MODELLING THE DISTRIBUTION OF CITRUS BLACK SPOT CAUSED BY *GUIGNARDIA CITRICARPA* KIELY

by

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This thesis is dedicated to John Ross Wilson

Modelling the distribution of Citrus Black Spot caused by *Guignardia citricarpa* Kiely

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Abstract

Citrus is a valuable fruit crop in world trade. Citrus Black Spot (CBS), caused by *Guignardia citricarpa* Kiely, is a fungal disease of citrus. It occurs in many citrus producing countries including parts of Australia and South Africa, but it does not occur in the countries of the European Union (EU) or the United States of America (USA). To prevent the introduction of CBS, the EU and the USA have phytosanitary regulations that restrict the import of citrus fruit from areas where CBS is found.

This study uses two bioclimatic modelling approaches — CLIMEX and response surface modelling — to predict which areas have climates suitable for CBS to establish. The work focuses on the citrus growing areas of South Africa and Europe, but other parts of the world are also considered. As CBS is dependent on citrus, geographical areas of global citrus production are also mapped, and models are used to predict which areas of South Africa have climates suitable for citrus cultivation under current and future climates. The potential impacts of climate change on CBS distribution in South Africa are also estimated.

Results indicate that under current and future climates many areas in South Africa where citrus is not currently grown have a climate suitable for citrus cultivation, but most of these areas are also climatically favourable for CBS. Of the current citrus producing areas in South Africa, only the Northern and Western Cape Provinces are predicted to be unsuitable for CBS. Under climate change scenarios, some citrus production areas of Western Cape are predicted to become suitable for CBS, but the greater part of the Northern Cape will remain climatically unsuitable for the establishment of CBS in future.

The climates of several CBS-free citrus producing areas around the world, such as Mexico, and Florida and Texas (USA) are suitable for CBS. However, European climate is unfavourable for CBS establishment, and provided importing countries comply to minimum standards, phytosanitary restrictions on the import of fruit from CBS infected areas may be unnecessary.

This study is the first of its kind in citriculture, and in South Africa it is one of the few studies that investigates the effects of climate change on the potential distribution of a plant pathogen. Bioclimatic modelling was found to be a very useful means to combine complex data in order to make predictions relevant to Pest Risk Assessments.

Declaration

I, the undersigned, hereby declare that this thesis, submitted for the degree of Doctor of Philosophy (Environmental Management), is my own and original work except where acknowledged. This work has not been submitted for a degree at any other tertiary institution.

Ida Paul

Disclaimer

This thesis consists of a series of chapters that have been prepared for submission to, or publication in, a range of scientific journals. As a result overlap may occur to secure publishable entities.

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SOLI DEO GLORIA

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Chapter 1 — Background and Aims

1.1 Citrus

Citrus has been cultivated for thousands of years (Reuther et al., 1967). The fruit is popular for consumption as fresh produce and in processed products like juices and jams. It is one of the most important fruit crops in world trade and globally, in terms of volume, it is the second biggest fruit crop (after grapes) (Spiegel-Roy & Goldschmidt, 1996).

In South Africa, the citrus industry significantly contributes to the economy and it is the second largest earner of foreign exchange in terms of agricultural exports (Mabiletsa, 2003). South Africa is also the third largest exporter of fresh citrus (FAO, 2002) and fruit is exported to more than 50 markets (Mabiletsa, 2003).

1.2 Citrus Black Spot

Citrus Black Spot (CBS) is a fungal disease of citrus leaves and fruit that causes superficial lesions on the rind of fruit. It is caused by *Guignardia citricarpa* Kiely (Brodrick, 1969; Kotzé, 1981). The disease was first described from Australia by Benson (1895), and has since spread throughout many of the citrus cultivation areas of South Africa (Kotzé, 1981; Wager, 1952) and around the world (European Union, 1998, 2000a).

1.3 Phytosanitary barriers to trade and Pest Risk Assessments

As a result of international travel and commerce, plant pathogens may be dispersed throughout the world. When these pathogens are introduced into a new area, and find a susceptible crop, they can have devastating consequences. Agricultural systems with an impoverished diversity are particularly vulnerable to new pathogens (Baker et al., 2000) and such introductions have had significant economic impacts (Pimentel et al., 2001).

Historically, invasive species have caused dramatic declines in citrus production and threatened citrus industries. Cottony-cushion scale (*Icerya purchasi* Maskell) arrived in California in 1869 from Australia and almost closed the Californian citrus industry. This pest was only brought under control by the introduction of an exotic ladybird beetle (*Rodolia cardinalis* Mulsant), a predator of the scale endemic to Australia (McKimmie, 2000). Citrus tristeza virus (CTV), a viral disease of citrus, was introduced into Spain between 1930 and 1935 through nursery trees imported from California. Since then, this virus has killed an estimated 40 million citrus trees in Spain, and caused major losses in Argentina, Brazil, California and South Africa. The planting of CTV resistant rootstocks and healthy nursery trees has reduced the incidence of CTV, and it is no longer a threat to the Spanish citrus industry (Cambra et al., 2000).

To prevent introductions of alien species, phytosanitary barriers to trade restrict the movement of citrus fruit, plants and plant products world-wide (Anonymous, 1986; Baayen et al., 2002;

European Union, 1998). However, countries may not impose unnecessary restrictions and these barriers are required to be based on scientifically justifiable principles (WTO, 1993). Ideally, the risk of pathogen introduction should be determined through a Pest Risk Assessment (PRA) that is supported by scientific research (IPPC, 1996).

Pest risk assessments evaluate the potential risks of introduction and establishment of a plant pest or pathogen into a new geographical location and assess the management options to reduce those potential risks (Rafoss, 2003). Pest Risk Assessments consider, amongst other things, the life-cycle, host specificity, and current and potential geographical distribution of the organism (McKenney et al., 2003). If findings suggest that the risk of introduction is very low, phytosanitary measures may be removed in part or all together.

Presently, phytosanitary barriers to trade restrict the export of citrus fruit from CBS infected areas in South Africa, and several other citrus producing countries where the disease occur, to the European Union (Bonants et al., 2003; European Union, 1998, 2000b) and the United States of America (Anonymous, 1986; Baayen et al., 2002). Whole consignments of fruit may be rejected at packinghouses or ports if, during inspection, they are found to contain affected fruit (Bonants et al., 2003). Consequently, CBS has a great impact on the global citrus trade, and is of great concern to growers.

1.4 Bioclimatic modelling of plant disease distribution

The survival and proliferation of a plant disease depends on favourable climatic conditions. In particular, temperature and rainfall strongly influence the occurrence of diseases (Booth et al., 2000a). This correlation between climate and disease occurrence means that the potential for a disease to occur in a particular area can be estimated from climate.

Bio-climatic modelling refers to the geographic modelling of the potential occurrence of a species as determined by climate (McKenney et al., 2003). These models may partly elucidate complex underlying climatic mechanisms that influence the geographical occurrence of plant pathogens and have proved useful tools in estimating the potential geographical ranges of exotic species (Baker et al., 2000; MacLeod et al., 2002; Rafoss & Saethre, 2003; Vera et al., 2002).

Bio-climatic modelling techniques are broadly divided into two categories: mechanistic and correlative models. Mechanistic models, also termed ecophysiological models or process models, are based on physiological characteristics of the species and aim to simulate the mechanisms that underlie species interaction with climate (Beerling et al., 1995; Peter et al., 2003). These models are difficult to build, complex, and time consuming, and rely on knowledge of the biology of the organism (Robertson & Palmer, 2002). Mechanistic models are very rarely used to predict species distributions because of the complexity in describing the species ecophysiological response to a variety of climate variables. Correlative models are based solely on observed correlations between climate and the known distribution of the species (Beerling et al., 1995). These models rely on distribution data and a set of predictor variables and they are easier to build than mechanistic models, less time consuming (Peter et al., 2003) and have been used extensively to predict the distributions of species (Beerling et al., 1995; Hill et al., 2002; Hill et al., 1999; Huntley et al., 1995; Leathwick, 1995). Correlative models that make use of species presence and absence data are referred to as group discrimination techniques and those that use only species presence data are referred to as profile techniques (Robertson & Palmer, 2002).

A large variety of correlative modelling techniques exist, all of which have different strengths and weaknesses. At its simplest, a correlative model is used to compare the climate in an organism's home range to the climate of another area to determine whether the other area is climatically suitable for the organism. More complex models infer the climatic requirements of the species from the known distribution and then assess the suitability of climatic conditions at thousands of locations. These locations are often represented using a regular grid (Baker et al., 2000).

These models require distribution data and suitable climate variables that are correlated to the species distribution. Methods that predict the potential distributions using climatic variable values inferred from the known distribution may prove fairly accurate, but greater precision can be achieved when selecting bioclimate variables or thresholds according to predetermined biological responses (Baker et al., 2000; Huntley et al., 1995; Prentice et al., 1992). Often these bioclimate variables and thresholds are in accord with the known distribution of the species (Baker et al., 2000).

Brasier and Scott (1994), gave one of the first examples of the bio-climatic modelling of plant disease distribution. They showed how the current distribution of a European disease of oak, caused by the fungus *Phytophthora cinnamomi* (Rands), was likely to shift northward under climate change. Since then, many other studies have modelled the geographical distributions of plant pathogens (Booth et al., 2000a; Booth et al., 2000b; Brasier, 1996; Ekins et al., 2002; Hoddle, 2004; Lanoiselet et al., 2002; Meentemeyer et al., 2004; Pethybridge et al., 2003; Pivonia & Yang, 2004; Van Staden et al., 2004; Yonow et al., 2004).

It should be stressed that bio-climatic modelling is an exploratory approach. It does not consider whether a species range is defined by biological interactions (Baker et al., 2000; McKenney et al., 2003) or physical barriers. Bio-climatic modelling may also not take human influences into consideration, for example agricultural environments allow more extensive distribution and spread of pathogens than would take place in a natural environment (Baker et al., 2000). Finally, bioclimatic models may not always take fundamental aspects of biology into account. The distribution of an obligate pathogen is limited by the distribution of its host regardless of climate (McKenney et al., 2003). Therefore, outputs from these models should be interpreted with caution, and should always be considered taking into account the input data (Nelson et al., 1999).

With these potential limitations in mind, bio-climatic modelling can be a valuable tool in estimating the potential distribution of organisms under current and future climates. It may be particularly relevant to studies in the agri-environment where competitors and natural enemies are limited by crop management techniques and the structure of the agro-ecosystem (Baker et al., 2000). Bio-climatic modelling can support PRAs and management decisions by providing a best estimate as to whether a pest or pathogen can occur in a given region. If an area may be vulnerable to infestation, resistant or tolerant crops can be planted, or an early detection system can be put in place to prevent the pathogen from becoming established. On the other hand, if the risk that a pathogen may become established in an area is extremely low, quarantine and preventative measures can be removed.

Unfortunately, the different modelling approaches can give different results (Robertson et al., 2003). Most studies that estimate potential distributions of pathogens only rely on the outcome of a single modelling approach without investigating different approaches. In this thesis two different modelling approaches are used to model the distribution of CBS.

1.4.1 CLIMEX

CLIMEX is a tool for estimating the potential distribution of invasive species. It has previously been applied to predict the occurrence of insect pests (D'Adamo et al., 2002; Kriticos & Wharton, 2004; Rafoss & Saethre, 2003; Robinson & Hoffmann, 2001; Venette & Hutchison, 1999; Vera et al., 2002; Worner, 1988) and some plant pathogens (Hoddle, 2004; Pivonia & Yang, 2004; Yonow et al., 2004). For a comprehensive list of previous studies see Sutherst et al. (2003).

CLIMEX contains two different climate-matching tools. The CLIMEX 'Match Climates' function and the CLIMEX simulation model also known as the 'Compare Locations' function. The Match Climates function compares the climate in the home range of the species to other areas to determine the similarity in climate and make a rough first assessment of the risk of establishment. To apply the CLIMEX model, the user infers the climatic conditions that the species can tolerate from the known geographical distribution of the species.

1.4.2 Response surface modelling

Predictions made using response surface modelling rely on the assumption that the present distribution of the species being modelled is determined by the bioclimate variables to which a correlation is demonstrated (Huntley et al., 1995). These techniques relate species distribution to environmental variables, which include climate and elevation data, by using a locally weighted regression. This approach has mainly been used to study the potential distribution of plants (Beerling et al., 1995; Huntley et al., 1995; Shafer et al., 2001) and butterflies (Hill et al., 2002; Hill et al., 1999) in the northern hemisphere, but recently it has also been used to predict the potential distribution of birds in Africa (BirdLife International, 2004).

1.5 The impact of climate change on plant pathogens

Human activities are changing the climate of the world. The emission of radiatively active gasses, in particular, are changing the composition of the atmosphere (IPCC, 2001). Global Climate Models (GCMs) that simulate the earth's climate system estimate that over the next century the mean surface air temperature will increase by 1.4–5.8°C and rainfall intensity and timing will become more variable (IPCC, 2001). These changes are already affecting ecosystems and species (Hughes, 2000; Parmesan & Yohe, 2003).

However, there have been few studies into the effect that climate change will have on the distribution of plant diseases (Coakley et al., 1999). Of these studies, most researchers concentrate on fungal plant pathogens (Baker et al., 2000; Bergot et al., 2004; Brasier, 1996; Brasier & Scott, 1994; Chakraborty & Datta, 2003; Chakraborty et al., 2000; Manning & Tiedmann, 1995).

Fungal growth and infectivity depend basically on temperature and moisture. An increase in humidity, dew, rainfall or temperature may directly affect the pathogen and its viability. The ecology of soil and plant surfaces may also be altered and a new climate may favour the development and survival of one microbe over another (Chakraborty et al., 1998).

