Chapter 6 — The effect of climate change on the distribution of Citrus Black Spot in South Africa

6.1 Abstract

Citrus Black Spot (CBS) is a fungal disease of citrus caused by *Guignardia citricarpa* Kiely. It occurs in most of the citrus growing areas of South Africa, but not in the cultivation areas of the Western and Northern Cape provinces. The objective of this study is to estimate the risk that the citrus growing areas of these provinces will become climatically suitable for CBS under climate change. The potential future distribution of the CBS pathogen was modelled using the software program CLIMEX. Several climate change scenarios were analysed: temperatures were increased by 1.5–3.5°C, and precipitation was either increased or decreased by 10%. Additionally, the influence of changes in temperature or changes in rainfall alone was also investigated. In most of the scenarios, some localities in the Western Cape became suitable for CBS establishment, but localities in the Northern Cape always remained unsuitable for CBS. This information can support the South African Citrus Industry in decision making and planning processes. Despite the importance of the impacts of climate change on plant pathogens, not much research is being done in this field. This study highlights the use of bioclimatic modelling to explore the potential impacts of climate change on the distributions of plant pathogens.

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6.2 Introduction

Citrus Black Spot (CBS) is an economically important fungal disease caused by *Guignardia citricarpa* Kiely (Brodrick, 1969; Kiely, 1948), which may cause superficial lesions on the rind of citrus fruit (Kotzé, 1981; Snowdon, 1990). Almost all commercially cultivated citrus species are susceptible to CBS (Kiely 1948; Kotzé, 2000), but Persian limes (Timmer, 2005, Personal Communication), and sour orange and its hybrids are resistant (Kotzé, 1981).

Citrus Black Spot has been recorded in various countries, including major citrus producers like Australia, Brazil and China (European Union, 1998). In South Africa, it was recorded for the first time in 1929 from an area close to Pietermaritzburg. At the time it was not seen as an economically important disease (Doidge, 1929). Diseased citrus material has since been reported from Kwazulu-Natal, Mpumalanga, Limpopo Province, North-Western Province (Kellerman, 1976), Gauteng and the Eastern Cape (Kotzé, 2004, Personal Communication). However, it has not been reported from any citrus growing area of the Northern (le Roux, 2004, Personal Communication; Mabiletsa, 2003a; USDA/APHIS, 2002) or Western Cape Provinces (European Union, 1998; Kellerman, 1976; Venter et al., 1995).

Citrus Black Spot has not been found in the European Union (EU)(European Union, 1998) or in the United States of America (USA). To prevent the spread of CBS, the EU and the USA restrict the import of citrus fruit from CBS infected areas (Baayen et al., 2002; European Union, 2000; Kotzé, 1981). Fruit may only be imported if it has been suitably treated against CBS and if no disease symptoms were found during pre- and post-harvest inspection (European Union, 2000). Consignments of fresh citrus fruits are inspected again at the port of entry by the phytosanitary services of the importing countries. Consignments found to contain CBS infected fruit are refused (Bonants et al., 2003; USDA/APHIS, 2002).

In South Africa considerable economic losses are incurred as a result of these phytosanitary restrictions. However, restrictions do not apply to the export of citrus fruit from the Western Cape to either the USA or the EU (European Union, 1998; Venter et al., 1995), or to the export of fruit to the USA from selected citrus growing areas in the Northern Cape (Mabiletsa, 2003b; USDA/APHIS, 2002). The EU does not certify any of the citrus growing areas in the Northern to be free of CBS (European Union, 1998).

Global climate is changing, at least in part as a result of human activities. These changes include increases in mean temperatures and variation in the timing and intensity of rainfall (IPCC, 2001). General Circulation Models (GCMs) predict that global mean surface air temperature will increase by 1.4–5.8°C over the next century. How rainfall will change is less clear as patterns in ocean circulation and cloud formation are not adequately understood (IPCC, 2001).

Climate change is expected to have a significant impact on the geographical distribution of plant pathogens and pests (Chakraborty et al., 1998; Chakraborty et al., 2000; Patterson et al., 1999).

The CLIMEX model has been used to study these potential impacts mostly on pests (Rafoss & Saethre, 2003; Sutherst et al., 2000; Yonow et al., 2000) (see Sutherst et al. (2003) for more examples) but also on a pathogen of Oak — *Phytophthora cinnamomi* Rands — which causes Oak Decline (Brasier, 1996; Brasier & Scott, 1994).

The objective of this study is to investigate the risk of CBS expanding its existing distribution to the Western and Northern Cape provinces under conditions of climate change. If, in future, CBS is found to establish itself in these provinces, then the export of citrus from these provinces to the EU and/or the USA may be restricted with considerable financial consequences for the citrus industry in South Africa.

6.3 Methodology

The potential future distribution of CBS was modelled using the software program CLIMEX (Hearne Scientific, Melbourne, Australia). This program is used to estimate the geographic distribution of a species as determined by climate (Sutherst & Maywald, 1985; Sutherst et al., 1999). A specific parameter set is used to represent the climatic responses of a given species. Once the parameter values have been estimated, they may be used to predict the potential occurrence of the species in other locations under current or future climates (McFadyen & Skarratt, 1996). This is done by calculating an Ecoclimatic Index (EI) for each geographical location. The EI is an index of how suitable a location is for the persistence of the species. In this study, we used the CBS model as outlined in Chapter 6, but run it under different climate change scenarios. Parameters are as specified by Paul et al. (2005) (Table 5.4).

6.3.1 Climate data

The meteorological database within CLIMEX Version 2 contains monthly averages for maximum and minimum temperatures and rainfall. Data are from 3092 meteorological station localities world-wide, including 129 localities in South Africa. Models were run only using South African localities.

6.3.2 Climate change scenarios

Climate change scenarios were chosen to reflect the range of possible future climatic conditions in South Africa (Perks et al., 2002). Mean monthly temperatures were increased by 1.5, 2, 2.5, 3 or 3.5°C; and monthly rainfall values were either increased by 10%, decreased by 10%, or left unchanged. Scenarios for rainfall either increasing or decreasing with 10% under current temperature and a scenario that represented current conditions were also included. This gives 18 scenarios (six levels of temperature and three levels of rainfall).

6.3.3 Predicting the potential distribution of Citrus Black Spot

The CLIMEX parameter values were first fitted under present day climate averages and used to predict the potential distribution of CBS in South Africa under current climate. The model was then run using the remaining 17 different climate scenarios. For CBS the following categories of EI values were suggested by Paul et al., (2005) from a global analysis of disease presence: EI ≤ 4, climate unfavourable for the persistence of the species; 5 ≤ EI ≤10, marginally suitable for disease development; EI ≥ 11, favourable for disease development; and EI > 20, highly favourable for the persistence of CBS. For each scenario results are returned as tables of the EI values at certain localities. These tables were imported into ArcView GIS 3.3 (Environmental Systems Research Institute) and the EI values were divided into the four categories.

6.4 Results and discussion

In general, EI values increased with increasing temperature (Figure 6.1, Table 6.1). Changes in rainfall had a much smaller effect, but generally higher rainfall leads to higher EI values. No interaction between rainfall and temperature was apparent.

Under all climate change scenarios there were thirty-eight localities around the country that always remained climatically unsuitable for the establishment of CBS. Eight of these were within areas where citrus is currently being produced: Addo, Hermitage (Eastern Cape), Deepwalls, Heldervue Matroosberg, Montague, Robertson (Western Cape) and Upington (Northern Cape). The other 30 localities included all localities in the Northern Cape (other than Upington) and localities scattered throughout the Western Cape, the Eastern Cape and the Free State (Figure 6.2). None of these 30 localities are presently under citrus cultivation.

Barberton, Nelspruit, Melmoth, and Onderstepoort had EI values above 20 for all of the climate change scenarios, indicating climatic conditions consistently highly favourable for disease establishment. Grahamstown, Komatipoort, Louis Trichard, Lydenburg and Pretoria had EI values that were always greater than 11, indicating climates favourable for disease development. All of the above mentioned localities fall in or nearby citrus growing areas.

Only three localities; Komatipoort, Mesina and Punda Maria had a decrease in EI values under all climate change scenarios. Mesina was the only locality where the climatic favourability for the establishment of CBS shifted from marginally suitable to unsuitable. At Punda Maria, EI=38, and Komatipoort, EI=33, the EI values under current conditions were highly favourable for disease establishment. These values consistently decreased to a lowest value of 20 for Punda Maria and a lowest value of 12 for Komatipoort for a scenario in which rainfall was decreased by 10% and temperature increased by 3.5°C. Nevertheless, both localities were favourable for CBS establishment under all scenarios.

