera* under present and future climate scenarios using CLIMEX were modeled for Oman. The differences in the outcomes from the two GCMs emphasize the uncertainties associated with the state of climate modeling associated with greenhouse emission patterns (Jain *et al.*, 2011b). It is clear that different models may produce different results. For example, the MR model predicts that temperature will increase approximately 4.31°C, while the CS model predicts a rise of only 2.11°C by 2100. From the rainfall perspective, some differences can be found between the MR and CS models. For example, the CS model predicts a 14% decrease in future mean annual rainfall, whereas the MR model predicts a 1% reduction (Suppiah & Hennessy, 2007; Chiew *et al.*, 2009). It should also be highlighted that suitability projections are only potential distributions based on climatic factors and not predicted future distributions (Jain *et al.*, 2011b). Thus, it is highly recommended that any projection of future suitable areas based on CLIMEX also should incorporate non-climatic factors such as land-use type, soil type, soil drainage and soil-nutrients (Elshibli *et al.*, 2009a).

Here, our model provided a good fit to the present global distribution records of date palm in Oman. In this study, both CS and MR GCMs projected that in Oman, some regions will become less climatically suitable towards 2100. However, the CS GCM projected western Oman becoming more unsuitable than the MR GCM by 2100 due the projection of a greater increase in temperature and smaller decrease in the amount of rainfall in the MR GCM (Suppiah & Hennessy, 2007; Chiew *et al.*, 2009). A comparison between these two models also indicated that, based on the CS GCM, more regions in Central Oman may be less suitable for date palm growth compared to the MR projection (Figures 2-4 and 2-7).

A comparison between the results of CS and MR GCM for Oman indicated that *P. dactylifera* suitability ranges appeared to increase in Eastern cites the future. However, the CS GCM projected that most western regions may be climatically unsuitable by 2100, but, based on MR GCM, this suitability may be limited to the eastern and northern regions due to an increase in some stresses in central and western Oman (Figures 8 and 12).

There were some agreements and disagreements in projection of suitable areas for date palm growth in Oman between CS and MR GCMs. For example, both models projected that northern and western Oman may remain climatically suitable for *P. dactylifera* growth by 2100. Furthermore, both models projected that western Oman may become unsuitable for this species. On the other hand, the CS model projected that by 2100, western regions may become unsuitable for date palm growth since the MR model projected that same regions may remain climatically less suitable for date palms growth by 2100 (Figures 8 and 12).

The results of the climate change modeling provide an indication of the possible change in the potential future distribution of *P. dactylifera*. As the climate changes, some areas where *P. dactylifera* currently occurs may become climatically unsuitable, and as a consequence, the economies in those areas may decline. However, preliminary studies indicate that large areas of Algeria and Saudi Arabia may become climatically unsuitable and may not be able to cultivate this profitable crop to the same extent in the future. Consequently, the results of this report provides some advance awareness of how productivity may change and affect national economics. Furthermore, by making some strategic plans, many economic disadvantages can be prevented. This information is particularly important for Oman.

CONCLUSION

These illustrated maps (Figs 5 to 12) could be used by agricultural organizations in Oman to make strategic, long-term plans. This may include research into alternative crops in areas where climate will become unfavorable for date palms.

In interpreting these results, the following should be considered:

- The modeling was performed based only on climate;
- This research was based on currently available climate data;
- It is indicative because a certain level of uncertainty is associated with future levels of greenhouse gas emissions;
- It does not take into consideration other factors such as land uses, soil types, biotic interactions, diseases, competition.

In conclusion, this research has demonstrated shifts in areas conducive to date palm cultivation and how different areas of Oman may be affected due to climate change based on climate change over the next hundred years.

IN THE NEXT REPORT:

1. We will identify the reasons of why some regions in Oman are projected to become unsuitable for date palm cultivation as it could be a consequence of only one stress for date palm growth, such as wet, hot, dry, cold stress or it is the consequences of a combination of multiple stresses. Such modeling is useful in planning future strategies and minimizing economic impacts in areas that may be adversely impacted, while preparing to take advantage of new opportunities in regions that may be positively impacted.

2. We will identify the risk levels of one of the most important fungus of date palm in response to climate change in Oman.
3. Depending on availability of non-climatic data such as land use, soil type and water, the results shown in this document will be refined.

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