In general, predicting the consequences of climate change remains very complicated and speculative, especially as predictions cannot be validated (Chakraborty et al., 1998; Dukes & Moony, 1999). Nevertheless, bioclimatic models can help give a best estimate as to how the geographical distribution of pathogens may change (Scherm & Coakley, 2003). Results obtained from these models may assist with the timely implementation of plant disease management strategies (Rafoss & Saethre, 2003).

1.6 Thesis aims

In 2000, a PRA study was undertaken by South African researchers to estimate the potential risk of CBS introduction into European countries through commercial citrus fruit exports (Hattingh et al., 2000). Results suggest that the risk of introducing CBS based on the etiology of the pathogen and epidemiology of the disease is low. In response, the European Commission stated that there is not enough scientific evidence to support a final decision to amend current phytosanitary regulations (European Union, 2001). They required more research on the climatic conditions necessary for the establishment of CBS. This project was designed, in part, to address this question.

The main aim of this study is to model the geographical distribution of CBS primarily in South Africa, Australia and Europe under current and future climates. The premise is that CBS currently only occurs in areas that are climatically suitable for disease development. An underlying objective was to clarify where CBS does not occur and where it is unlikely to establish.

To gain confidence in the results, two different correlative modelling approaches are used to map the potential distribution of CBS; the climatic modelling program CLIMEX, a profile technique correlative model (Hearne Scientific, Melbourne, Australia) (Sutherst & Maywald, 1985), and response surface modelling, a group technique correlative model (Beerling et al., 1995).

The approach is to:

1. review citrus and map areas of cultivation (Chapter 2);
2. review Citrus Black Spot (Chapter 3);
3. estimate the potential geographical occurrence of CBS under current climate [Chapter 4 (CLIMEX — Match Climates), Chapter 5 (CLIMEX — Compare Locations), Chapter 8 (Response Surfaces)];
4. estimate the potential geographical occurrence of citrus under current and projected future climates [Chapter 7 (Response Surfaces)]; and
5. model the potential occurrence of CBS under climate change [Chapter 6 (CLIMEX — Compare Locations), Chapter 8 (Response Surfaces)].

A summary of the conclusions is presented in Chapter 9.

Since this study is novel within the field of citriculture, it may serve as an example for future applications of bio-climatic modelling. When considering climate change, similar research applied to pathogens that globally threaten citrus cultivation could support the sustainability of citriculture.

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Chapter 2 — A review of citrus and of global citrus production

2.1 Abstract

Citrus has been cultivated and enjoyed by people for thousands of years. It is a diverse crop with many different kinds and varieties of fruit that can be consumed in different ways. Today, it is the second largest fruit crop in the world and the largest in global trade. In this chapter, the history, taxonomy and production of citrus, and the citrus industry in South Africa are reviewed. Then the current global citrus production areas of the world are reviewed and mapped.

2.2 Origin and history

Citrus has an important place in human history, featuring in the religion and mythology of many cultures. In India, a reference to citrus appears in a collection of devotional texts dated *circa* 800 B.C. In China, sweet oranges have been grown for centuries and were mentioned in a poem written in 314 B.C. Roughly in the same period, citrus fruits are mentioned for the first time in European literature (Reuther et al., 1967). The spread of citrus is well documented as travellers mentioned trees and fruit in their narratives. As humans explored the world, citrus — popular for its fruit, its fragrant flowers and as an ornamental — accompanied them (Reuther et al., 1967).

The exact origins of citrus are uncertain, but it is speculated that species of the genus *Citrus* is native to the tropical and subtropical regions of Asia and the Malay Archipelago. The oldest citrus growing area in the world is probably between south-east China, the Malay Peninsula and Burma. It is thought that mandarins, pummelos and limes originated from this region. From here, citrus appears to have been first taken south-east through the Philippines and the Pacific Islands (Spurling, 1969). Citrus was subsequently introduced to Europe around 310 B.C. and only arrived in the southern parts of Africa around 1650 A.D. (Reuther et al., 1967).

Citrus cultivation entered a period of rapid expansion around the start of the twentieth century, in response to a growing market demand and improvement of market quality as a result of refrigeration. The discovery of vitamin C and its importance in the human diet also increased the positive consumer attitudes towards citrus (Reuther et al., 1967).

Today, in terms of volume, citrus is the second largest fruit crop in the world, and the most important fruit in world trade (Spiegel-Roy & Goldschmidt, 1996). In 2002, the total world-wide annual citrus production was estimated at 104 505 157 metric tons (FAO, 2002a), and, in 2000, the value of global exports was 4000 million US dollars (FAO, 2004).

2.3 Uses of fruit

Citrus is mainly consumed as fresh fruit or juice (either fresh or processed). However it has many other uses. Processed citrus products include citric acid, essential and distilled oil, jams, jellies, gel products and citrus alcohol, wines and brandies (Spiegel-Roy & Goldschmidt, 1996). By-products from juice extraction are important in soft drink, pectin and cattle feed production. Citrus fruit is also popular as an ingredient in confectionary (Ray & Walheim, 1980); and several flavonoid compounds are used by the pharmaceutical and food industries (Spiegel-Roy & Goldschmidt, 1996).

2.4 Taxonomy and commercially important groups

The genus *Citrus* belongs to the order Geraniales and family Rutaceae (Davies & Albrigo, 1994). The Rutaceae contain about 150 genera, 1600 species, and is divided into seven subfamilies. True citrus and related genera are part of one of the seven subfamilies called the

Aurantioideae (Spiegel-Roy & Goldschmidt, 1996). Citrus hybridise naturally and therefore there is no clear reproductive separation among species (Davies & Albrigo, 1994; Spiegel-Roy & Goldschmidt, 1996).

World-wide there are five major groups that are of commercial significance: sweet oranges (*Citrus sinensis.* [L.] Osb.), mandarins (*Citrus deliciosa* Ten., *Citrus reticulata* Blanco and *Citrus unshiu* Marc.), grapefruit (*C. paradisi* Macf.), lemons (*Citrus limon* Burn. F.) and limes (*Citrus aurantifolia* L.) (Davies & Albrigo, 1994). Within each species are various cultivated varieties (cultivars), which differ in fruit size, shape, seed content, quality, and season of maturity (Timmer & Duncan, 1999).

2.4.1 Sweet oranges

Sweet orange (*C. sinensis*) is the most widely distributed and the most produced citrus crop in the world (Ray & Walheim, 1980). Climatic adaptability and a variety of cultivars give it the ability to grow in different growing regions. Sweet oranges are divided into four groups: round, navel, blood and acid-less. Round oranges are commercially the most important group, followed by navels. Blood oranges are mainly grown in Mediterranean areas and acid-less oranges are confined to backyard use and do not have commercial importance (Davies & Albrigo, 1994).

2.4.2 Mandarins

Mandarins are primarily produced for the fresh fruit market. They include numerous species, and may be divided into several groups including the Mediterranean mandarins (*C. deliciosa*), the common mandarins (*C. reticulata*), the Satsuma group (*C. unshiu*), the naturally occurring hybrids (e.g. the Temple mandarin) and other mandarin hybrids (e.g tangelos). The term “mandarin” is used in Japan, China, Spain and Italy. The term “tangerine” is used to refer to mandarin-type citrus in Australia and the United States of America (USA). In South Africa, mandarins are referred to as soft citrus (Davies & Albrigo, 1994).

2.4.3 Grapefruit

Grapefruit (*C. paradisi*) is probably not a true species, but a hybrid of pummelo and sweet orange (Spiegel-Roy & Goldschmidt, 1996). It is divided into two groups, white and red-fleshed grapefruit. Although these fruit are the largest of the major commercial cultivars, they are not as widely produced as mandarins or oranges. Grapefruit are mostly sold as fresh fruit (Davies & Albrigo, 1994).

2.4.4 Lemons

Excluding those used as rootstocks, lemons (*C. limon*) are divided into three groups: Femminello, Verna (Berna) and Sicilian. Distribution and production of lemons are limited to semi-arid to arid subtropical regions with minimum temperatures of greater than about 4°C (Davies & Albrigo, 1994).

2.4.5 Limes

Lime trees (*C. aurantifolia*) are the most frost sensitive of all commercial citrus species. Their distribution is limited to warm and humid tropical and subtropical regions where minimum temperatures remain above approximately 2°C. The two major groups of limes are the acid and acid-less limes, of which only acid limes are of commercial importance (Davies & Albrigo, 1994).

2.5 Climatic and geographic factors that influence cultivation

The culture of citrus requires a low frost incidence, enough moisture to sustain the trees, and suitable soils. These factors have a marked influence on the growth, development and productivity of trees (Davies & Albrigo, 1994; Timmer & Duncan, 1999). Nevertheless, citrus can be grown in a wide range of conditions.

Temperature, especially low temperatures and frost, is the main factor that governs the global range of citrus production (Davies & Albrigo, 1994; Spiegel-Roy & Goldschmidt, 1996). Limited growth occurs in all citrus tree organs at temperatures below 13°C. Extremely high temperatures of above 50°C also influence growth and development of citrus trees (Davies & Albrigo, 1994).

Significant induction of flowering requires that there is a period of drought of longer than 30 days and that temperatures stay below 25°C for several weeks. The degree of induction is proportional to the severity of and duration of stress. Flowering is not induced below 9.4°C (Davies & Albrigo, 1994).

Good quality irrigation water is a basic requirement for the successful cultivation of citrus (Srivastava & Singh, 2002). A lack of quality irrigation water limits citrus production in various regions of the world, including parts of Brazil, China and Mexico (Davies & Albrigo, 1994).

Citrus is grown in, and can adapt to, a wide range of soil conditions, but it grows best in sandy or clay loam soils. Soil properties may influence the growth habit of trees, especially root distribution. Adequate soil drainage is vital for growth as tree growth is reduced in poorly drained soils (Davies & Albrigo, 1994). Accumulation of free water in the root zone may also result in poor aeration and eventually lead to root injury (Timmer & Duncan, 1999).

2.6 Other factors that influence cultivation

The most significant limitation to profitable citrus production, other than climate and soil, is disease (Davies & Albrigo, 1994). A disease of citrus may be defined as differences from the normal appearance, form or functioning of a citrus tree or its fruit. Diseases are classified as infectious (biotic) or non-infectious (abiotic) diseases (Timmer & Duncan, 1999). Biotic diseases are caused by bacteria, fungi, mycoplasmas or viruses. They may cause the death of citrus trees or seriously limit production (Davies & Albrigo, 1994; Timmer & Duncan, 1999). Abiotic diseases are caused by nutritional and genetic defects and incorrect cultural practices, such as the inappropriate application of chemicals (Timmer & Duncan, 1999).

The occurrence and severity of a biotic disease is determined by, amongst other factors, the local climatic and environmental conditions, the virulence of the pathogen, and the susceptibility of the host plant (Timmer & Duncan, 1999). The absence of a biotic disease in a specific citrus growing region may be attributed to geographical isolation or to active exclusion of the causal agent. The local climatic conditions may also be unfavourable for infection or pathogen survival. This is often the case in arid and semi-arid areas where there is insufficient humidity for the causal agents to persist or cause infection, even if they were introduced (Timmer & Duncan, 1999).

2.7 Citrus health management

Prevention is the only truly effective means of reducing the losses caused by most citrus diseases (Timmer & Duncan, 1999). Disease control is usually specific to a particular disease, but there are some general concepts that are applicable to disease control in general. Most importantly, disease-free material should always be used in citrus cultivation (Davies & Albrigo, 1994). Pathogen-free and healthy sources of bud-wood are maintained for distribution to nurserymen and growers. A reliable source of disease-free planting material is essential to the success of any citrus industry as dissemination of diseased trees may have catastrophic effects. For this reason, citrus producing countries have stringent nursery regulations (Davies & Albrigo, 1994). In most countries where citrus is produced there are also restrictions on the import of citrus fruit and propagating material from areas where particular diseases occur.

Diseases may also be avoided by planting rootstocks and scions tolerant of or resistant to local diseases (Davies & Albrigo, 1994). However, the choice of cultivar is usually dictated by consumer demand and growers often plant disease susceptible cultivars even though more resistant cultivars are available (Timmer & Duncan, 1999).

Chemical control of diseases can be costly and labour intensive. Despite the potential adverse environmental impacts they might cause, copper and copper-based products are still widely used to prevent citrus diseases (Davies & Albrigo, 1994), but concerns about chemical residues are beginning to restrict the market access of fruit treated with chemicals. Moreover, there is an increasing public expectation that chemical inputs to the environment should be minimised. Therefore research is being focussed on alternatives to chemicals for the prevention and control of citrus diseases (Obagwu & Korsten, 2003).

2.8 The South African Citrus Industry

2.8.1 Origin and history

The arrival of citrus fruit in Southern Africa is documented in the journal of Jan van Riebeeck, the first governor of the Dutch colony in Cape Town (Reuther et al., 1967). On the 11th of June 1654, citrus plants arrived from the island of St. Helena, where citrus material had previously been established by Dutch merchants trading with the Orient (Oberholzer, 1969).

As pioneer settlers moved inland, they took citrus seed with them, but for over two centuries citrus production was only on a small scale and localised. With the discovery of diamonds and gold in the late 1800s, European immigrants flocked into the country. This created an increased demand for agricultural produce, including citrus. Initial plantings were small, as fruit was destined for local consumption (Oberholzer, 1969), but these plantings would eventually lead to the development of the South African export industry (Ray & Walheim, 1980).

2.8.2 The industry today

Citrus represents one of South Africa's most important agro-commodities. The total area under citrus cultivation is estimated at about 57 000 ha (Mabiletsa, 2003a) and citrus yields in mature orchards average about 40 to 60 tons per hectare (Mabiletsa, 2003b). Oranges are the most important citrus grown, with Valencias being the most important cultivar (Mabiletsa, 2003b). Lemons and grapefruit are also produced, but to a lesser extent (von Broembsen, 1986).