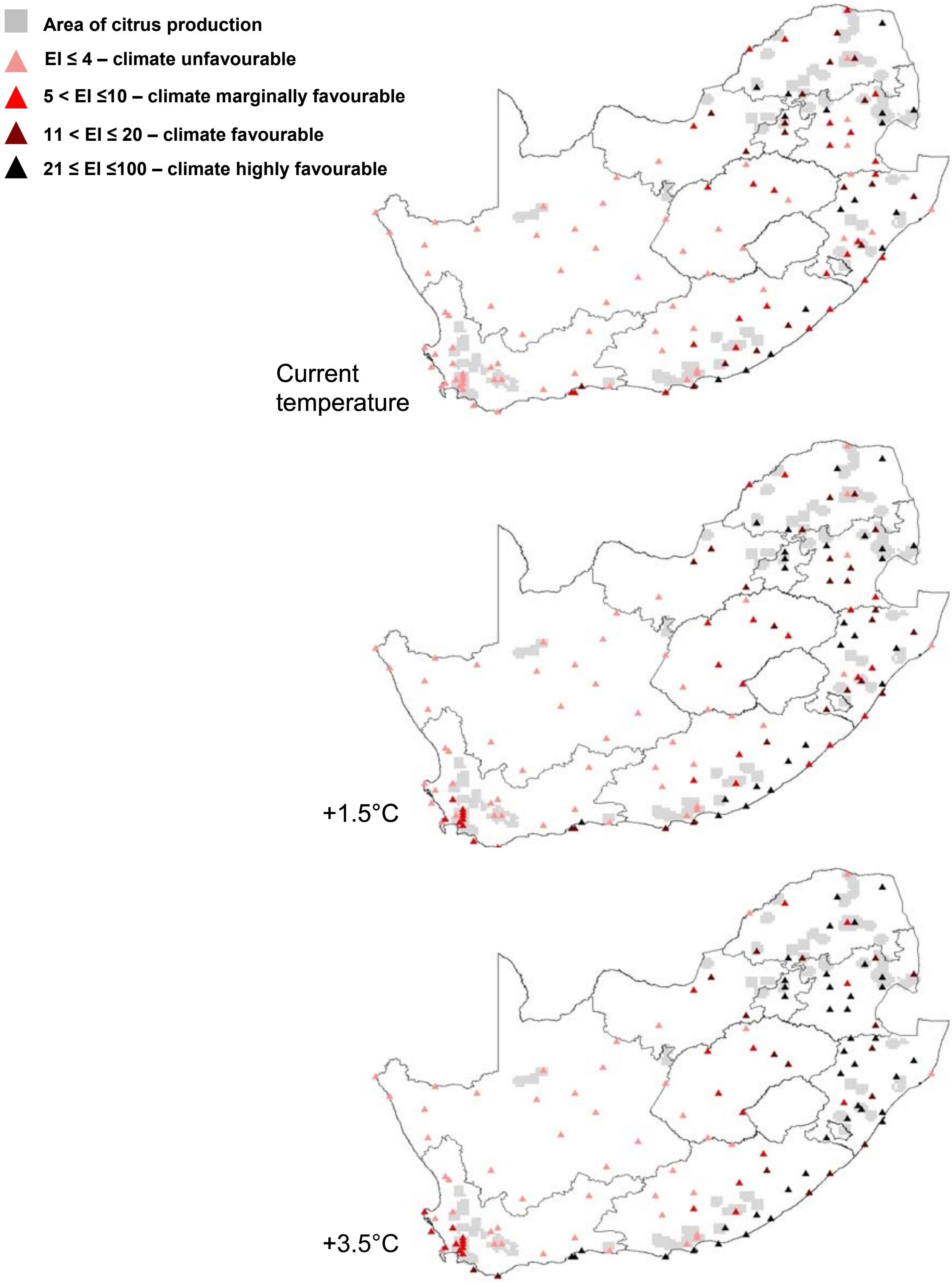

Figure 6.1 — The effect of an increase in temperature on the suitability of South African climate for CBS, indicating the differences in suitability of climate at different localities.

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In the Western Cape, the EI values of the following citrus cultivation areas generally increased with an increase in temperature: Bien Donne, Elsenburg, Groot Drakenstein, Jonkershoek, Langgewens, Paarl and Wellington. Under current climate the EI values of these localities are not suitable for the establishment of CBS (EI ≤ 4); but with an increase of 1.5°C the climate of all localities, except Elsenburg, became marginally suitable for CBS establishment; and with an increase of 3.5°C, the climate of all these localities became marginally suitable for the establishment of CBS (EI values of 8–10). The biggest changes in EI value in the Western Cape occurred at George (from 14 to 46), Cape Agulhas (from 3 to 19) and Mosselbay (from 10 to 26) when temperature is increased by the extreme of 3.5°C (most unlikely climate scenario) (Table 6.1). However citrus is not commercially cultivated at these localities. The expansion in the potential range of CBS in the Western Cape with increasing temperature is in line with previous predictions that cold stress limits the disease in the Western Cape (Paul et al., 2005).

Table 6.1 — The EI of South Africa localities under different increases in temperatures (but with no change in rainfall). EI generally increases with temperature.

	EI current climate	Increase in temperature				
		1.5°C	2°C	2.5°C	3°C	3.5°C
Elsenburg	2	4	5	6	7	8
Langgewens	2	5	6	7	9	10
Bien Donne	3	5	6	7	8	8
Jonkershoek	3	6	7	8	9	9
Cape Agulhas	3	8	10	13	16	19
Paarl	4	6	7	8	8	9
Groot Drakenstein	4	6	7	8	9	10
Wellington	4	6	7	8	9	9
Mossel Bay	10	18	20	22	24	26
George	14	29	33	37	42	46

In general the results of this study suggests that the geographical distribution of CBS may not shift dramatically under conditions of climate change. This was the case for all localities in the Northern Cape that is presently CBS free, whereas some areas in the Western Cape may become marginally favourable for CBS establishment. Most localities in the Eastern half of the country can be expected to become more favourable for CBS establishment. An exception is the result for Mesina, where predictions were that the climate may change from favourable for CBS to becoming unfavourable. In general, it seems unlikely that climate change will make the South African climate less suitable for CBS establishment. The broad changes in climatic suitability for CBS establishment at different South African localities under the various climate change scenarios are depicted in Figure 6.3.

The results of this study suggest that it may be in the interest of the citrus industry to develop measures for restricting the spread of CBS to the Western Cape, but that similar measures are probably unnecessary for the Northern Cape. The current absence of CBS in the Northern Cape and the fact that it is likely to remain CBS free despite climate change suggests that CBS phytosanitary restrictions on the export of citrus fruit from the Northern Cape region to CBS free localities such as the EU and the USA can probably be lifted.

Until now, there has been little planning and very little research on the potential impact of climate change on plant pathogens in South Africa. It is important that South African plant pathologists recognise the importance of climate change and the impacts this will have on the severity, transmission and distribution of plant diseases throughout the country. Disease management systems and control options will be forced to adapt to changes in pathogen virulence and occurrence, especially since host resistance, which some industries rely on, may be altered. Assessments of the socio-economic importance of the impact of climate change on diseases of major crops should also be conducted. Finally, the impact of climate change on the pathogens of native vegetation seems to be another important aspect in climate change research that is poorly understood at present.

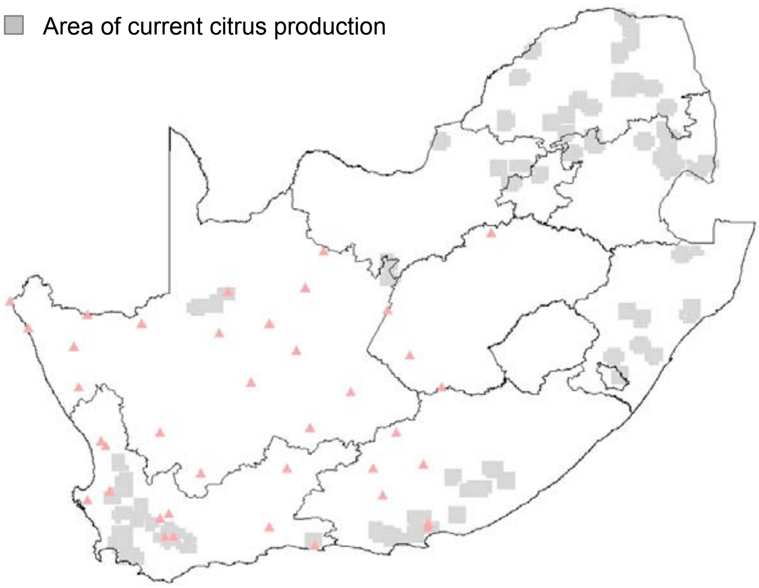

Figure 6.2 — Localities in South Africa, where climate will not become suitable for the establishment of CBS for 17 different climate change scenarios.