Citrus is grown in almost every province in South Africa. Main areas of production are found in Limpopo Province in the areas surrounding Tzaneen, Letsitele and Letaba; in Mpumalanga around Nelspruit, Hectorspruit, Groblersdal and Marble Hall; in North Western Province around Rustenburg; in Kwazulu-Natal around Muden; in the Western Cape Province around Clanwilliam (Kotzé, 2004, Personal Communication), Citrusdal, Somerset West and Grabouw (Kelly, 1995); and in the Eastern Cape Province around Uitenhage, the Kat River and the Sundays River Valley (Mabiletsa, 2003b; Oberholzer, 1969; Reuther et al., 1967; Urquhart, 1999). Smaller areas of citrus cultivation can be found in the Vaalharts and Warrenton areas (Mabiletsa, 2003a) and other parts of the Northern Cape (le Roux, 2004; Urquhart, 1999).

Citrus is cultivated in a variety of different climatic regions which allows a range of cultivars and varieties of fruit to be produced across South Africa (Mather, 1999). The Western Cape and Eastern Cape are considered to be cooler citrus growing areas and production is focussed on lemons (Veldman & Barry, 1996), Navel oranges and soft citrus (mandarins). In these two regions farm sizes are smaller than in Mpumalanga, Limpopo and KwaZulu-Natal, where the climate is better suited to the cultivation of grapefruit and Valencia oranges. In terms of volume, Mpumalanga and Limpopo provinces produce the greatest amounts of citrus (Mather, 2003).

Citrus cultivation requires access to water and the majority of farms operate with capital-intensive irrigation equipment. Fruit farming is labour intensive, particularly during harvesting season. More than 100,000 farm workers are permanently employed with an additional unknown number of seasonal workers also employed (Mather, 1999). The other main cost associated with citrus production is agrochemicals (London & Myers, 1995).

2.8.3 Export of citrus from South Africa

The introduction of refrigerated shipping facilities led to the first ever successful export of 3000 standard cases of citrus fruit to the U.K. in 1906. This was a great stimulus for citrus production in South Africa (Oberholzer, 1969). Since then export of citrus fruit has increased steadily. By the 1960s, South Africa was exporting over half of all southern hemisphere fresh citrus and was ranked amongst the top five fresh citrus exporters in the world (Mather, 2003). Currently, South Africa is the world’s third largest exporter of fresh citrus fruit after Spain and the USA (Citrus Growers Association, 2004; FAO, 2002a), and up to 70% of the citrus produced is exported annually, with more than 50 million cartons sold world-wide. This earns South Africa around R2 billion in foreign exchange (Mabiletsa, 2003b).

South African citrus exports provide overseas markets with a steady supply of citrus as fruit from different geographical areas in this country matures at different times. In Limpopo Province and Mpumalanga, fruit ripens earlier than the citrus varieties in the relatively cooler Western and Eastern Cape regions (Mather & Greenberg, 2003). The combination and assortment of fruit available and South Africa’s counter-season advantage in being able to supply fruit to countries in the northern hemisphere during its summer is central to the South African Citrus Industry’s marketing strategy (Mather, 1999).

The export period is from April to October. South Africa’s most important competitors are Argentina, Chile and Australia during the main season; and Israel, Spain, Egypt and the USA towards the end of the marketing season. The biggest export market is Europe, followed by the Middle East, Japan, the Far East and the USA (Mabiletsa, 2003b).

Global citrus consumption is increasing very slowly, but competition for citrus markets is strong. Markets in the northern hemisphere are regularly oversupplied. Longer seasons in northern hemisphere citrus production have also exacerbated problems of oversupply (Mather, 2003).

Citrus which cannot be exported because of quality and excessive chemical residues is sent to the domestic market (Urquhart, 1999).

2.9 Citrus production around the world

Citrus trees are sensitive to below freezing temperatures and outdoor growing areas are limited to the tropics and subtropics. Production is mostly limited to latitudes of between 40°N and 40°S, where minimum temperatures are greater than approximately 7°C (Davies & Albrigo, 1994).

The three major citrus producing countries; Brazil, USA and China dominate global production, producing around 40% of the world's citrus. Other major citrus producing countries include Mexico, Spain and India, but these together produce only 8% (FAO, 2004).

The citrus industry of the world is vast and constantly changing as millions of trees are uprooted or planted every year. Production areas may shift as a result of diseases or market forces. However, there is no recent overview of global citrus cultivation. In the following section citrus production areas of the world are reviewed and mapped. The aim is to collate information on geographical areas of citrus cultivation, to document the major types of citrus grown, and to produce maps that broadly indicate areas of citrus cultivation. A review of global citrus production areas is a daunting task as information of citrus growing areas are not generally published and if it is available, the information is often presented in the countries' native language. Therefore the database presented is incomplete and will need regular updating, but still it has several important applications. For example it may enable the collation of more detailed distribution of citrus within these broad areas and also the collation of citrus pathogen distribution data for future use in citrus disease management.

World-wide, citrus production regions can be divided into 6 major regions, (with approximate percentage of world production in 2002 indicated): Asia (31%), South America (25%), North and Central America (22%), Africa (11%), Southern Europe and Asia Minor (10%) and Oceania (0.6%) (FAO, 2002b). Citrus producing counties in these six regions are reviewed in descending order of the volume of total citrus fruits produced in 2002.

2.9.1 Asia

In Asia, citrus has been cultivated for thousands of years (Iwagaki, 1991; Reuther et al., 1967; Zhaoling, 1986). Many types of citrus originated in South East Asia and today it is one of the most important agricultural crops produced. Much of Asian production occurs on small farms. These farms have higher production costs and lower yields than Western citrus producing countries (Bové, 1995), as diseases, especially virus-like diseases, impair production. Additionally, there is a lack of suitable improved varieties and of disease-free planting material (Anonymous, 1996; Bové, 1995).

Citrus industries in the Far East mainly produce mandarins (Anonymous, 1990; Bean et al., 2003; Hardy, 1997; Iwagaki, 1991; Mahajan, 2002; Singh, 1969). Citrus industries of Near East Asia are far smaller and less developed and grow different kinds of citrus, such as oranges, mandarins, limes, lemons and grapefruit (Bové, 1995; Catara et al., 1988; Reuther et al., 1967). The industries of the Near East are particularly affected by high temperatures and water scarcity (Bové, 1995; Singh, 1969).

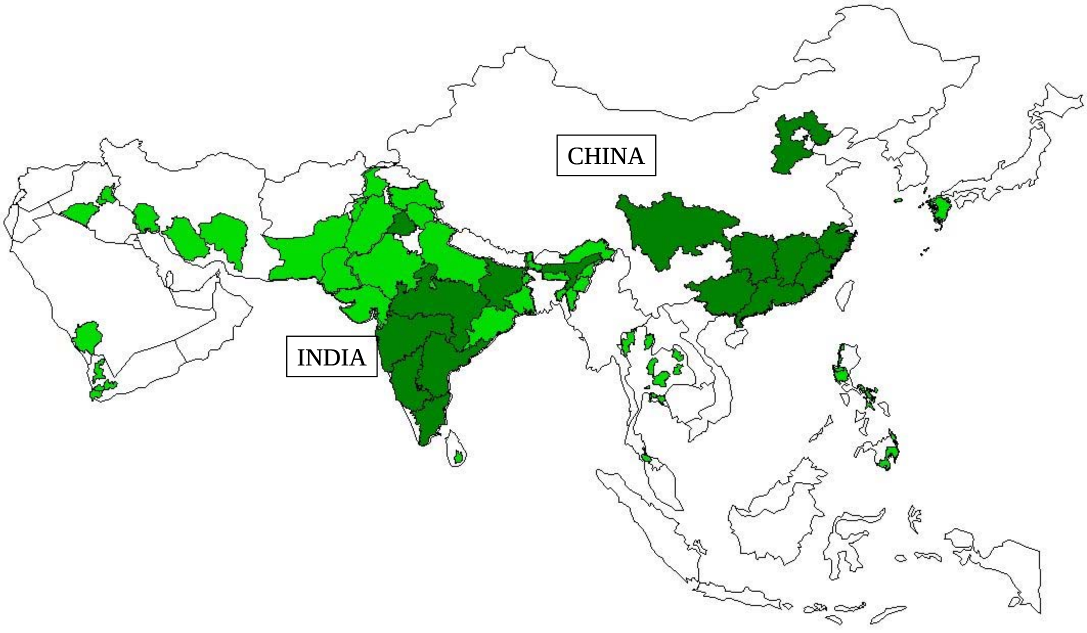

Figure 2.1 — Some of the administrative regions where citrus is produced in Asia. The two countries which produce the most citrus are indicated. Major areas of production are indicated in a darker colour.

2.9.2 South America

Citrus is cultivated in all South American countries, although there is significant variation in the quality and quantity of production. Mainly oranges and lemons are produced, with Brazil being the world's biggest producer of oranges (Barros, 2003; Donadio et al., 1996; Passos et al., 1999) and Argentina being third in the production of lemons and limes (FAO, 2002a). Lemons and limes also dominate citrus cultivation in Peru, as they are used in local beverages. In Brazil, citrus canker and Sudden Death of Citrus disease are the greatest threats to the industry. Unofficial estimates of 2002 suggest that between one and three million plants could be affected by the Sudden Death of Citrus disease in this country (Barros, 2003).

Figure 2.2 — Some of the administrative regions where citrus is produced in South America. The two countries which produce the most citrus are indicated. Major areas of production are indicated in a darker colour.

2.9.3 North & Central America

The USA is the second largest producer of citrus globally, and, as a result, citrus ranks as the fruit crop of greatest economic value in this country. Production is concentrated in the states of Florida, California, Arizona and Texas. The differences in climate between these states result in different patterns of production. Frost is the main concern of the industry (Hearn, 1986; Jacobs, 1994). The USA mainly grows oranges and grapefruit, of which 75% of oranges and 50% of grapefruit are processed (Jacobs, 1994). Fresh citrus exports are small in comparison to other citrus industries (Jacobs, 1994), but the USA is the world's biggest supplier of fresh grapefruit.

Citrus is produced throughout the countries of Central America. Mexico is the fourth largest producer of citrus in the world, and the largest producer of lemons and limes (FAO, 2002b).

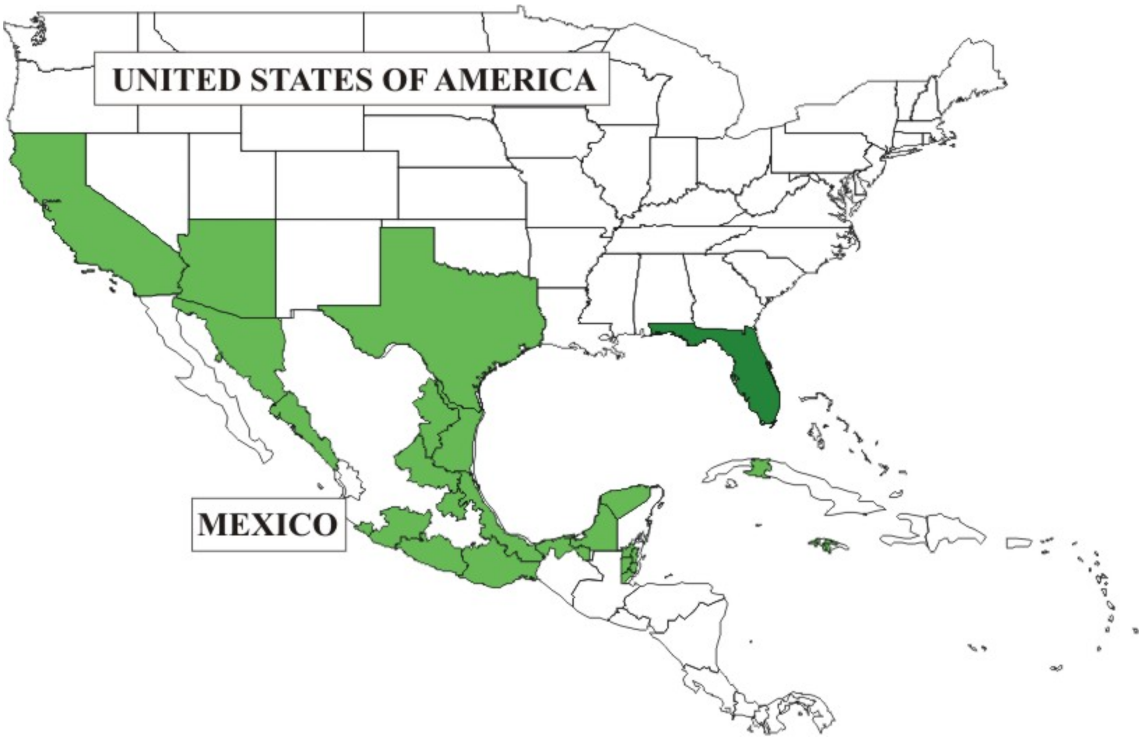

Figure 2.3 — Some of the administrative regions where citrus is produced in North and Central America. The two countries which produce the most citrus are indicated. Major areas of production are indicated in a darker colour.

2.9.4 Africa

In Africa, citrus is cultivated over a wide range of geographical and climatic zones (Rey, 1997; Stanbury, 1996). Rootstocks and varieties have been specially developed to suit the varying climatic conditions.

In Central and Western Africa, citrus is the second largest fruit crop after bananas. The main constraints to production are disease, including African leaf and fruit spot disease, tristeza and Huanglongbing (Citrus Greening). In rainforest areas citrus is grown with cocoa trees and other small cash crops as part of mixed cropping systems. In Western and Central Africa the entire citrus crop is sold on local markets as fresh fruits. Fruits tend to stay green as a result of inadequate periods of low temperatures and are thus not suitable for the export market (Rey, 1997).

In Southern Africa the industry is dependent on export. Most citrus production areas are situated in rural areas. These industries are of major importance to the economies and provide employment for hundreds of thousands of people (Stanbury, 1996).