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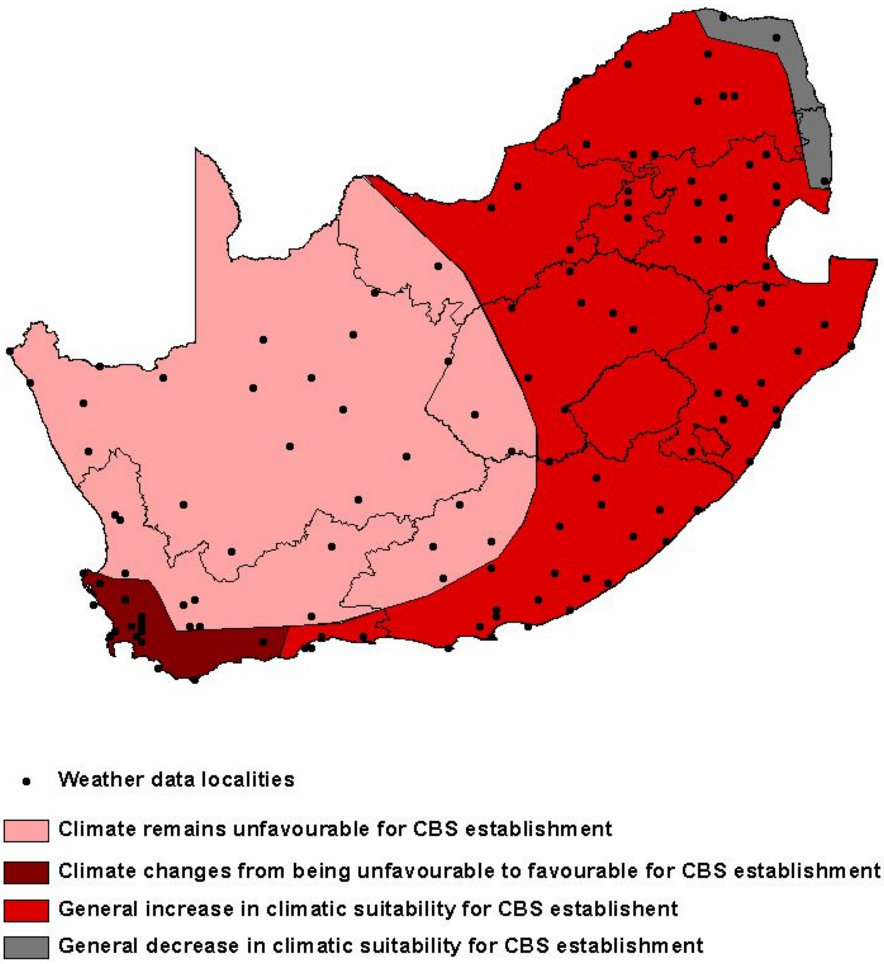

Figure 6.3 — Broad changes in climatic suitability of localities in South Africa for the establishment of Citrus Black Spot under all of the 17 different climate change scenarios.

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Chapter 7 — Modelling the potential range of citrus production in South Africa: a response surface approach

7.1 Abstract

In this study, the relationship between climate and citrus trees in South Africa is described and the effect of climate change on the geographic distribution of citrus cultivation areas is explored. This was done using response surfaces — statistical functions that estimate the probability of the occurrence of a taxon within a climate space, an approach that has been widely used to predict species distributions. Response surfaces have widely been used to predict species distributions. Here, response surfaces were fitted using the recorded distribution of citrus in South Africa and three bioclimate variables. Two response surfaces were produced, one based on a climate data set collected between 1931 and 1960, and the other based on climate data collected between 1961 and 1990. Results provide information on the extent to which citrus production in South Africa is governed by climate. Simulations of climates suitable to citrus cultivation under a current and a future climate scenario suggest that there is significant climatic potential for the extension of the citrus industry in South Africa.

7.2 Introduction

Citrus spp. are evergreen trees originating from tropical and subtropical Asia (Reuther et al., 1967; Timmer & Duncan, 1999). These trees were first cultivated in South Africa in 1654 (Oberholzer, 1969; Reuther et al., 1967), but large-scale production only started in the late 1800s. Since then, the industry has grown steadily, and today South Africa is the third largest exporter of fresh citrus fruit (FAO, 2002). Citrus is one of the country's major agricultural export products — valued at over 2,200 million rand for the financial year 2002/2003 — and the industry is heavily dependent on exports, with up to 70% of produce exported (Mabiletsa, 2003b; South African Department of Agriculture, 2003). The biggest market for export is Europe, followed by the Middle East, Japan, the Far East and the United States of America (Mabiletsa, 2003b).

Oranges are the most important citrus product grown in South Africa, with the main cultivar being Valencia (Citrus Growers Association, 2004; Oberholzer, 1969; Reuther et al., 1967). Lemons, grapefruit and soft citrus are produced to a lesser extent (Citrus Growers Association, 2004; Veldman & Barry, 1996; von Broembsen, 1986).

Citrus cultivation regions in South Africa are sub-tropical (South Africa lies approximately between 22°S and 34°S). Citrus is widely cultivated in almost all provinces with more than 70% of the citrus produced in Limpopo, Mpumalanga and the Eastern Cape Provinces. Major citrus growing areas in Limpopo are the areas surrounding Tzaneen, Letsitele and Letaba. In Mpumalanga, citrus is found in the areas surrounding Crocodile Valley, Hectorspruit, Groblersdal, Marble Hall and Nelspruit, and in the Eastern Cape Province major citrus production areas are found in the vicinity of Uitenhage, the Kat River and the Sundays River Valley (Kelly, 1995; Mabiletsa, 2003a; Oberholzer, 1969; Reuther et al., 1967). Smaller areas of citrus production are found in the Western Cape Province around Citrusdal, Somerset West and Grabouw; in the North Western Province around Rustenburg, and in Kwazulu-Natal around Muden (Kelly, 1995). About one percent of the total citrus production originates from the Northern Cape, where citrus is produced in the Vaalharts and Warrenton areas (Citrus Growers Association, 2004; Mabiletsa, 2003a) and also in close proximity to the Orange River (le Roux, 2004, Personal Communication). However, because of cold temperatures and frost, citrus is not cultivated on the inland plateau (Srivastava & Singh, 2002).

The cultivation of citrus is dependent on an amenable climate, suitable soil, and sufficient irrigation. Of these, macro-climate is the most important component for the commercial cultivation of citrus as it influences the growth and yield of citrus trees world-wide (Srivastava & Singh, 2002). If the climatic requirements of citrus are known then it may be possible to identify areas where the climate is suitable for citrus cultivation, and to predict how climate change will affect the distribution of suitable areas. Rising temperatures and changes in rainfall may shift the distribution of the optimum areas of cultivation. Moreover, some areas currently unsuitable

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may become suitable for citrus production and previously successful cultivation areas may become unsuitable (Gaoudriaan & Zadoks, 1995).

Strong correlations exist between the geographical distributions of tree species and climate (Austin & Meyers, 1996; Huntley et al., 1995; Leathwick, 1995; Matsui et al., 2004), reflecting, in particular, their ability to survive low temperatures (Woodward, 1987). Huntley et al. (1995) used response surfaces to predict the geographical ranges of several European plants, including four species of trees, under current and future climate scenarios. Their results suggest that the European distribution of the eight plant species investigated are mainly determined by macroclimate.

Response surfaces use information obtained from the geographical distribution of a species and the climates of those areas as described by bioclimate variables (Huntley et al., 1995). Bioclimate variables represent the underlying mechanisms that influence species distribution, and are calculated from meteorological database values.

For the outcomes of the response surface to be reliable, the geographical distribution of the species must be known accurately, and a suitable climate data set must be used. Previous studies applying response surfaces have not tested the effect of using more than one historical climate data set (Beerling et al., 1995; Hill et al., 2002; Hill et al., 1999; Huntley et al., 1995), and, although the outcomes of using the same input data in different modelling approaches has been compared (Robertson et al., 2003), the effect of using different climate databases on species distribution modelling has not been explored (Booth et al., 2000a; Booth et al., 2000b; Brasier, 1996; Brasier & Scott, 1994; Leathwick, 1995; Meentemeyer et al., 2004).

In this study, the relationship between the current distribution of citrus cultivation in South Africa and climate was investigated using two different climate data sets.

7.3 Methodology

Data on the occurrence of citrus cultivation were transcribed onto a grid of a map of South Africa (7.3.1), and meteorological station data values were interpolated onto this grid (7.3.2). These climate data were used to estimate bioclimate variable values for each grid cell (7.3.3). The response surface was then fitted to the occurrence data using these bioclimatic values, and the potential geographical distribution of citrus cultivation was simulated for current (7.3.4) and future (7.3.5) climates.

7.3.1 Mapping the areas of citrus production in South Africa

Fitting a response surface requires an accurate geo-referenced map of the occurrence of a species. Such a map of citrus cultivation areas in South Africa was compiled by geo-referencing 119 localities of citrus production from an internet based gazetteer (http://www.calle.com/world/SF/, Falling Rain Genomics 2004). These citrus localities were verified by personal communications with citrus experts (Barry, 2004; Kotzé, 2004; le Roux,

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2004). Two maps that broadly define citrus cultivation areas in South Africa were also used for guidance (Barry, 2004, Personal Communication; Mather & Greenberg, 2003). A buffer of 15km radius was placed around each point locality of citrus production.

A grid of regular points was generated for the surface area of South Africa at a resolution of 15'. This comprised 1974 grid squares, and could be related to the climate data sets. Data on the presence and absence of citrus cultivation areas within South Africa were manually transcribed onto this grid using ArcGis 8.3 (Environmental Systems Research Institute) (referred to as the citrus grid from this point forward). Areas with climates suitable for citrus cultivation, but where citrus is not grown, (such as metropolitan areas, national parks and land used to produce other subtropical crops) were transcribed to the grid as areas of no data (Figure 7.1).

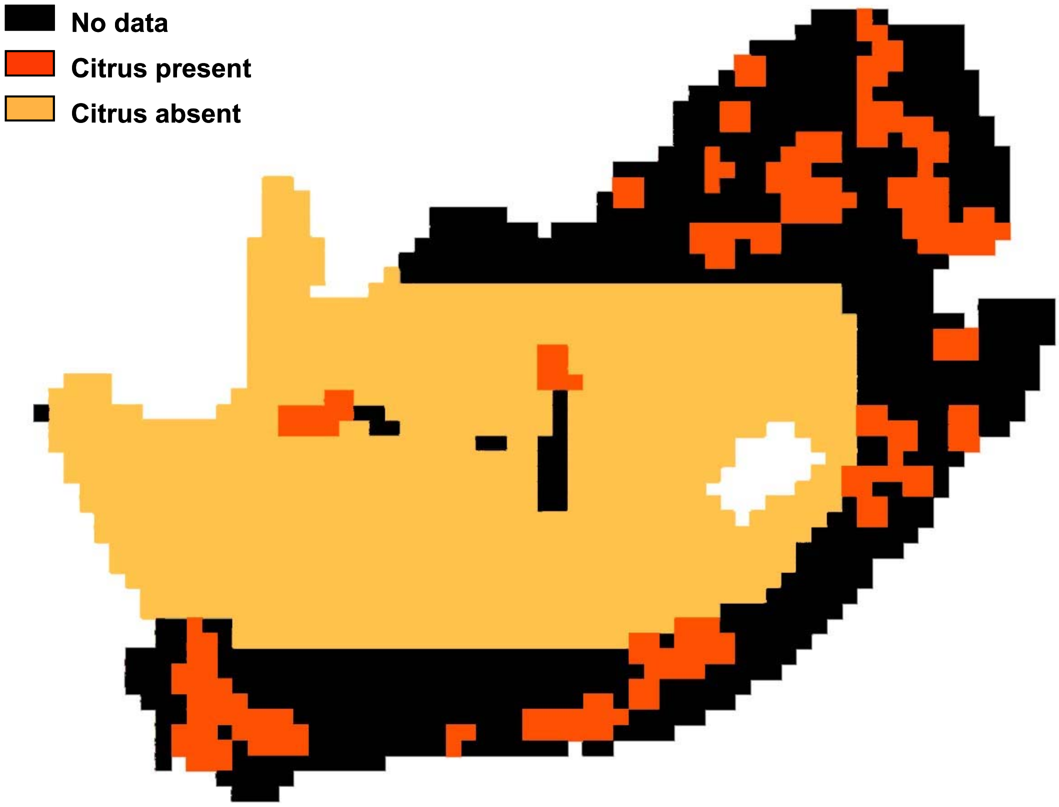

Figure 7.1 — The occurrence of citrus cultivation areas in South Africa in 2004.

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7.3.2 Climate data

Two separate climate data sets were used. The Spatial Characterization Tool data set (SCT data) (Corbett & O'Brien, 1997) and a data set initially compiled by Leemans and Cramer (1991) which was later significantly enlarged by Cramer (Cramer data) (Cramer & Leemans, 2001).

The SCT data consists of climate data over the period of 1961–1990. Mean monthly values for precipitation and temperature were used in this study. The Cramer data set consists of climate data over the period of 1931–1960. Mean monthly values for temperature, precipitation and cloudiness were used in this study.

7.3.2.1 SCT data

The SCT data are spatially interpolated and comprise a grid of the African continent at a 3' resolution. These climate data were used to calculate the three bioclimate variables. The bioclimate variables from the 3' grid were then reduced onto a 15' grid so that they were compatible with the citrus grid. For each 15' grid cell, bioclimate data values were determined at the minimum, maximum and median elevations for that cell. For this study, the bioclimate data values of the minimum elevations were used.

7.3.2.2 Cramer data

The Cramer data are not spatially interpolated. To transform point climate data, recorded by individual meteorological stations, to a value for a 15' grid cell, elevation should be considered. Minimum, maximum and modal elevations for a grid at a resolution of 10' were obtained from the Fleet Numerical Oceanography Center data set (NOAA, EPA Global Ecosystems database Project 1992). The mean elevation of each 15' grid cell was computed as a weighted mean of the modal elevations of all those 10' squares that were partially or completely enclosed by a 15' grid cell.

Climate station data were interpolated to localities at the geographical midpoint and mean elevation of each of the 1974 grid cells. Interpolations were performed by means of LaPlacian thin-plate spline surfaces fitted to the station data (Hutchinson, 1989). The independent variables for these surfaces were latitude, longitude, and elevation of the stations. Bioclimate variables were calculated from these climate data for each of the 15' grid cells.

7.3.3 Bioclimate variables

Prentice et al. (1992) used five bioclimate variables for modelling the distribution of vegetation: mean temperature of the coldest month (MTCO); mean temperature of the warmest month (MTWA); the ratio of actual to potential evapotranspiration (AET/PET); temperature sum above 5°C (GDD5); and the temperature sum above 0°C (GDD0). MTWA and GDD5 are measures of warmth and are highly correlated and MTCO and GDD0 are measures of cold and are also highly correlated. Therefore, in this study, several combinations of three from the potential five bioclimate variables were tested. The combination of MTCO, MTWA, and AET/PET gave the

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best statistical fit between observed and simulated distributions of citrus cultivation in South Africa.

The bioclimate variables were calculated using the program BioCli (written by W Cramer, Department of Global Change and Natural Systems, Potsdam Institute for Climate Impact Research, Germany and R Leemans, Environmental Sciences Department, University of Wageningen, The Netherlands), AET/PET values were calculated using the Bucket subroutine within BioCli (written by W.Cramer [address as above] and I.C. Prentice, Department of Earth Sciences, University of Bristol, U.K.). The values for the three bioclimate variables for each climate data set are mapped (Appendix B).

7.3.3.1 Mean temperature of the coldest month (MTCO)

There is a correlation between absolute minimum temperature and the geographical limits of tree species (Woodward, 1987). Citrus trees are no exception. Low temperatures have a marked influence on the growth, development and productivity of citrus trees. In particular, citrus trees are sensitive to below-freezing temperatures. (Davies & Albrigo, 1994; Reuther et al., 1967).

Data on absolute minimum temperatures were not available at a suitable resolution for the purposes of this study, but, as there is a strong correlation between absolute minimum temperature and MTCO, MTCO is a suitable surrogate (Prentice et al., 1992). The lower limit of MTCO is related to the species ability to survive cold temperatures. The upper limits of MTCO can be related to the chilling requirement which delays budburst until the plant has been exposed to a certain cold period of winter dormancy (Shafer et al., 2001).

7.3.3.2 Mean temperature of the warmest month (MTWA)

Different types of citrus grow optimally at different temperature ranges (Barry & Veldman, 1996; Coops et al., 2001). However, root and shoot growth generally occurs at soil temperatures of between 24–27°C but ceases at soil temperatures below 10°C (Srivastava & Singh, 2002). MTWA is related to accomplishing basic physiological functions during the growing season (Shafer et al., 2001) and is used as a surrogate for the heat requirement for the growth of citrus trees.

7.3.3.3 The ratio of actual to potential evapotranspiration (AET/PET)

Citrus performs well in extremely wet conditions and is also able to survive severe water stress (Srivastava & Singh, 2002). However, moisture availability plays an important role in the growth and productivity of citrus trees. In the field, droughts longer than 30 days are required to induce significant flowering, with the degree of induction being proportional to the severity and duration of water stress (Davies & Albrigo, 1994).