Figure 2.4 — Some of the administrative regions where citrus is produced in Africa. The two countries which produce the most citrus are indicated.

2.9.5 Southern Europe and Asia Minor

This region mostly produces oranges and mandarins, but also a wide range of other citrus. Most of the industries sell fruit in the EU, with the industries in Turkey and Spain largely depending on this market. Italy produces blood orange varieties (Tarocco), which have a good market share in Europe (Regini, 2002). Italy, Spain and Greece also produce large quantities of organic citrus for sale in the EU, with Italy being the largest producer of organic citrus in the world (Liu, 2003).

Figure 2.5 — Some of the administrative regions where citrus is produced in Southern Europe and Asia Minor. The two countries which produce the most citrus are indicated.

2.9.6 Oceania

Most of Australia's citrus production is consumed locally, although some fresh citrus is exported, particularly to the USA and Asia. Citrus is the largest overall horticultural export and significant amounts of research are aimed at overcoming market access barriers (Horticulture Australia, 2002). In New Zealand the industry is small, but it is also of economic importance (Reuther et al., 1967).

Citrus is also produced in many South Pacific Islands, and is an important part of the food crops grown for domestic use (Clarke & Thaman, 1993). However, citrus production suffers from diseases, insect pests, and damage from tropical cyclones and high winds. Consequently, citrus crops are uneconomic and further development will require aid.

Figure 2.6 — Some of the administrative regions where citrus is produced in Oceania. The two countries which produce the most citrus are indicated.

2.10 Tables of the citrus producing countries of the world

Seven tables are presented here, one for each citrus producing area of the world, and one for the citrus producing states of the USA. Countries are presented in descending order of volume produced in 2002 (FAO, 2002b) with production expressed as metric tonnes. Only countries where detailed information could be obtained are presented in the tables, but after each table is a list of countries that also produces citrus in that region. A list of references for the specific countries is presented in Table 2.8. For most countries, information was obtained from FAO 2002b, but for brevity this reference is not repeatedly included.

Table 2.1 — Citrus producing countries of Asia.

Country (Asia)	**2002 production (tonnes)**	**Types cultivated**		**Citrus cultivation areas (areas in bold are indicated on the map)**	**Notes**	**Refs**
		Major types	**Other types**			
China	12 469 639	Mandarin Orange	Pummelo Kumquat Ornamental citrus	Commercial citrus is grown in 19 provinces. The provinces where most citrus is produced are **Sichuan, Guangdong, Zhejiang, Guangxi, Hunan, Fujian, Hebei Chongqing** and **Jiangxi**.	Third largest producer of citrus world-wide. Greatest producer mandarins.	17 36
India	4 580 000	Mandarin Sweet orange Acid lime	Grapefruit Pummelo Lime	Citrus is grown in the states of **Maharashtra, Andhra Pradesh, Punjab, Karnataka, Bihar, Tamil Nadu, Madhya Pradesh Gujarat, Uttaranchal, Haryana, Himachal Pradesh, Punjab, Rajasthan, Jammu, Kashmir, Orissa, Uttar Pradesh, West Bengal, Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim** and **Tripura.**	Sixth largest producer of citrus world-wide, but does not play important part in citrus trade. Citrus productivity is low and post-harvest losses occur due to a lack of cold storage and modern processing facilities.	53 75 78
Iran	3 723 000	Orange Mandarin	Acid lime	There are three major citrus regions - the Caspian Sea belt; the southern coastal belt (including the Persian Gulf and the Gulf of Oman) and the southern inland belt. The southern inland belt is scattered through the low valleys of the southern Zagros mountain range and is part of the provinces of **Khuzestan**, **Fars** and **Kerman** (including areas around Dezful and Ahwaz, Kazerun, Jahrom, Darab, Minab, Jiroft, Bam and Shadad).	The seventh biggest producer of citrus in the world in 2002.	21

Country (Asia)	2002 production (tonnes)	Types cultivated Major types	 Other types	Citrus cultivation areas (areas in bold are indicated on the map)	Notes	Refs
Pakistan	1 995 000	Mandarin (Kinnow, Feutrell) Orange (Bloodred, Musambi)	Grapefruit Lemon Palestine lime	**Punjab** (including the cities of Islamabad-Rawalpindi, Sargodha, Faisalabad, Lahore, Sahiwal, Multan and Bahawalpur), Peshawar, **North-West Frontier Province (NWFP)** and the province of **Sind** (in Hyderabad).		21 23 75
Japan	1 438 000	Mandarin (Satsuma)		The citrus-growing area extends from Tokyo to the island of **Kyushu**. The principle areas are confined mainly to the south-western coastal prefectures of Shizuoka, Wakayama and Ehime. Other areas include Fukuoka, Saga, Nagasaki, Kumamoto, Oita, Kachoshima, Kochi, Tokushima, Yamaguchi, Hiroshima, Aichi, Mie, Kagawa, Shime, Osaka and Kanagawa.	Fourth largest producer of mandarins in 2002, but these are consumed locally and not exported. Despite large production, great quantities of citrus are imported. Phytosanitary barriers preventing the import of citrus from Argentina to Japan (due to Mediterranean fruit fly) were lifted in April 2003	42 44 45 48 49 53 60 72 78
Thailand	1 114 800	Mandarin	Orange	The two main areas of production in Thailand are the central coastal region and the mid-north inland region. Important areas of cultivation include the Ping river valley, Lamchi valley, Donburi and Haadyai. Citrus is also produced in **Chiengmai, Chonburi, Chandhaburi,** Pathom**, Nakhon, Nan valley, Petchboon, Roiet, Sonkla-Pattoni, Sakon Nakhon**.	Trees are harvested three to four times a year, but insect pests severely restrict production	6 78
Indonesia	986 132	Orange	Mandarin		Citrus fruits are a significant part of mixed village gardens (which constitute up to 20% of the agricultural land in Java)	7 72
Syrian Arab Republic	756 150	Orange	Mandarin Lemon	Main citrus growing areas are along the Mediterranean coast.	Citrus cultivation is economically important, but because fruits are consumed locally and not exported, there is price recession.	9 21 72

Country (Asia)	2002 production (tonnes)	Types cultivated Major types	 Other types	Citrus cultivation areas (areas in bold are indicated on the map)	Notes	Refs
Republic of Korea	643 525	Mandarin (Mikans)		The citrus industry is centred in the **Cheju** Province (an island of the southern tip of the Korean Peninsula).	Yields are improving and planting areas expanding as governmental support programs boosts the industry. The majority of fruit is consumed locally. Considerable amounts of citrus exports to the USA were refused due to citrus canker in 2002. This phytosanitary barrier remains.	10 66
Israel	510 487	Orange	Grapefruit Lemon Mandarin	Main areas extend along the coastal plain from Kfar Rosh Hanikra in the extreme north-western Gaza to Beer Sheba in the South. Citrus production is concentrated in the central area, within about 20 kilometres from the Mediterranean coast. A belt of citrus stretches inland along the Yesreel valley from Haifa to the Jordan River area below the Sea of Galilee. Newer plantings of mandarins can be found in the Northern Negev and internal valleys.	Water shortage, low profitability, aging orchards and competition from Spain and Morocco contribute to the steady decline of the industry. As an indication of its decline in importance, the Israeli Citrus Marketing Board closed at the end of 2003.	7 15 18 24 40
Lebanon	289 300	Orange (mainly Valencia)	Lemon Lime Grapefruit Sour orange	All areas are located on the coastal plain. Growing areas include Tripoli and Akkar in the north, and Sidon and Tyre in the south.		40 72
Yemen	198 182	Sweet orange	Lemon Sour orange Mandarin Small-fruited acid lime	Major area is the Lawdar-Mudia region, with production concentrated in Tihama. Other areas include: Say'un-Tarim (in Wadi Hadramawt), Mukayras, Zinjibar-Gaar areas and the Jawl-Madrum district (near Al Musaymir, **Al Baida**), **Ta'izz**, in the Barakani area, Mauza, Hammam Ali and **San'a** (Wadi Dahr), **Ibb** and Warazan (Al Rahida region).	There has been a decrease in citrus acreage in the last decade. This may be due to a decrease in rainfall as most irrigation water comes from wells and the Lawdar-Mudia area is running short of irrigation water.	21
Philippines	179 000	Mandarin	Orange	Mandarins were extensively grown in the Batangas region of Luzon but many orchards there have been destroyed by huanglongbing (Citrus Greening) and production has shifted to **Mindanao, Bicol, Ilocos** and the **Southern Tagalog** region in Luzon. Valencia oranges are grown in the Davao region of **Southern Mindinao.**		6 72

Country (Asia)	**2002 production (tonnes)**	**Types cultivated**		**Citrus cultivation areas (areas in bold are indicated on the map)**	**Notes**	**Refs**
		Major types	**Other types**			
Saudi Arabia	140 000	Orange (Navel, Valencia)	Lemon Lime Small amounts of grapefruit	Citrus is primarily produced in the highland oases of the **Asir**, from Taif to Najran, and in the Fayfa, Abha and Buraidah-Unaizah regions of which the Najran area is the most important area.	Phytophthora gummosis is a major disease of citrus in Saudi Arabia	21 90
Jordan	124 207	Mandarin	Orange Lemon Lime Small amounts of grapefruit	Citrus is primarily cultivated in the Jordan Valley, with mild wet winters and extremely hot dry summers.	Some citrus is exported, but, out of season, importation is necessary to meet local demand	21
Nepal	80 644	Mandarin	Junar orange Kagzi lime Pummelo Sweet lime Citron Bitter orange	The citrus zone in Nepal is between 900 and 1,500m above sea level. Kagzi lime is grown in the Hills and in the Tarai. Areas include: Baglung, Baitadi, Bhojpur, Dailekh, Dadeldhura, Dhankuta, Gulmi, Gorkha, Ilam, Jararkot, Kavre, Kaski, Lamjung, Palpa, Ramechap, Sankhuwasabha, Sindhuli, Sindhupalchok, Syangja, Tanahu and Tehrathum.		67 78
Palestine	74 589	Orange	Lemons Limes Mandarins Grapefruit		Citrus producing areas have been declining during the past 15 years, due to water-scarcity, poor institutional support and the poor quality of fruit produced.	12
Malaysia	30 391	Mandarin Orange	Lime Lemon Pummelo Grapefruit	The Cameron highlands are one of the major citrus growing areas in Malaysia.	Citrus are usually grown in home gardens	57 72
Sri Lanka	26 920	Mandarin Orange	Lime	The largest citrus area centres around Bibile-Moneragla in lower **Uva** Province. Small citrus areas exist north and west of this in the Lagalla district and the upper Gal Oya Valley. Other plantings may be found on the northern part of the island in the Vavuniya-Omantai district.	Citrus plantings are found throughout the island and are mainly home garden plantings, ranging from a few trees to half an acre.	72

Country (Asia)	2002 production (tonnes)	Types cultivated		Citrus cultivation areas (areas in bold are indicated on the map)	Notes	Refs
		Major types	Other types			
United Arab Emirates	21 255	Lemon Lime			Citrus comprises about 5% of the total fruit production with 80% of production being dates and about 10% being mangoes.	21
Iraq	data not available	Sweet orange (Mahali)	Mandarin Lemon	Citrus is grown mainly in central Iraq, north and south of **Baghdad**, along the banks of the River Tigris and its tributary, the River **Diyala**, as well as along the River Euphrates, north and south of **Kerbala**.	Citrus is mostly grown in the shade of date-palms to protect the citrus trees against high temperatures and solar radiation. This practice also protects against frost in the winter.	21 75
Oman	8385	Small-fruited acid lime	Palestine lime		Limes are an important export commodity and are grown in the northern coastal plain (Al Batinah).	21

Other citrus producing countries in Asia include Vietnam, producing 456,800 metric tons of citrus. Several other countries produce less than 100 000 metric tons a year and these include: Laos, Cambodia, Republic of Azerbaijan, Bangladesh, Georgia, Bhutan. Countries that produce less than 1000 metric tons yearly are Uzbekistan, Tajikistan, Bahrain, Qatar, Brunei Darussalam, Timor-Leste, Kuwait and the West Bank (FAO, 2002b).

Table 2.2 — Citrus producing countries of South America.