AET/PET is used to estimate moisture availability. This bioclimate variable is an integrated measure of the annual amount of growth limiting drought stress on plants. The lower limits of this moisture index represent the ability of the species to tolerate drought and the upper limits

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represent the intolerance to moist surroundings (Shafer et al., 2001). The soil water capacity values of a 30' grid, compiled by Prentice et al. (1992), were used to calculate AET/PET values for the citrus grid. The value of AET/PET was estimated using a bucket model with a daily time step. Methods for the calculation of AET/PET are fully described in Prentice et al. (1992).

7.3.4 Fitting the response surfaces and simulating distributions

The methodology of P.J. Bartlein (Department of Geography, University of Oregon, USA) was used to fit the response surfaces (using an unpublished computer program written by P.J. Bartlein [address as above] and modified by B. Huntley, School of Biological and Biomedical Sciences, University of Durham, UK). A response surface was fitted, using presence and absence of citrus in South Africa as the dependent variable (see citrus grid, section 7.3.1 page 115) and the values for the three bioclimate variables, for each climate data set as the independent variables. The surfaces were fitted using locally weighted regression (Cleveland & Devlin, 1988). The fitted values represent the probability of citrus occurring at a given locality within the climate space.

Once a response surface is fitted, it may be applied to simulate the suitability of climate for the occurrence of the species in a given geographical area. This is done using the same locally weighted regression procedure as when first fitting the surface, and, where necessary, by extrapolation.

The 'goodness of fit' of between the simulated distribution and the observed distribution can be assessed using the kappa statistic (κ).The Kappa statistic is used to measure the agreement between two sets of categorical data while correcting for chance agreements between the categories.

κ is derived as: (description from Prentice et al. 1992, based on work by Monserud and Leemans, 1992) "Let p_{ij} be the proportion of the total number of grid cells assigned to category i by one map and to category j by the other map. These values form a square matrix, whose main diagonal contains proportions of grid cells on which both maps agree (p_{ij}). The sum of these proportions is the overall proportion of observed agreement (p_o = sum(p_{ii})). Chance alone would be expected to produce some agreement; the expected value of pii being due to chance alone is the product of the row and column sums $p_{i.}$ and $p_{.i}$ for category i. (These sums are simply the proportions of grid cells assigned to each category by each map). The overall expected value of agreement due to chance is the sum of these row and column cross-products (p_e=sum for all i ($p_{i.}p_{.i}$). This is subtracted from the overall proportion of observed agreement and the result normalized by the maximum possible value of the difference to give the kappa statistic: $\kappa=(p_o-p_e)/(1-p_e)$."

The value for κ lies between zero and one. A value of one indicates an exact fit, while a value close to zero would indicate a fit no better than random (Monserud, 1990). However, since the response surface model predicts probability values for each cell, these need to be converted into presence absence values in order for the kappa statistic to be calculated. Kappa values are

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calculated using threshold values from 0.001 to 1.0, at increments of 0.001. If the probability values is below the threshold value then the species is absent in that square otherwise it is present. The simulation with the highest value for κ is that which correctly predicts species presence and absence for the most grid cells.

7.3.5 General Climate Model Scenario

If the fit of a response surface to the distribution of a species is good, then climate is probably important in determining where the species will be successful. Therefore, the response surface may be applied to simulate the impact of climate change on the potential distribution of that species.

Over the next 100 years it is expected that there will be significant changes in climate, in particular it is believed that mean temperatures will increase and the intensity and timing of rainfall will became more variable (IPCC, 2001). Global climate models (GCMs) generally predict an increase of 1.4–5.8°C in global mean surface air temperature, but potential changes in precipitation are not well understood and increases and decreases of 5-20% are projected for different parts of the world (IPCC, 2001). The predicted changes in climate are of sufficient magnitude to have a great influence on citrus cultivation in South Africa.

Potential changes in the South African climate were obtained from the HadCM3 model. This model is a coupled model of the global climate system in which the primary sub-models are an atmospheric general circulation model (AGCM) and an oceanic general circulation model (OGCM). The model also incorporates a sophisticated surface-vegetation-atmosphere transfer (SVAT) model. Model outputs from the B2 scenario were chosen. In this scenario, the world has a continuously growing population, and there is an emphasis on local solutions to economic, social, and environmental sustainability. The scenario is seen as mid-range and includes an increase in global carbon emissions and a decrease in sulphur emissions. It can be seen as representative of the potential changes in climate over the next century. Information was obtained from the Intergovernmental Panel on Climate Change Data Distribution Centre (http://ipcc-ddc.cru.uea.ac.uk/).

Anomalies between the future (2070) and present day HadCM3 B2 climate scenarios were calculated for precipitation and temperature (cloudiness was not changed). Smooth overlays of these anomalies were obtained by fitting thin-plate LaPlacian spline surfaces using latitude and longitude as the independent variables, and the anomaly as the dependent variable within the program splinb (Hutchinson, 1989). The Lappnt10 program was then used to derive the anomaly values for the 15' citrus grid covering South Africa (Both the splinb and Lappnt10 programs were written by M.F. Hutchison, Centre for Resource and Environmental studies, Australian National University, Canberra, Australia). BioCli was used to combine the anomaly data with the current climate data for both the SCT and Cramer data sets in order to obtain data sets that represent future climate as it is based on the B2 scenario. The bioclimate values were

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calculated from these future climate data. Potential future distributions of citrus were simulated in the same manner as the current potential distributions of citrus (section 7.3.4).

7.3.6 Simulated distribution in Australia

The Cramer data comprise of climate data for the whole world. The predictive capacity of the Cramer response surface was tested by simulating potential patterns of citrus cultivation in Australia (same methodology as section 7.3.4). This was not possible for the SCT data response surface as the SCT data are only from Africa.

Observed citrus cultivation areas in Australia were mapped by geo-referencing citrus production localities from an internet based gazetteer (http://www.calle.com/world/SF/, Falling Rain Genomics 2004). Mapped areas of citrus cultivation were confirmed by P. Barkley (2004, Personal Communication). A buffer of 15km radius was placed around each point locality of citrus production. These presence data were then manually transcribed onto a 15' grid of the surface of Australia in ArcGIS 8.3. (Environmental Systems Research Institute). A kappa statistic could not be calculated for this simulation as data on the absence of citrus cultivation areas in Australia were not available. However, as presence data were available, the percentage of grid cells where the presence of citrus was correctly simulated was calculated.

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7.4 Results

7.4.1 Response surface of citrus in South Africa

The response surface represents the probability that citrus occurs under any combination of three bioclimate variables. It is shown as a bioclimate envelope on a three-dimensional climate space. Each axis of this climate space represents a bioclimate variable that was used to fit the response surface (figures were drawn using an unpublished computer program written by B. Huntley).

The SCT data response surface suggests citrus grows in regions with MTCO values of 10–19°C; MTWA values of 20–27.5°C; and at a wide range of AET/PET values, ranging from at least 0.250 to 0.625. At AET/PET values of 0.125 and lower citrus is not found (Figure 7.2).

The Cramer data response surface suggests citrus requires MTCO values of 7–18°C and MTWA values of 17–27.5°C. Citrus may occur at a range of AET/PET values, with occurrences of citrus at AET/PET values of $\leq$ 0.825 and > 0.125 (Figure 7.3).

7.4.2 Simulated distributions in South Africa under current and future climate

7.4.2.1 SCT Data

At a threshold probability of occurrence of 0.51, the simulated distribution of citrus corresponds to the observed geographical distribution (Figure 7.4). The main areas of discrepancy are the two citrus growing areas of the Northern Cape, where citrus is highly irrigation dependent, that were not included in the simulated distribution. Other than these minor areas of citrus production, all citrus growing areas are included in the simulation. With the HadCM3 B2 climate change scenario, the simulated range of citrus cultivation mainly expands inland and great parts of the Northern Cape remain unsuitable for citrus cultivation (Figure 7.5).

7.4.2.2 Cramer Data

Using a threshold probability of occurrence of 0.29, the simulated range of citrus cultivation closely matches the observed geographical occurrence. Only one area of citrus cultivation in the Northern Cape is not included in this simulation (Figure 7.6). The simulation for the HadCM3 B2 climate change scenario the climatic range for citrus production is simulated to expand mostly inland, with potential occurrence also predicted in the Kgalagadi Transfrontier Park (Northern Cape) (Figure 7.7). The greater part of the Northern Cape, however is predicted to be unsuitable for citrus production.