Country (South America)	**2002 production (tonnes)**	**Types cultivated**		**Citrus cultivation areas** **(areas in bold are indicated on the map)**	**Notes**	**Refs**
		Major types	**Minor types**			
Brazil	20 844 915	Orange	Mandarin Lemon Lime Grapefruit	Oranges are produced in 22 of the 27 states of Brazil. Citrus is predominantly produced in the state **São Paulo** with 80% of production coming from this state (main citrus growing areas within the state include Campinas, Ribeirão Preto, São Jose do Rio Preto and Sorocaba). A further 15% comes from **Bahia, Sergipe, Minas Gerais** and **Rio Grande do Sul**. Other citrus areas include **Espirito Santo and Rio de Janeiro** in the Southeast; **Alagoas, Ceará, Maranhão, Paraiba, Pernambuco** and **Piaui** in the Northeast; **Paraná** and **Santa Catarina** in the South; **Amazonas, Pará** and **Rondonia** in the North; and **Distrito Federal, Goiás, Mato Grosso do Sul** and **Mato Grosso** in the Central West.	The number one orange producer in the world produced almost 20% of the total world citrus production in 2002. It is the greatest exporter of frozen concentrated orange juice, but fresh orange exports are relatively small. Citrus canker, Citrus Black Spot, Greening and Sudden Death of Citrus disease are the greatest threats to the industry. Unofficial estimates in 2002 reports 1 to 3 million plants could be affected by the Sudden Death of Citrus disease.	16 27 29 46 56 64 69 79
Argentina	2 566 000	Lemon	Orange Mandarin Grapefruit	Large orange plantings can be found in **Corrientes, Misiones** and **Entre Rios** and lemons are grown in the **Tucuman**, **Salta** and **Jujuy** provinces.	Phytosanitary barriers to trade preventing the import of citrus from Argentina (due to Mediterranean fruit fly) to Japan was lifted in April 2003	25 36 48 72
Peru	727 614	Orange (mainly Valencia) Lemon Lime	Mandarin Grapefruit	Production areas are found along the Northern and central coastal areas and on the East Andean Slope. Orange production is concentrated within 90 miles of **Lima,** and limes are grown in the northern coastal area of **Piura,** adjacent to Ecuador. Mandarin, grapefruit and sweet lemon are produced in the areas of Lima, **Ica** and Piura.	Great amounts of citrus trees were devastated in the 1970s and early 1980s as a result of a then unknown pathogen, now thought to be Tristeza virus.	86
Bolivian Republic of Venezuela	630 883	Orange Mandarin	Lemon Lime Grapefruit	Main production areas are found in the states of **Aragua, Carabobo, Falcon, Miranda, Monogas, Sucre, Yaracuy** and **Zulia.**		54 72

Country (South America)	**2002 production (tonnes)**	**Types cultivated**		**Citrus cultivation areas** **(areas in bold are indicated on the map)**	**Notes**	**Refs**
		Major types	**Minor types**			
Paraguay	291307	Orange	Grapefruit Mandarin Lemon Lime	The country is divided into two major citrus producing areas. The eastern areas including: **Central, Cordillera, Caaguazu, Alto Parana, San Pedro, Concepcion, Amambay,** and **Itapua** and the western areas including: **Presidente Hayes** (area of Colorado and Teniente Irala Fernandes) and **Boqueron.**	Paraguay has a small domestic citrus industry and citrus groves are widely scattered throughout the country.	39 72
Chile	254 000	Orange Lemon	Mandarin Grapefruit	Citrus production falls within the provinces of **Coquimbo, Valparaiso, the Metropolitan Region, Libertador General Bernardo** and **Maule.** Citrus production areas include: Copiapó, Vallenar, Ovalle, La Ligua, Quilloca, Santiago, Santa Cruz and the valleys of La Serena, Elqui, Azapa, Petorca (near La Ligua), lower Aconcagua (near Quillota), Limarí and Huasco, Cachapoal (near Peumo Santiago) and Tinguiririca (near Nancagua).	Production areas lie within a hundred miles north and south of the capital Santiago. The Peumo-San Vicente Valley is the most important lemon and orange producing area, followed by scattered plantings on the Pacific Coast south and west of Santiago. Limes are grown at Pica near the Peruvian border.	35 63
Uruguay	235 516	Orange Mandarin	Lemon Grapefruit	**Salto** is the major area and, with exception of plantings in Melo, nearly all citrus is grown near the Uruguay River, including **Paysandú, Rivera, Cerro Largo, Maldonado, Montevideo, Canelones, San Jose** and **Florida.**	Mandarins are mainly grown in the north, while oranges are mainly grown in the south.	7 8 19 72

Other citrus producing countries in South America include Colombia, producing 297,962 metric tons, Bolivia, producing 255,355 metric tons, and Ecuador, producing 264,033 metric tons (FAO, 2002b).

Table 2.3 — Citrus producing countries of North and Central America

Country (North and Central America)	**2002 production (tonnes)**	**Types cultivated**		**Citrus cultivation areas** **(areas in bold are indicated on the map)**	**Notes**	**Refs**
		Major types	**Minor types**			
United States of America	14 690 951	Orange (Valencia) Grapefruit	Lemon Mandarin	Almost all citrus fruit is produced in four states- **Florida**, **California, Arizona**, and **Texas**. **Florida** is the largest producer, with over 70% of total production. Hawaii and Louisiana also produce some citrus (Table 2.7).	Second largest producer of citrus after Brazil. Citrus is mainly processed. Fresh citrus exports are relatively small, but the USA is the largest supplier of grapefruit.	7 43 46 68 72
Mexico	6 260 119	Orange	Lime Grapefruit	Citrus is produced in the states of **Colima, Michoacan, Guerrero, Oaxaca, Tamaulipas, Veracruz, San Luis Potosi, Hidalgo,Yucatan, Tabasco, Nuevo Leon, Sonora, Sinaloa Campeche**, states in the southern part of Mexico. Each of these states specialises in certain types of citrus with the production of Persian Limes, Mexican Key limes and Oranges being concentrated in different areas. All of Mexico's citrus is grown in the hot and temperate zones.	The area planted with Persian and Key Limes has increased in response to an increase in domestic demand, good prices on the international market, little competition from other countries and few phytosanitary concerns. Mexico is now the world's largest producer of Persian limes. Frosts and drought are the major problems faced by the Mexican citrus industry.	2 20 30 37 76 72
Cuba	480 501	Orange (Valencia)	Grapefruit Persian lime Lemon (Eureka) Mandarin (Dancy)	The biggest citrus growing area in Cuba is Jaguey Grande (in the province of **Matanzas**). Other citrus areas include Isle of Youth (located southwest of the coast) Guane, Ceiba, Sola, Ciego de Avila, Troncoso, Contramaestre, Arimao, Cap Thomas, Vilorio and Moron.	Citrus is widely grown throughout Cuba and citrus plantings can be found in every province. Persian lime is the most widely cultivated citrus. One of the industry's major concerns is the Tristeza virus.	2 29 41 38 56
Jamaica	221 000	Orange Grapefruit		Citrus production in Jamaica is concentrated in **Manchester, Clarendon, Westmoreland, St. Ann, St. James** and **St. Mary.**		2 72
Belize	213 414	Orange (Valencia)	Grapefruit	Historically citrus in Belize were grown mainly in the **Stann Creek Valley**, but now there are plantings in the **Belize, Cayo, Toledo** and **Orange Walk** districts as well.	Fires and hurricane damage threatens the industry. The export of citrus production is the Belize's an important source of income for the country.	8 10 72

Country (North and Central America)	2002 production (tonnes)	Types cultivated		Citrus cultivation areas (areas in bold are indicated on the map)	Notes	Refs
		Major types	Minor types			
Honduras	195 936	Orange	Grapefruit	Production areas include Bajo Aguan, Valle de Lean, the Sula Valley, Guinope, Valle de Angeles and Signatepeque.	Oranges are grown at low altitudes and are not of a high quality.	2

The Caribbean Community and Common Market (CARICOM) is made up of The Bahamas, Barbados, Belize, Dominica, Grenada, Guyana, Jamaica, Montserrat, St. Kitts and Nevis, St. Lucia, St. Vincent, The Grenadines, Suriname, and Trinidad and Tobago. In these countries, citrus is sold on the fresh fruit market predominantly for domestic consumption. Belize, Jamaica, and Trinidad and Tobago account for almost 90% of the regional citrus production. In these three countries, the citrus industry makes a significant contribution to economic development and rural livelihoods and contributes to foreign exchange earnings. Moreover, the industry represents an important source of income for thousands of small-scale rural agricultural producers. Oranges are the main citrus produced (approximately 65% of total production), followed by grapefruit (comprising 26% of production) (Donovan, 2002).

Other citrus producing countries are Costa Rica, producing 394,920 metric tons, and Guatemala, producing 252,877 metric tons. Countries producing less than 100,000 tonnes a year include Nicaragua, El Salvador, Haiti, Panama, Puerto Rico and the Bahamas. Countries that produce less than 1000 metric tonnes include: Guadeloupe, French Guiana and Martinique.

Table 2.4 — Citrus producing countries of Africa

Country (Africa)	**2002 production (tonnes)**	**Types cultivated**		**Citrus cultivation areas (areas in bold are indicated on the map)**	**Notes**	**Refs**
		Major types	**Other types**			
Nigeria	3 250 000			Citrus is mainly produced in western Nigeria. Two major processing plants are established in Ibadan (Oyo state) and Abeokuta (Ogun state)	Nigeria is the biggest producer of citrus in Africa, although citrus is mainly for domestic consumption.	61
Egypt	2 527 276	Orange	Lemon Sweet and sour lime Mandarin Small amounts of grapefruit	Most commercial production is within the Nile River delta provinces of Kalioubiya, Charkieh, Menoufieh, Gharbieh and Behera. Major citrus production, however, is concentrated in Lower Egypt. More recently planted orchards can be found in the newly reclaimed lands.	Egypt has recently seen large increases in production. The climate is well-suited for orange production, and this accounts for over half total production.	1 7 72
South Africa	1 712 149	Orange (mainly Valencia)	Grapefruit Lemon	Main areas are in **Limpopo Province** (in the areas surrounding Tzaneen, Letsitele, Letaba), **Mpumalanga** (areas surrounding Crocodile River Valley, Hectorspruit, Groblersdal, Marble Hall and Nelspruit), **North Western Province** (areas surrounding Rustenburg), **Kwazulu-Natal** (areas around Muden), **Western Cape Province** (areas surrounding Citrusdal, Somerset West, Grabouw) and the **Eastern Cape Province** (areas surrounding Uitenhage, the Kat River and the Sundays River Valley). Smaller areas of citrus cultivation can be found in the Vaalharts and Warrenton areas and other parts of the **Northern Cape.**	Lemons are predominantly produced in the Eastern and Western Cape Provinces.	47 51 52 61 72 81 82 83
Morocco	1 152 200	Orange	Mandarin Small amounts of grapefruit	The coastal areas of the Mediterranean Sea and Atlantic Ocean. The Souss Valley is one of the main production regions and about half of all citrus and half of all mandarins in Morocco are produced in this area. Other regions include the interior district of Tadla (at Beni-Mellal) the northern inland citrus areas of Meknes, Fes, the small coastal areas of Rabat and Casablanca, the greater inland areas of Marrakech and Gharb, and the northern coastal Oriental area.	Moroccan citrus orchards are old and more than 55% of the trees are older than 30 years. Citrus production areas are localized due to climate, topography, and water availability. Morocco has the capacity to increase its citrus output and the mandarin industry continues to grow.	7 21 28 87

Country (Africa)	2002 production (tonnes)	Types cultivated		Citrus cultivation areas (areas in bold are indicated on the map)	Notes	Refs
		Major types	Other types			
Algeria	520 019	Orange	Mandarin Small amounts of lemon, grapefruit and other mixed varieties	Citrus is produced along the coastal area at altitudes below 400m, where frosts are rare. Orchards are concentrated in five main areas namely **Blida** (in the Valley of Mitidja), **Mascara, Chlef, Mostaganem** and **Annaba.** Smaller plantings are found in the areas of **Skikda, Algiers, Tlemcen, Bejaia, Tizi Ouzou, Oran, Jijel, Guelma** and **Bouira.**	Generally, production per tree is low because of age, availability of irrigation water and cultural practices. Recently the government initiated a programme to reinvigorate the industry. About 130 000 nursery trees were introduced in order to meet future domestic demand and to develop the export market.	21 40 72
Tunisia	312 000	Orange	Grapefruit Mandarin Lemon Lime	The Cape Bon peninsula near Soliman, Menzel Bou Zelfa, Grombalia and Beni Khaled. Other citrus areas are on the southern side of Cape Bon near Hammamet, Nabeul and Ben Kriar as well as adjacent to the city Tunis.		72 78
Guinea-Conakry	210 000	Orange		Oranges are mainly grown in the area of the Foutah Djallon mountains.		71
The Sudan	148 460	Lemon Lime Grapefruit	Orange Mandarin		The first report on citrus trees in the Sudan dates back to 1896.	21
Zimbabwe	122 680	Orange	Lemon Lime Mandarin Grapefruit	The Mazoe Valley, Umtali, Sinoia and Beit Bridge. Major new plantings can be found in the Shama Valley district.	Citrus Black Spot is one of the more serious diseases affecting the citrus industry in Zimbabwe.	61
Angola	78 000	Orange Mandarin		Citrus is produced in the provinces of **Bengo,** Kuito, **Huambo** and Sumbre	The industry is not significant.	61
Swaziland	73 500	Grapefruit Orange		The Theumani, Tambuti, Ngonini and Big Bend areas.	Plantings are mainly concentrated in large estates.	61 72
Libyan Arab Jamahiriya	67500	Orange Lemon Lime	Mandarin	Citrus production is concentrated mainly around coastal areas extending from Surma to Gharabulli and into the interior (40 km south to Azizia). Some orchards are also planted in the **Benghazi** area and around Fueihat (15 km south of Benghazi).	All citrus produced is consumed locally, imports and exports of citrus are negligible.	21

Country (Africa)	**2002 production (tonnes)**	**Types cultivated**		**Citrus cultivation areas (areas in bold are indicated on the map)**	**Notes**	**Refs**
		Major types	**Other types**			
Côte d'Ivoire	61 250	Orange Lemon Lime	Small amounts of grapefruit		One of the primary producers of citrus oils including lemon, lime, bitter orange oils and Bergamot.	11 61
Kenya	40 390	Orange Grapefruit	Small amounts of lemon and mandarin	Production areas are confined to the Eastern and Coastal parts.	The industry is not significant.	61
Senegal	31 000	Orange	Lime	Lime trees are established in Casamance.		71
Mozambique	30 500	Grapefruit Orange	Lemon Lime Small amounts of mandarin	Production areas are found in **Maputu** and Beira.	Citrus production is affected by Citrus Black Spot.	61
Somalia	data not available	Grapefruit Small fruited acid lime		Citrus is mainly produced in the Mogadishu region.		21

Citrus is also produced in the Democratic Republic of the Congo (92,816 metric tons produced in 2002).

Countries that produced less than 100 000 metric tonnes include: Madagascar, Sierra Leone, Tanzania, Ethiopia, Central African Republic, Togo, Benin, Republic of Congo, Guinea-Bissau, Liberia, Réunion, Malawi, Djibouti, Burkina Faso, Gabon and countries producing less than 1000 metric tons are: Botswana, Mauritius, Cameroon, Seychelles (FAO, 2002b) and Uganda (citrus production data not available) (Oberholzer, 1969).

Table 2.5 — Citrus producing countries of Southern Europe and Asia Minor.

Country (S. Europe, Asia Minor)	**2002 production (tonnes)**	**Types cultivated**		**Citrus cultivation areas**	**Notes**	**Refs**
		Major types	**Minor types**	**(areas in bold are indicated on the map)**		
Spain	5 778 396	Orange (Navel, Valencia) Mandarin	Lemon Grapefruit	Citrus is grown in three autonomous communities, **Valencia, Murcia** and **Andalucia**. The majority of plantings (more than 80%) are situated in the east coast region of Levante, in the provinces of Valencia, Castellón de la Plana, Alicante and Tarragona. Minor plantings can be found in the southern coastal Andalusian provinces of Sevilla, Málaga, Almería, Córdoba, Huelva, Cadiz and Granada. Newer plantings can be found in the provinces of Sevilla and Huelava. Oranges are mainly grown in Valencia and Castellón de la Plana, lemons in Alicante and Murcia, and sour oranges in Sevilla.	Spain is the sixth largesr producer of lemons. The industry is reliant on export and plays an important role in the Spanish economy. Spain is the largest exporter of fresh citrus fruits, with about 65% going to other countries of the EU. About 40% of new citrus plantings are mandarin. Based on the past ten years' growth, the industry will most likely continue to expand.	3 34 40 53 62 65 87 88 89
Italy	2 789 185	Orange Lemon Mandarin	Small quantities of bergamot, grapefruit and citron	Seventy percent of all citrus grown in Italy is grown in **Sicily**, with the greatest density of citrus plantings on the East Coast. Other citrus growing areas are **Calabria**, **Basilicata**, **Campania**, **Lazio** and **Puglia**.	Blood orange varieties such as Tarocco have a good market share in Europe, but the majority of production is for local consumption. The industry suffers structural problems such as old varieties, lack of water, and fragmentation (the average size of farms in Sicily is less than one hectare).	5 40 70
Turkey	2 493 000	Orange Red grapefruit Mandarin (Satsuma)	Lemon	Areas are fragmented and widely separated, but mainly coastal. Over 90% of production comes from the Mediterranean Sea Coast, especially **Antalya** and **Izmir**. Almost all oranges are produced in the provinces of **Icel, Hatay, Adana** and **Antalya**. Lemon production is centred on the **Icel** and **Antalya** provinces. The rest of production occurs along the Aegean and Black Sea Coasts.		7 21

Country (S. Europe, Asia Minor)	**2002 production (tonnes)**	**Types cultivated**		**Citrus cultivation areas (areas in bold are indicated on the map)**	**Notes**	**Refs**
		Major types	**Minor types**			
Greece	1446 795	Orange (Navel, some Valencia)	Lemon Mandarin	Citrus plantings are scattered throughout Greece. Main areas are the Arta-Préveza district of **Ipiros**; Vólos district of **Thessalia**, Mesolóngion district of **Central Greece**, Corinth, Amalias, Pírgos, Pátrai, Návplion, Sparta and Kalámai districts of the **Peloponnesus** and the Khanía district of **Crete** as well as Argolis, Messinia and Achaia.	Fresh fruits are exported. Competition from other Mediterranean citrus producing countries is a major concern. Lemon production is declining due to older trees being uprooted and replaced by apricot trees or grapes.	40 72 74
Portugal	351152	Orange	Mandarin Small amounts of lemon and grapefruit	Major citrus production areas are in the districts of Ribatejo, **Braga,** Oeste, Sotavento, Algarve, Baixo-Douro, Outra-Banda, **Coimbra, Beja-Vidigaeira**, Barlavento Algarvio and Alto Douro.		40 72
France	30492	Mandarin Grapefruit	Small amounts of orange and lemon	Most citrus plantings are located on **Corsica.** Other plantings of lemon and orange trees can be found in the **Alpes-Maritimes** province centred around Nice.		40 72
Cyprus	15100	Sweet orange	Mandarin Grapefruit Lemon	Plantations are concentrated in the warm littoral regions of the island including the areas **of Nicosia, Famagusta, Limassol** and **Paphos.**	The export industry is economically important and a major employer. Most orchards are small plantations.	21 72

Table 2.6 — Citrus producing countries of Oceania

Country (Oceania)	**2002 production (tonnes)**	**Types cultivated**		**Citrus cultivation areas** **(areas in bold are indicated on the map)**	**Notes**	**Refs**
		Major types	**Minor types**			
Australia	575 000	Orange (Valencia, Navel)	Mandarin Lemon Grapefruit (mainly white-fleshed Marsh) Lime	About 80% of total citrus production is irrigated areas in the south-east around the Murrumbidgee and Murray Rivers, with about 90% of orchards in the Riverina, Sunraysia and Riverland irrigation areas of **New South Wales** (NSW), **Victoria** and **South Australia.** These areas include Renmark, Loxton, Berri and Waikerie, with small plantings in Mypolonga and Lyrup. Most of the remaining 20% is from **Queensland**, including Central Burnett (Mundubbera / Gayndah), Central Highlands (Emerald), Wide Bay / Burnett Coastal, Sunshine Coast, Mareeba and Charters Towers. Queensland produces about 70% of the total mandarins. Limes are produced on small mixed farms in the coastal areas of Queensland. Other citrus areas are the south west of **Western Australia**, the central coastal region and northwestern parts of NSW and the **Northern Territory**.	Although the Australian citrus industry is relatively small by world standards, it is an economically important horticultural crop. However, recently, about one million Valencia trees were removed due to low market prices. Citrus is grown in all states except Tasmania. New trees (15 000) were planted fairly recently in Katherine (Northern Territory). The availability of water remains a constraint. Citrus Black Spot is one of the major citrus pathogens in Australia.	7 13 26 31 33 34 80
New Zealand	31 211	Mandarin Sweet orange	Lemon Grapefruit	There are four main citrus growing areas on the north island, namely Kerikeri (Bay of Islands), **Auckland, Bay of Plenty** and Gisborne.	Climatically, New Zealand is at the southern limit for citrus production. Only frost-free eastern areas of the north island are suitable for commercial production. The citrus industry is not large, but is economically important.	72 77

Most Pacific Islands produce relatively small quantities of citrus, the largest producer being Tonga (3,500 metric tonnes) (FAO, 2002b).

Table 2.7 — Citrus producing states of the United States of America

State	Types cultivated		Citrus cultivation areas	Notes	Refs
	Major types	**Minor types**			
Florida	Orange (Valencia) Grapefruit Mandarin Lime	Lemon	The Lake, Polk, Orange and Highlands and the coastal Indian River section of Brevard, St. Lucie, Martin, Palm Beach and Indian River counties. Almost every county in the state has some small citrus groves. Dade is the major lime-producing county.	Produces 40% of the world's grapefruit and More than 80% of the total mandarins and lemons produced in the USA	22 46 72
California	Orange (Navel)	Lemon Grapefruit Mandarin Other citrus	Commercial areas are limited and include coastal valley and desert sections with different climatic conditions. The coastal sections extend from the Mexican border to Santa Barbara, and inland for forty kilometres. The coastal valley splits into three distinct districts, Santa Ana River Valley, San Joaquin Valley, and Sacramento Valley. These areas include San Diego and Riverside, which is a major grapefruit production area. In coastal areas, citrus is grown in gardens as far north as Butte and Tehama counties.	Oranges are mainly produced for the fresh fruit market.	7 46 55 59 84 85
Arizona	Grapefruit	Lemon Orange Mandarin	The lower Colorado River Valley, desert plateaus around Yuma, the Wellton-Mohawk area and the Salt River Valley centring around Phoenix. In the Phoenix area there is considerable orange production.	Citrus produced are mainly for the fresh citrus market.	46 55 72
Texas	Grapefruit	Mandarin Orange	Citrus are grown in the three southern-most counties of Texas-Cameron, Willacy and Hidalgo and in the Lower Rio Grande Valley.		32 46 58 73
Louisiana	Orange(Navel) Mandarin (Satsuma)		On the edge of the Gulf of Mexico citrus is grown in a part of the Louisiana Delta known as Plaquemines Parrish.	All fruits are sold on the fresh market.	55
Hawaii	Mandarin Orange	Mexican lime Pummelo Grapefruit	The industry is confined to the most southern island.		72

Table 2.8 — List of references used in the tables of citrus production.

Ref.	Citation	Countries used for
1	Abdi & Ibrahim, 2003	Egypt
2	Albrigo & Menini, 1984	Honduras, Jamaica, Cuba, Mexico
3	Anonymous, 1988	Spain
4	Anonymous, 1990	Democratic Republic of Korea
5	Anonymous, 1992	Italy
6	Anonymous, 1996	Philippines, Thailand
7	Anonymous, 1997	Australia, Egypt, Indonesia, Israel, Morocco, Turkey, USA California
8	Anonymous, 1999a	Belize
9	Anonymous, 1999b	Syria
10	Anonymous, 2000a	Belize
11	Anonymous, 2000b	Côte d'Ivoire
12	Anonymous, 2000c	The Palestine
13	Anonymous, 2001	Australia
14	Anonymous, 2004	Angola
15	Barak, 2003	Israel
16	Barros, 2003	Brazil
17	Bean et al., 2003	P. R. China
18	Bedford, 1971	Israel
19	Betancur et al., 1984	Uruguay
20	Bocardo et al., 2001	Mexico
21	Bové, 1995	Algeria, Cyprus, Iran, Iraq, Jordan, Libya, Morocco, Oman, Pakistan, Saudi Arabia, The Sudan, Somalia, Syria, Turkey, United Arab Emirates, Yemen
22	Brown & Brown, 2001	USA Florida
23	Catara et al., 1988	Pakistan
24	Chalutz & Roessler, 1986	Israel
25	Contreras de Alcain & Marmelicz, 1984	Argentina
26	Darby, 2003	Australia
27	Donadio et al., 1996	Brazil
28	Et-Otmani et al., 1990	Morocco
29	Fairchild & Gunter, 1986	Brazil, Cuba
30	Flores, 2003	Mexico
31	Forsyth & Cope, 1986	Australia
32	French, 1984	USA Texas
33	Gallasch et al., 1984	Australia
34	Gallasch et al., 1998	Australia, Spain
35	Gallasch et al., 2000	Chile
36	Garran, 1996	Argentina

Ref.	Citation	Countries used for
37	Garza-López & Medina-Urrutia, 1984	Mexico
38	González et al., 2000	Cuba
39	Gonzáles et al., 1997	Argentina, Paraguay
40	Gonzáles-Sicilia, 1969	Algeria, France, Greece, Israel, Italy, Lebanon, Portugal, Spain
41	Hardy, 1991	Cuba
42	Hardy, 1997	Japan
43	Hearn, 1986	U.S.A
44	Iwagaki, 1991	Japan
45	Iwamasa, 1988	Japan
46	Jacobs, 1994	Brazil, USA Arizona, California, Florida
47	Kelly, 1995	South Africa
48	Kenzo, 2003	Japan, Argentina
49	Kitagawa & Kawada, 1986	Japan
50	Korf, 1998	Japan
51	Mabiletsa, 2003a	South Africa
52	Mabiletsa, 2003b	South Africa
53	Mahajan, 2002	India, Japan, Spain
54	Mendt, 1988	Bolivia
55	Melnick, 2001	USA Arizona, California, Louisiana, Texas
56	Muraro & Spreen, 1996	Brazil, Cuba
57	Murthi & Speldewinde, 1991	Malaysia
58	Neff, 1999	USA Texas
59	Newcomb, 1977	USA California
60	Nishiura, 1977	Japan
61	Oberholzer, 1969	Angola, Côte d'Ivoire, Kenya, Moçabique, Nigeria, South Africa, Swaziland, Zimbabwe
62	Oritz et al., 1988	Spain
63	Ortúzar et al., 1996	Chile
64	Passos et al., 1999	Brazil
65	Pazos, 2003	Spain
66	Phillips & Seung, 2003	D. R. Korea
67	Pokhrel, 1997	Nepal
68	Powell & Huang, 1977	USA
69	Prates et al., 1984	Brazil
70	Regini, 2002	Italy
71	Rey, 1997	Guinea-Conakry, Senegal
72	Reuther et al., 1967	Algeria, Argentina, Belize, Bolivia, Cyprus, Egypt, France, Greece, Jamaica, Japan, Indonesia, Lebanon, Malaysia, Mexico, New Zealand, Paraguay, Philippines, Portugal, Sri Lanka, South Africa, Swaziland, Syria, Tunisia, Uruguay, USA Arizona, Florida, Hawaii
73	Sauls, 1998	USA Texas

Ref.	Citation	Countries used for
74	Sekliziotis, 2003	Greece
75	Singh, 1969	India, Iraq, Pakistan
76	Spreen et al., 1996	Mexico
77	Spurling, 1969	New Zealand
78	Srivastava & Singh, 2002	India, Japan, Nepal, Thailand, Tunisia
79	Timmer, 2005	Brazil
80	Tugwell & Gallasch, 1998	Australia
81	Urquhart, 1999	South Africa
82	Veldman & Barry, 1996	South Africa
83	von Broembsen, 1986	South Africa
84	Warner, 1997	USA California
85	Warner, 1998	USA California
86	Wahl, 2000	Peru
87	Witney & Chao, 2000	Morocco, Spain
88	Zaragoza & Agustí, 2001	Spain
89	Zaragoza & Hensz, 1986	Spain
90	Zekri & Al-Jaleel, 2000	Saudi Arabia
91	Zhaoling, 1986	P. R. China

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Chapter 3 — A review of Citrus Black Spot

3.1 Abstract

Citrus Black Spot (CBS) is an important fruit disease of Citrus species in many parts of the world. It was first recorded in Australia and today it is prevalent in many of the major citrus producing countries, including Brazil, China and India. The pathogen causes mainly fruit spots that render fruit unacceptable to the export market and in humid areas fruit loss is a major concern. Of more importance is the potential phytosanitary risk and resultant barrier to trade associated with the disease. Recent renewed interest in CBS has been brought about by the need to provide scientific justification for the phytosanitary barriers to trade, since countries may not pose unnecessary or disguised restrictions on international trade unless based on scientific justifiable principles. Within this chapter the current literature regarding the pathogen, disease, etiology and epidemiology are reviewed.