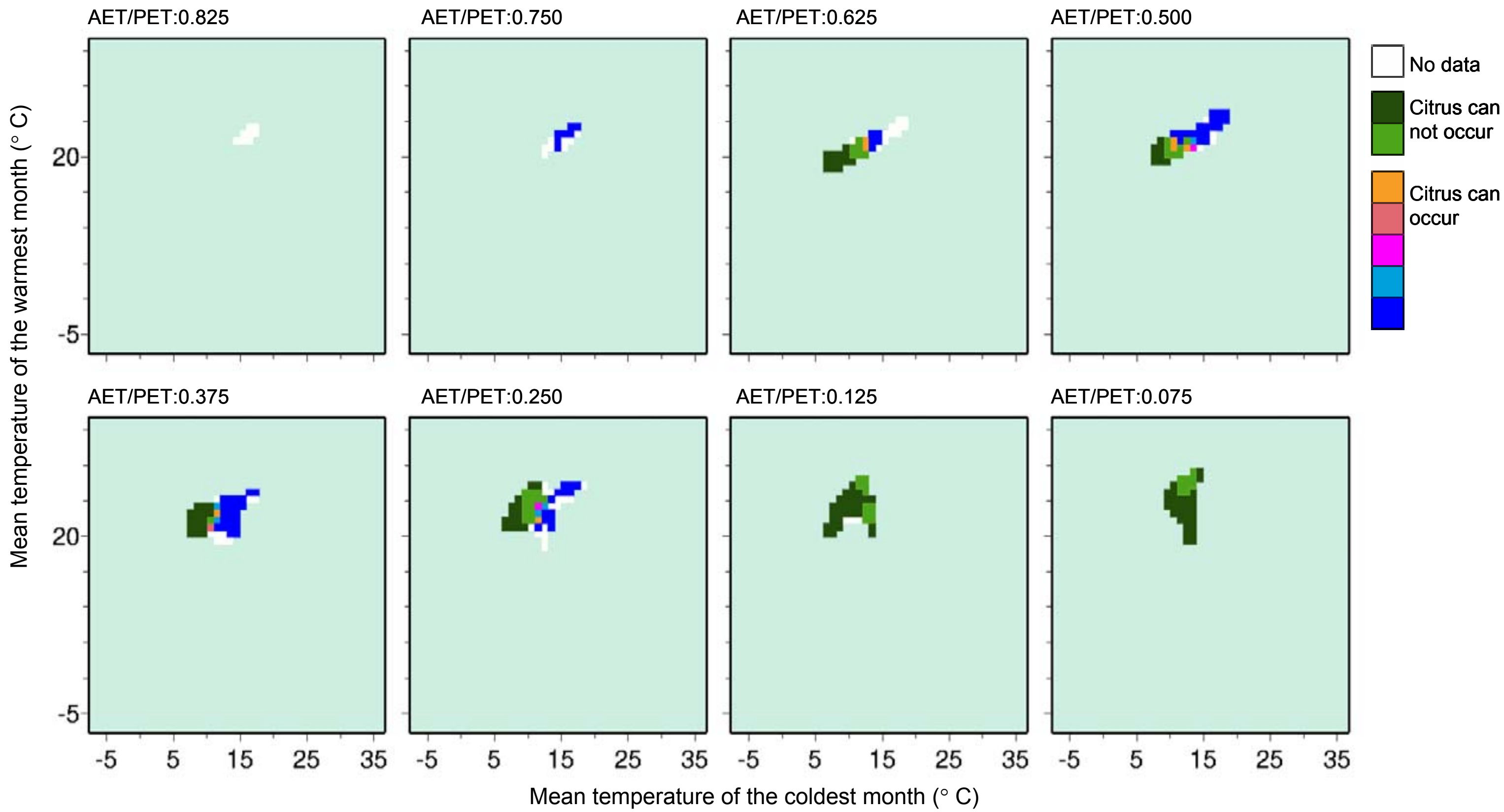

Figure 7.2 — SCT data citrus response surface. Three dimensional climate response surfaces for citrus in South African climates. The response surface is shown as a series of eight slices with respect to the ratio of actual to potential evapotranspiration (AET/PET) axis, with each panel representing a cross-section at a different value of AET/PET. Each slice has mean temperature of the coldest month as its horizontal and mean temperature of the warmest month as its vertical axis (Huntley et al., 1995). The coloured tiles indicate the potential for citrus to occur; green indicates that citrus will not occur and the remaining tiles indicate an increasing climatic suitability for citrus with dark blue indicating most suitable climates.

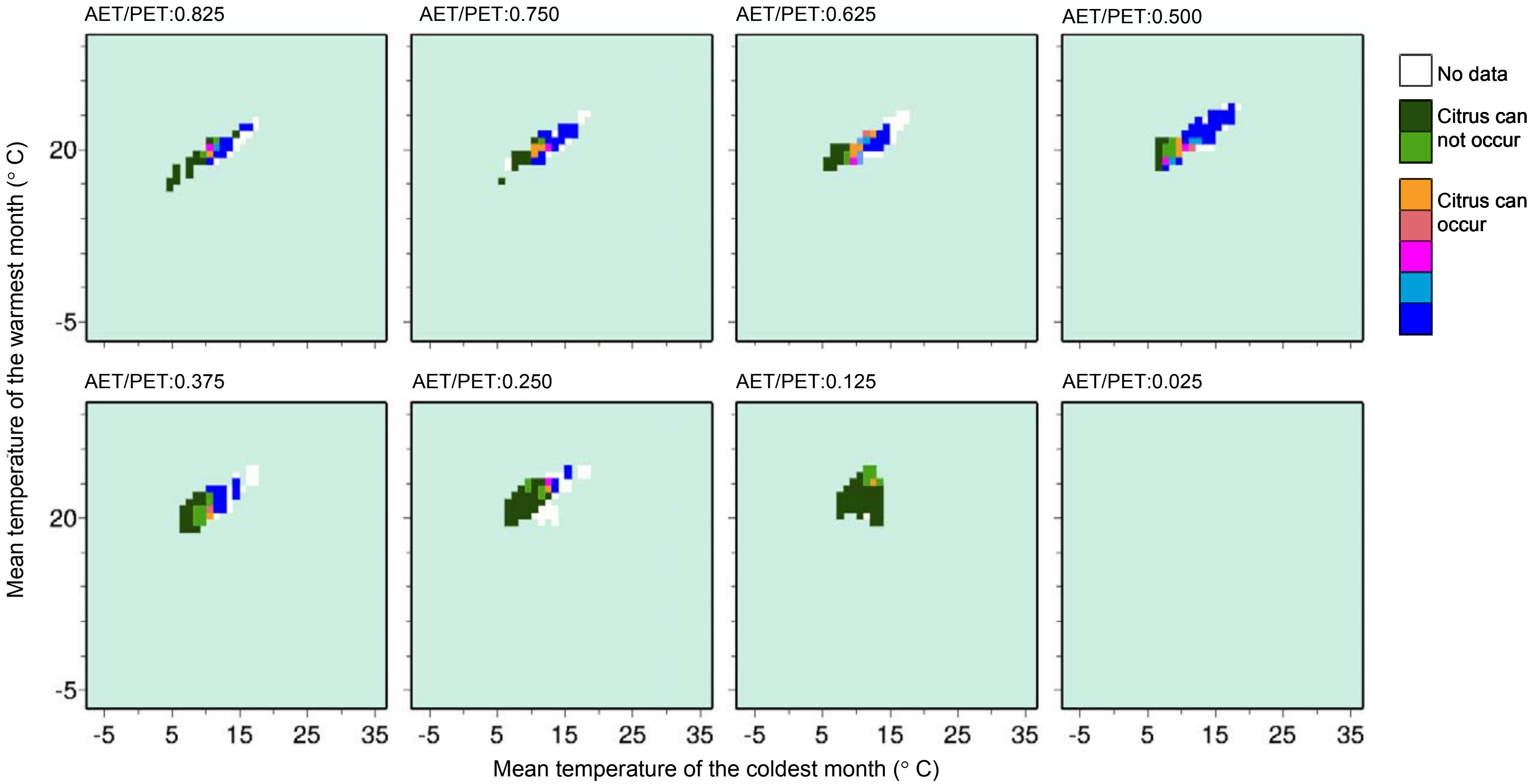

Figure 7.3 — Cramer data citrus response surface. Three dimensional climate response surfaces for citrus in South African climates. The response surface is shown as a series of eight slices with respect to the ratio of actual to potential evapotranspiration (AET/PET) axis, with each panel representing a cross-section at a different value of AET/PET. Each slice has mean temperature of the coldest month as its horizontal and mean temperature of the warmest month as its vertical axis (Huntley et al., 1995). The coloured tiles indicate the potential for citrus to occur; green indicates that citrus will not occur and the remaining tiles indicate an increasing climatic suitability for citrus with dark blue indicating most suitable climates.

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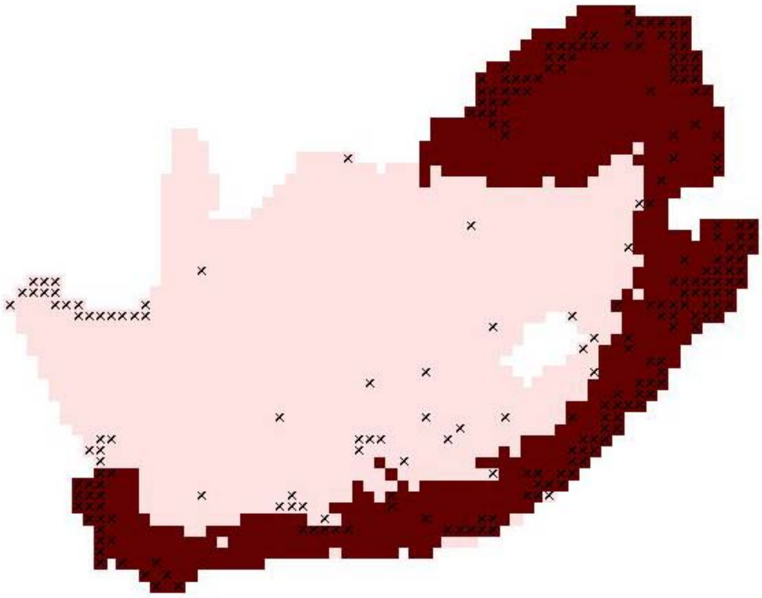

Figure 7.4 — Simulated potential distribution of citrus in South Africa under current climate for the SCT climate data set. κ=0.904, which indicates an excellent fit. Grid cells where the response surface was extrapolated are indicated by an x.

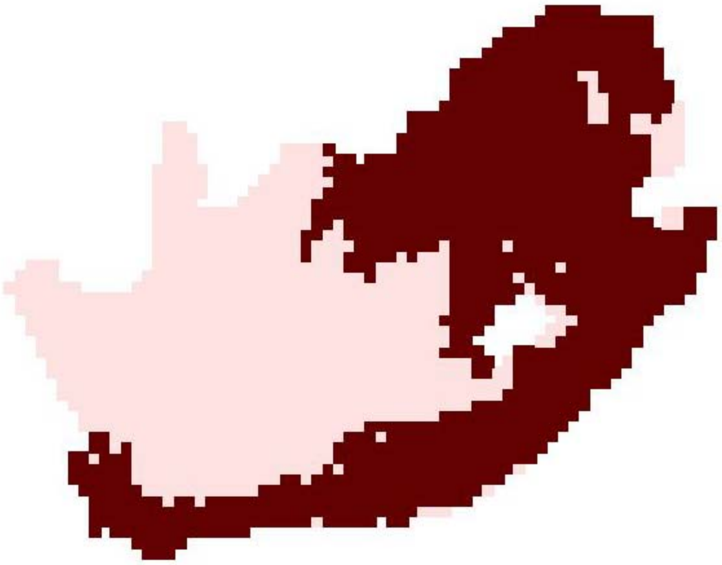

Figure 7.5 — Simulated potential distribution for citrus in South Africa as calculated for the HadCM3 B2 climate change scenario from the SCT climate data set.

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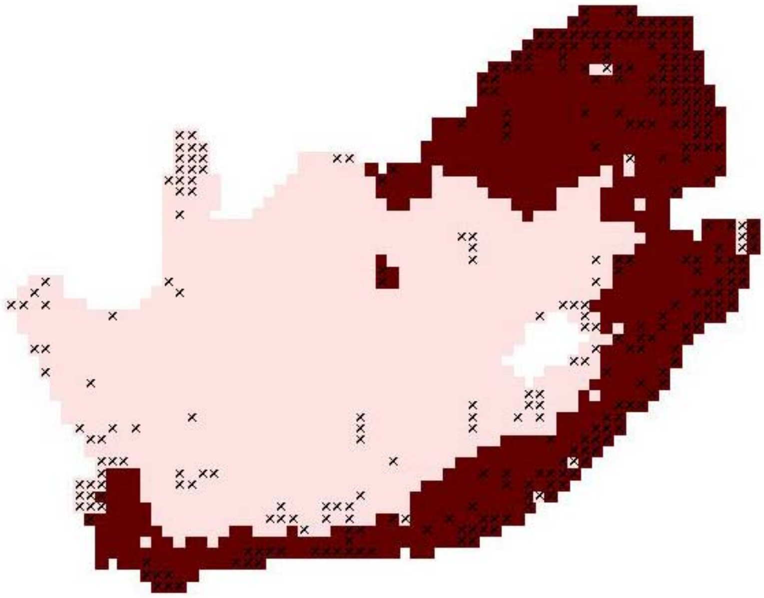

Figure 7.6 — Simulated potential distribution of citrus in South Africa under current climate for the Cramer climate data set. κ=0.91, which indicates an excellent fit. Grid cells where the response surface was extrapolated are indicated by an x.

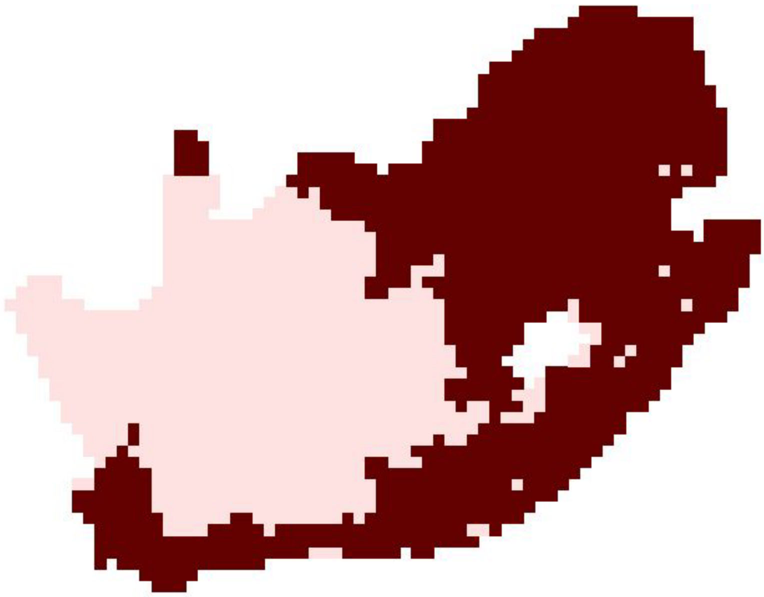

Figure 7.7 — Simulated potential distribution for citrus in South Africa as calculated for the HadCM3 B2 climate change scenario from the Cramer climate data set.

7.4.3 Simulated distribution in Australia

The Cramer data response surface simulated 56.5% of the grid cells in Australia where citrus cultivation is observed (Figure 7.8). It predominantly failed to predict citrus producing areas in the south-east.

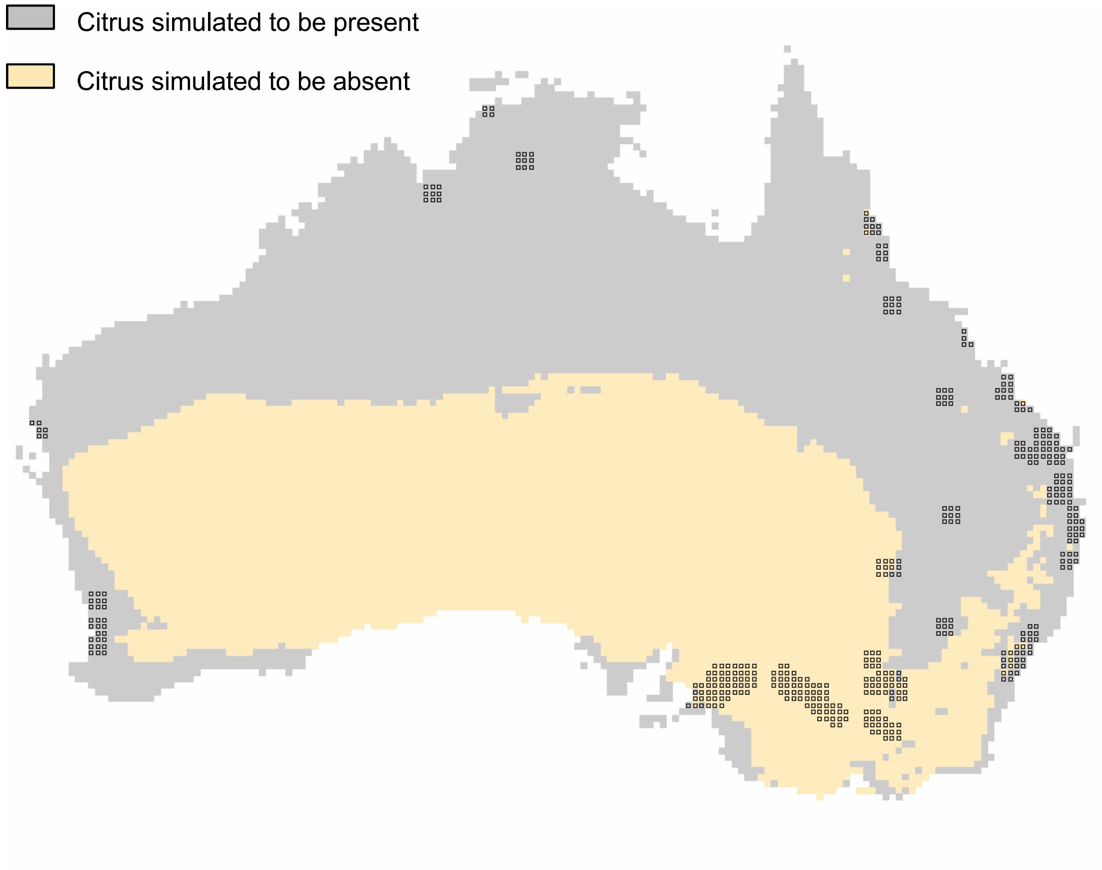

Figure 7.8 — Simulated distribution of citrus in Australia on a 15' grid using the Cramer data response surface and present climate. Grid squares in which citrus is cultivated are marked with small black squares.