3.2 Origin, history and distribution

The origin of Citrus Black Spot (CBS) is not certain, but it is speculated that CBS originated in Asia which is also the centre of origin of the citrus host (Reuther et al., 1967). In English literature this disease was first described by Benson (1895) and subsequently recorded by Cobb (1897) from diseased fruit in Australia. The first record of CBS in South Africa (SA) was in 1929 (Doidge, 1929). The disease is widespread and has been recorded in Argentina (Garran, 1996), Bhutan (European Union, 1998), Brazil (European Union, 2000a), China (European Union, 1998), Ghana (Timmer, 2005, Personal Communication), India (Brodrick, 1969), Indonesia, Kenya, Mozambique (European Union, 1998), Nigeria (Baayen et al., 2002), Philippines, Swaziland, Taiwan, Uruguay (Kotzé, 2000) West Indies (Calavan, 1960), Zambia and Zimbabwe (European Union, 1998).

In some countries where CBS occurs, certain production areas are known to be free of the disease. In South Africa, these disease-free areas include all the citrus production regions within the Western Cape (European Union, 1998; Mabiletsa, 2003) and the Northern Cape (le Roux, 2004, Personal Communication; Mabiletsa, 2003; USDA/APHIS, 2002). Citrus Black Spot has not been reported in some of the citrus producing areas of Australia (Barkley, 2003, Personal Communication; European Union, 1998; Kiely, 1970), Brazil (European Union, 2000a) and China (European Union, 1998).

CBS has also not been recorded in any part of the Mediterranean or Europe (European Union, 1998; Baayen et al., 2002; Kotzé, 2000) and is absent from Chile and the citrus growing areas of the United States of America (USA)(Figure 3.1)(Baayen et al., 2002; Cook, 1975; European Union, 2000b; Kotzé, 1981). In some countries, such as Japan and New Zealand, the status of CBS is uncertain and reports on the occurrence of the disease in these countries are conflicting (CABI/EPPO, 1998; Sutton & Waterson, 1966).

The profile of global CBS distribution appears to reflect the historic introduction and distribution of citrus with the exception that it is restricted to areas where climate favours the occurrence of the pathogen. The disease is known to have spread to areas where the climate is conducive for the persistence of the species (Wager, 1952). The risk of CBS spreading to areas where it does not currently occur appears to depend on climate.

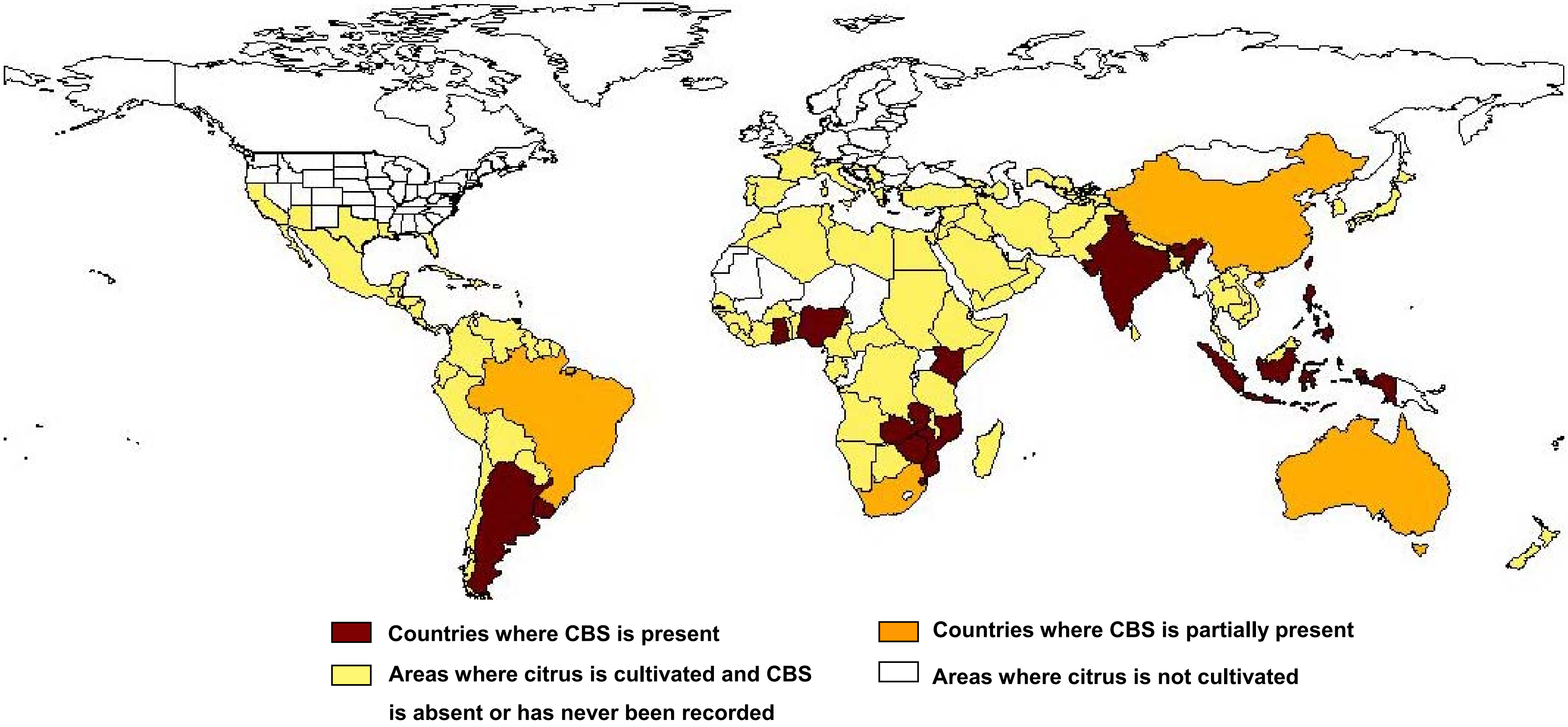

Figure 3.1 — The global distribution of Citrus Black Spot (CBS) as officially recorded.

3.3 Symptoms

The CBS pathogen mainly causes symptoms on fruit and to a lesser extent on leaves. It is thought that the pathogen may also cause some damage to twigs, but this has not been unequivocally confirmed (Calavan, 1960; Sutton & Waterson, 1966).

3.3.1 Leaf symptoms

Symptoms occur more frequently on the leaves of lemon trees than on those of oranges. Leaf infection within a tree varies considerably, and the number of lesions per leaf may be a few or numerous (Wager, 1952). On immature leaves symptoms are not prevalent (Kiely, 1949). Symptoms first start to appear three to ten months after initial infection (Wager, 1952). Small pin-point sunken lesions are visible on both sides of the leaf (Kiely, 1948b; Wager, 1952). These lesions are perfectly round, have a grey or light brown centre, a black to reddish circumference and are surrounded by a yellow halo. Sometimes pycnidia can be seen in the centre of the lesion on the upper side of the leaf (Wager, 1952). Further colonisation of the leaf only happens after leaf drop. The fungus eventually produces perithecia and pycnidia over the surface of the dried leaf within the leaf litter (Kotzé, 1996).

3.3.2 Fruit symptoms

Disease symptoms are most noticeable on mature fruit (Kiely, 1969), although symptoms may appear on immature fruit (Whiteside, 1965), especially lemons (Wager, 1952). Symptoms are confined to the surface of the fruit (Wager, 1952). Lesions may appear as a single spot or up to a thousand spots per fruit (Calavan, 1960). Even though the rind of infected fruit may become severely necrotic, the disease rarely causes post-harvest decay (Kotzé, 1981), but may cause premature fruit drop (Wager, 1952). Three kinds of symptoms are widely recognised: hard spot, first described by Cobb (1897); freckle spot; and virulent spot, both first described by Kiely (1948b). Lesions are well defined and occur at various stages of rind maturity (Kiely, 1948b). Two other symptoms, speckled blotch and cracked spot are not as widely recognised and occur predominantly in South Africa (McOnie, 1965b) and Brazil (De Goes et al., 2000) respectively.

CBS symptoms are variable in appearance and can easily be confused with symptoms caused by other citrus pathogens, especially freckle spot and speckled blotch (Bonants et al., 2003). Since the disease influences citrus trade world-wide, recent research has focused on developing fast and reliable methods for the detection of CBS from lesions on fruit (Baayen et al., 2002; Bonants et al., 2003; Meyer et al., 2001).

3.3.2.1 Hard spot

Hard spot consists of circular brown lesions originating from an initial slight depression. These lesions tend not to increase in diameter, but sink in the centre and form a crater-like depression. The tissue in the centre turns grey-white and pycnidia may develop therein (Korf, 1998). Perithecia never develop within hard spot lesions (Kotzé, 1981). The rim of these lesions is typically black (Korf, 1998). Generally hard spot lesions are few in number per fruit, but more than 50 lesions per fruit have been observed (Kiely, 1948b). These lesions appear when fruit start maturing and may even appear before the colour has changed from green to orange (Kotzé, 1981).

Figure 3.2 — Hard spot lesions on a mature Valencia orange. Photograph courtesy of Hennie Korf.

3.3.2.2 Freckle spot

Multiple (up to several hundred), separate, deep orange to brick red lesions may appear simultaneously on a portion of the fruit surface, usually the side that is more exposed to the sun (Kiely, 1948b). Fruit become affected while still on the tree and lesions are at first about a millimetre in diameter and slightly depressed at the centre. Lesions grow fast and reach two to three millimetres in diameter before turning brown and ceasing growth. The depth of the lesion might increase, depending on the thickness of the rind. These symptoms are generally devoid of pycnidia (Bonants et al., 2003). Fruit with freckle spot are usually more unsightly than those with only hard spot, and this symptom severely influences the marketability of fruit (Kiely, 1948b). Individual lesions may coalesce or form a tearstain lesion. Coalesced lesions could turn into virulent spot. This symptom mostly appears after the fruit have changed colour from green to orange (Kotzé, 1981).

3.3.2.3 Virulent spot

Virulent spot appears on unblemished and blemished fruit (Kiely, 1948b). On blemished fruit, freckle spot lesions coalesce to form virulent spot. Infection centres develop rapidly and black pycnidia may develop inside these centres (Calavan, 1960; Kiely, 1948b). Lesions on unblemished fruit may originate as small sunken red to brown spots or as irregularly depressed centres approximately 6 mm in diameter showing no colour change (Calavan, 1960). Lesions assume irregular shapes and develop late in the season on fully mature fruit. These lesions could be surrounded by brown necrotic tissue and cause post-harvest losses (Kiely, 1948b; Kotzé, 1981).

3.3.2.4 Speckled blotch

Another symptom, known as speckled blotch, occurs infrequently on fruit. It was first thought to be Melanose [*Diaporthe citri* (Faw.) Wolf], but later it was concluded that the causal organism was *Guignardia citricarpa* (Kiely) (McOnie, 1965b). Blotching consists of separate, roughly circular spots, 1–2 mm in diameter, either depressed or slightly raised. At first appearance the spots are brick red but turn dark brown in colour over a period of two weeks (Kiely, 1960). Speckled blotch may develop into hard spot as the season progresses (Kotzé, 1981). These lesions are usually devoid of pycnidia (Bonants et al., 2003). In South Africa, all of the above-mentioned symptoms have been reported (Wager, 1952).

3.3.2.5 Cracked spot

In Brazil, a new symptom has recently been associated with CBS. This symptom appears in fruit older than 6 months and is characterized by the presence of superficial lesions which are variable in size and appear cracked. The symptoms are slightly salient, can occur individually or in groups and do not contain any pycnidia. Cracked spot has been proposed as the name for this new type of symptom (De Goes et al., 2000).

3.4 Factors that influence symptom development and severity on fruit

Symptoms may first be expressed during fruit development on the tree or after harvesting. Expression is generally promoted by relatively high temperatures and high light intensities (Brodrick & Rabie, 1970; Kellerman, 1976; Kellerman & Kotzé, 1977; Kiely, 1969; Kotzé, 1961; Kotzé, 1963, 1971; Whiteside, 1967). Low temperatures reduces fruit symptom development (Brodrick, 1969).

Pre-harvest symptom development on fruit is dependent on weather conditions, and on the age and condition of the host tree (Kiely, 1969; Kotzé, 1996). Consequently, older trees (Kotzé, 2000); trees suffering from root rot (Whiteside, 1965), wilting, or element deficiencies (Kotzé, 1961); and trees affected by drought (Kiely, 1969) or hail damage (Kellerman, 1975) are more susceptible to CBS. Symptoms also develop more rapidly as the rind matures. Thus, factors that influence rind maturation, such as soil moisture, can also influence the occurrence of symptoms (Kiely, 1969).

Fruit can also develop symptoms while in transit to export markets (Brodrick, 1969; Kiely, 1948b; Loest, 1958; Smith, 1962), particularly if fruit are not moved rapidly into the cold chain. Fruit exported from South Africa are shipped in chilled containers, however transport from farms to ports is not usually part of the cold chain (Mather, 1999) and fruit sometimes develop symptoms during this period.