7.5 Discussion

There is great variation in the mean temperatures under which citrus is cultivated. For instance, in Riverside, California, USA, the variation in mean monthly temperature is between 11 and 24°C, and in Madagascar mean monthly temperatures of citrus cultivation lie between 13.9 and 20.9°C (Srivastava & Singh, 2002). This variability means that the exact climatic limits of citrus are difficult to estimate. However, successful citrus cultivation cannot occur if average minimum temperatures drop below 7°C, and temperatures above 13°C are required for growth. Average temperatures lower than 24°C are also necessary to induce flowering (Davies & Albrigo, 1994).

For both response surfaces, the ranges of MTCO and MTWA values calculated to be favourable for citrus production fall within a similar range, although the lower limits of the Cramer data response surface are lower than those of the SCT data response surface (MTCO 7°C vs. 10°C;

MTWA 17°C vs. 20°C). Nevertheless, the ranges of MTCO and MTWA values correspond well with the temperature requirements that have been recorded for citrus in the field (Srivastava & Singh, 2002). In broad terms the two response surfaces correspond well to the climatic requirements of citrus observed in the literature (Davies & Albrigo, 1994; Spiegel-Roy & Goldschmidt, 1996; Srivastava & Singh, 2002).

Citrus may be grown in very wet climates which correspond to the higher values of AET/PET that were obtained (> 0.625) from the response surfaces. Citrus is also adapted to survive under water stress (Srivastava & Singh, 2002). Therefore it is not surprising that the response surfaces predict citrus to occur at relatively low values for AET/PET (< 0.250). However, the potential for citrus to occur decreases as the AET/PET values decrease.

The dissimilarity in the two response surfaces originates from the distinct differences in the two climate data sets (i.e. time periods and mean vs. minimum elevation interpolation — see Appendix B). Bioclimate variable values calculated for the Cramer data tend to indicate greater moisture availability in the south-western coastal areas of South Africa than the bioclimate variable values calculated for the SCT data set. MTWA and MTCO values also vary, with MTWA values of some grid cells notably cooler when calculated using the Cramer data than when calculated using the SCT data. The means and standard deviations of the various measures for the Cramer data-set vs. the SCT data-set are: MTCO, 11.1 ± 2.7 °C vs. 11.7 °C ± 2.8; MTWA, 22.9 °C ± 2.5 vs. 23.9°C ± 2.4; APET (logit transformed values), -0.87 ± 1.01 vs. -0.65 ± 1.24. See Appendix B for further details.

Both the Cramer and SCT data response surface simulations indicate that under current climate there are extensive areas, where citrus is not grown in South Africa, that are climatically suitable for citrus cultivation. However, since climate is not the only factor that governs the potential distribution of citrus, considerable care must be taken when interpreting these results. Citrus trees may be excluded from certain areas by non-climatic factors such as unsuitable soils (Shafer et al., 2001), and many of these areas may be subject to other land uses (Schulze & Kunz, 1995). Nevertheless, this study does suggest that the South African Citrus Industry could be spatially extended.

The greatest discrepancy between the SCT data response surface and the observed map of citrus production is that the response surface did not simulate the presence of citrus in all the citrus cultivation areas of the Northern Cape (South Africa). Although the Cramer data response surface accurately simulated the citrus production areas in the Vaalharts region of the Northern Cape, it also failed to simulate the citrus production areas surrounding the Orange River (Northern Cape). In this citrus cultivation area, the AET/PET calculations, based only on the macro-climatic data and not on values for irrigation, may give moisture availability values lower than are actually found in the orchards. Therefore the models predict this area not to be naturally suitable for citrus. Furthermore, in total, very little citrus is produced in the Northern Cape (Citrus Growers Association, 2004) as it can only be produced in close proximity to rivers (le Roux, 2004, Personal Communication) where local climate and the availability of irrigation

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water facilitate cultivation. The 15' resolution of the response surface may also be too coarse to include local climate effects. Nevertheless, macro-climate still remains the most important factor in determining the potential for citrus cultivation. This relationship between climate and citrus cultivation is supported by the high kappa values obtained when the response surfaces were used to simulate the potential distribution of citrus.

When applying the Cramer response surface to simulate citrus cultivation areas of Australia, it largely failed to simulate the citrus cultivation areas in the south-east. This was because the climate of this part of Australia does not correspond to any South African climate and is therefore not represented by the response surface. According to the response surface based solely on South African climates, South-Eastern Australia is too cold for the cultivation of citrus. However, globally citrus is being cultivated in colder and warmer climates than those found in South Africa (Srivastava & Singh, 2002). Therefore it is expected that the South African derived response surface will not reliably predict the occurrence of citrus in other parts of the world. Nevertheless, the ability of the Cramer data response surface to successfully predict the occurrence of some citrus cultivation areas of Australia indicates that the response surface does represent at least some climates in which citrus may be cultivated, but that it cannot circumscribe the total global climates suitable for citrus cultivation.

Under a possible future climate, the SCT data response surface suggests that the climates of the citrus cultivation areas north of Swaziland will become unsuitable for citrus cultivation. However, both simulations suggest that the area climatically suitable for citrus cultivation will substantially increase. In particular, inland areas, that were unsuitable for citrus cultivation due to cold temperatures, are simulated to become suitable. Both simulations also indicate that most of the Northern Cape and some inland parts of the Eastern, and Western Cape provinces will remain climatically unsuitable for citrus cultivation.

To illustrate the projected changes in South African climate, modern analogues of future climate and bioclimate variable values for the future climates were mapped (Appendices B and C). For both the SCT and the Cramer data sets, future climates of South Africa, as calculated with the HadCM3 B2 scenario, differ substantially from current South African climates.

Under the climate change scenario the response surfaces do not consider the physiological responses of the species to elevated levels of carbon dioxide. Only a few studies have been done on the influence of increased carbon dioxide on citrus trees. One study found that after two years, sour orange trees planted in an enhanced carbon dioxide environment had almost a three fold increase in trunk and branch volume compared to trees planted under ambient levels of carbon dioxide. Trees grown under enhanced carbon dioxide also produced at least seventy percent more fruit than trees grown under ambient conditions (Idso & Kimball, 1997) (Other potential impacts of climate change on the citrus host are summarised in Appendix D). These changes in physiology could alter the climatic requirements of citrus. If this is so, then the response surface, as based on current climate, may not reflect the future climatic requirements of citrus.

Most approaches to modelling species distributions using response surfaces only rely on the outputs obtained from the use of a single climate data set (Bartlein et al., 1997; Beerling et al., 1995; Hill et al., 2002; Hill et al., 1999; Huntley et al., 1995). Although the results obtained for current climate and future climate were generally in agreement, there were some differences in the results obtained. These results indicate that modelling outputs vary according to the choice of climate data. Therefore, especially as model outputs may be used to support decision-making processes, more than one climate data set should be assessed. The best climate data set should be chosen in order to make reliable recommendations on the potential distribution of species, and possible effects of climate change on the ranges of species (See Appendix B).

Inherently models do not replicate reality. In general, there tends to be some discrepancy between the observed and simulated distributions when modelling with response surfaces (Beerling et al., 1995; Huntley et al., 1995). The impact of climate change is also uncertain. Therefore, simulations on the impact of climate change on the potential range of the species should not be seen as forecasts, but rather as measures of potential implications of future climate changes to the range of the species. However, given the importance of knowing where species can occur, and how this will be affected by climate change, there needs to be some scientific input into policy decisions. Bio-climatic modelling can assist this process.

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