3.5 Nature of the causal organism and biotypes

McAlpine gave the first detailed descriptions of the anamorphic stage of the causal organism in 1899. He assigned the pathogenic organism to the genus *Phoma* and described it as a new species, *Phoma citricarpa* McAlpine (Kiely, 1948b). In 1953, the name was changed to *Phyllostictina citricarpa* (McAlp.) Petrak (Hudson, 1962) and in 1973 van der Aa renamed the anamorph *Phyllosticta citricarpa*, by which name it is still recognised today (Kotzé, 1996). The teleomorphic stage was described by Kiely as *Guignardia citricarpa* (Kiely, 1948b). The spermatial state is in *Leptodothiorella* and the synanamorph has not formally been described (Baayen et al., 2002).

Guignardia citricarpa is an endophyte of citrus and has been isolated extensively from healthy citrus tissue (Araujo et al., 2001; Azevedo et al., 2000; Glienke-Blanko et al., 2002). The term endophyte means that the organism colonises internal plant tissues of the host and inhabits the plant organs for a part of its life cycle without causing apparent harm (Petrini, 1991).

The endophytic nature of species belonging to the Genus *Guignardia* caused confusion in the past, since all isolates of *Guignardia* obtained from citrus plant material were previously considered to be the citrus pathogen. Sueda (1941) indicated that the pathogen could be found in healthy citrus plants of all ages and varieties. Similarly, Wager (1952) and Kiely (1950) showed that *G. citricarpa* occurred in disease-free regions and that it could be isolated from wild plants. However in 1964, McOnie described a non-pathogenic form of *G. citricarpa* that was similarly isolated from symptomless citrus and 14 other wild plants from South Africa. At the time, this non-pathogenic form of *Guignardia* was distinguished in culture from the pathogenic type by its darker colour, faster growth, and production of perithecia containing ascospores.

The geographical distribution of the non-pathogenic form is much wider than that of the pathogen. Furthermore, non-pathogenic *Guignardia* occurs in countries without CBS such as Spain, Sicily and Israel (Baayen et al., 2002). Although the pathogen may also be isolated from symptomless citrus, in culture it produces pycnidia rather than perithecia (Sutton & Waterson, 1966).

Finally, in 2001, Meyer et al. (2001) distinguished the pathogenic form from the non-pathogenic form of *Guignardia*. They used restriction enzyme digestion fingerprints of the Polymerase Chain Reaction (PCR) product of a portion of the internal spacer region (ITS) of the ribosomal DNA operon. Baayen et al. (2002) confirmed that there are two distinct species of *Guignardia* through analyses of the sequences of the ITS region. They distinguished ITS groups I and II of *Guignardia citricarpa*, *senso lato*. Group I consisted of all isolates from CBS infected fruit and had similar growth rates and morphology to the pathogen as described by McOnie (1965a). Group II grew rapidly, was not associated with CBS symptoms, and originated from a range of host species. Baayen and co-workers (2002) proposed that isolates with the morphology and ITS sequence of group II should be designated *Guignardia mangiferae* A.J. Roy. This fungus is a cosmopolitan endophyte of woody plants. It can be pathogenic in some instances and is known to cause minor fruit spot of guava (Baayen et al., 2002), but is not pathogenic on citrus.

As the identity of the pathogen has been ambiguous for so many years, much of the past research on *G. citricarpa* is questionable. For instance, Frean (1964) and Brodrick (1969) conducted physiological studies on what they believed to be *G. citricarpa*. Unfortunately, there is evidence to suggest that some of the isolates used during these studies were the non-pathogenic type of *Guignardia* (Baayen et al., 2002; Meyer et al., 2001). Their results, therefore, may not be entirely representative of *G. citricarpa*. The confusion surrounding the identity of the CBS pathogen has also caused inaccurate reports on the distribution and occurrence of the disease (McOnie, 1964c).

3.6 Epidemiology

3.6.1 Type of inoculum

Two kinds of spores, ascospores and pycnidiospores, may cause infection of citrus (Kotzé, 1996).

3.6.1.1 Ascospores

Windborne ascospores are seen as the primary source of inoculum (Kiely, 1948b; Kotzé, 1963; Sutton & Waterson, 1966). They are found abundantly within perithecia on the leaf litter. These fruiting bodies may also occur on dead twigs on the orchard floor but are never found on fruit or attached leaves (McOnie, 1965a).

Mature ascospores are forcefully discharged from mature perithecia. Perithecia maturation is not seasonal and mature ascospores may be found within leaf litter on the orchard floor all year round (Kiely, 1948b). In South Africa, perithecia ripen slower in winter than in summer and large numbers of ascospores may be trapped during summer (Kotzé, 1963). Alternate wetting and drying of the fallen leaves and variations in temperature provide optimal conditions for ascospore formation and maturation (Kiely, 1948a, 1948b). Perithecia will not mature in areas where the leaf litter is either constantly dry or constantly wet (Wager, 1949). In constantly wet weather conditions the leaf litter decomposes and the ascospore inoculum may be eliminated (Kiely, 1948b). This is thought to be a possible reason for the absence of CBS in certain parts of South Africa (Wager, 1949).

Ascospores are windborne, but their ejection from the mature perithecia is dependent on wetting; no spores are ejected if the perithecia are not wetted. The onset of rain, ascospore discharge and infection period are, therefore, closely related (Kotzé, 1963; McOnie, 1964b). However, heavy dews may also sometimes be sufficient to secure ejection of ascospores (Kiely, 1948a). Low temperatures do not influence the release of ascospores (Kotzé, 1963).

3.6.1.2 Pycnidiospores

In addition to perithecia, pycnidia containing pycnidiospores are abundant on dead leaves beneath trees (Kiely, 1948b). Pycnidia may occur in fruit lesions, on dead twigs, and sparsely within lesions on attached leaves or on fruit stalks.

In wet weather mature pycnidiospores ooze as a gelatinous mass from pycnidia contained in lesions on the rind of infected mature fruit hanging on the tree. These spores require water for dispersal (Sutton & Waterson, 1966; Whiteside, 1967). Similarly masses of gelatinous pycnidiospores are produced from pycnidia on fallen leaves. These pycnidiospores do not have any mechanisms of dispersal (Kotzé, 1996), nor do pycnidiospores originating from lesions on infected fruit which have fallen from the tree (McOnie, 1964b). What happens to these spores after release from the pycnidia is not known; it is suggested that some of these spores might reach the tree canopy by the splashing of raindrops (Kotzé, 1981) but presumably the majority of spores are washed into the soil when it rains.

3.6.2 Other sources of inoculum

Mycelium latently present in citrus trees may be a source of inoculum (Kiely, 1949). If the CBS pathogen in such trees is introduced to new, uninfected citrus production areas CBS might successfully establish in the new area (Calavan, 1960). In the past, CBS have been transmitted to uninfected areas via this source of inoculum (Kiely, 1949; Wager, 1952).

3.6.3 Infection of fruit

Young fruit are highly susceptible to infection. The period of susceptibility extends from blossoming (anthesis) until about five months later. Thereafter, infections no longer take place regardless of the prevailing weather conditions (Kotzé, 2000). This is as a result of an increase in fruit resistance, rather than a decrease in inoculum (Whiteside, 1965).

3.6.3.1 Infection by ascospores

Infection takes place when the thick walled apresoria of a germinating fungous spore penetrates the rind of the fruit. After penetrating the rind, the fungus forms a resting body within the rind tissue. This resting body remains dormant until rind maturity when conditions are conducive for growth (Kiely, 1948b, 1970; Kotzé, 1963). This kind of infection is known as a latent or quiescent infection (Kiely, 1969). The latent period may last several months (Cook, 1975; Kotzé, 1963). Consequently, *G. citricarpa* may be isolated from apparently healthy citrus fruit tissues (Yin et al., 1981). Ascospores cannot infect healthy mature fruit (Wager, 1949).

3.6.3.2 Infection by pycnidiospores

Infection by pycnidiospores happens when spores from late-hanging, infected, mature fruit are washed down to young susceptible leaves and fruit (Sutton & Waterson, 1966; Whiteside, 1965, 1967). Similar to ascospore infections, pycnidiospores from lesions on mature infected fruit are unable to infect other healthy mature fruit (Calavan, 1960; Korf, 1998; Wager, 1952).

Pycnidiospores from fallen leaves and fruit are not thought to readilly cause infection of fruit, since their dispersal to fruit hanging on the trees, unless splashed by raindrops, seems unlikely (Kotzé, 1996; Kotzé, 1981; Kotzé, 2004, Personal Communication; McOnie, 1964b). Since pycnidiospores are not seen as a major source of inoculum, the exact mechanisms of infection have not been investigated.

3.6.4 Infection of leaves

Only young leaves are susceptible to infection (Kotzé, 1996) and any new leaf flushes that coincide with wet weather may become infected (Whiteside, 1965). Leaves remain susceptible for up to nine months and the pathogen can readily be re-isolated from previously inoculated material (Labuschagne, 2003, Personal Communication). Leaf infections remain predominantly latent until leaf drop and desiccation, although lesions may appear on mature attached leaves (Whiteside, 1965).

3.6.4.1 Infection by ascospores

Infected leaves fall to the ground a year or longer after infection and eventually produce mature ascospores, which are forcefully released from perithecia and may infect young fruit and leaves and so complete the infection cycle (Whiteside, 1965). Specific mechanisms of ascospore infection of leaves have not been studied.

3.6.4.2 Infection by pycnidiospores

When a pycnidiospore reaches a susceptible leaf, the spore will germinate and form an appresorium which gives rise to infection pegs that penetrates the leaf. Pycnidiospores can only be dispersed by water and it seems unlikely that these spores will move from the leaf litter to infect the leaves still hanging on the tree (Kotzé, 1996). However, it is thought that water splashing up from the ground when it rains can carry pycnidiospores which might infect low hanging leaves (Kotzé, 1981; Kotzé, 2004, Personal Communication).

3.6.5 Factors that influence the infection of fruit and leaves by ascospores

Germinating spores require special climatic conditions before they can penetrate fruit or leaves. Ascospore infection frequency is determined by the rainfall pattern and climatic conditions greatly influence the intensity of infection (Wager, 1952; Whiteside, 1967). If conditions are not favourable for the development and maturation of the pathogen’s fruiting bodies, citrus fruit and leaves may escape ascospore infection (Whiteside, 1967). Additionally, availability of spore inoculum during the time when young fruit and leaves are susceptible has an important influence on the rate of infections and disease severity (Whiteside, 1965, 1967).

3.6.6 Importance of ascospores and pycnidiospores in infections

It is widely accepted that ascospores are the major source of inoculum in South Africa and Australia where predominantly only one cycle of disease infection occurs annually. The critical period for ascospore infection is approximately within a single five-month window period when fruit set coincides with rainfall. Late-hanging infected mature fruit are removed from trees a month before the new season's fruit sets (Kiely, 1948b, 1970; Kotzé, 1963, 1996; McOnie, 1965a). Therefore, pycnidiospores cannot be a major source of inoculum as mature CBS infected fruit and susceptible young fruit never occur simultaneously on the same trees. However, this is not true for citrus produced in Brazil where rain is not so confined to a single season and flowering may occur more than twice a year. Therefore, the epidemiology of CBS in Brazil is different to that found in other parts of the world and the role of pycnidiospores is as important as that of ascospores (Sposito et al., 2001). In Zimbabwe, where the disease is rare and localized, it was found that waterborne pycnidiospores, mostly seen as secondary inoculum, was the most important source of inoculum (Whiteside, 1967).

3.6.7 Recommendations for future research

Although in-depth research has been conducted into the nature of the CBS pathogen and its etiology, there are still major gaps in the knowledge base of this complex disease. For instance, all potential sources of inoculum, such as the latent mycelium found in leaf and fruit tissues, and the perithecia on dead twigs, have not been investigated. The survival of spores in soil and the potential role of soil in the disease cycle was only recently studied for the first time (Lise Korsten, 2004, Personal Communication), but has not as yet been elucidated. Similarly, little is known on the exact role of insects in the dissemination of CBS.

To a certain extent the confusion between the non-pathogenic and pathogenic types of *Guignardia* that existed in the past hampered attempts to fully understand the epidemiology of the disease. However, as molecular techniques to reliably distinguish between the pathogen and the non-pathogen now exist, it is recommended that aspects of the epidemiology of CBS be revisited.

3.7 Host plants

Almost all commercial citrus species are susceptible to CBS but lemons are the most susceptible. When CBS is found in a new area, it will probably first be seen on lemons before other citrus is affected (Kiely, 1948b; Kotzé, 2000). Persian limes (Timmer, 2005, Personal Communication) and sour orange and its hybrids are not susceptible (Kotzé, 1981), and rough lemons are thought to be tolerant (Wager, 1952).

Various non-citrus species native to Australia and South Africa were reported to carry latent infections of *G. citricarpa* that could act as a source of inoculum (Kiely, 1948a, 1948b; Wager, 1952). However, *Guignardia* isolates from non-citrus hosts were identified as *G. mangiferae* by McOnie (1964c), a result later confirmed by Meyer et al. (2001) and Baayen et al. (2002), using molecular techniques.

3.8 Control

CBS control is primarily chemical and reliant on effective disease forecasting models. However, the most important non-chemical approach in CBS control is to use cultural techniques to reduce transmission. Efforts to breed resistant varieties have not been successful (Calavan, 1960) and as far as can be determined, no major breeding program is being investigated.

3.8.1 Preventing spread

As trees that are in a poor condition are more susceptible to CBS, maintaining tree vigour can reduce the incidence of CBS (Calavan, 1960; Kellerman, 1975; Kiely, 1971; Kotzé, 1961; Loest, 1968). Sources of pycnidiospore inoculum may be removed by removal of diseased mature, late-hanging fruit before the new crop sets (Calavan, 1960; Kiely, 1969; Kiely, 1970; Kotzé, 1996). Similarly, ascospore inoculum can be removed by the removal of leaf litter from the orchard floor (Kotzé, 2002, Personal Communication).

3.8.2 Pre-harvest control

Citrus Black Spot can be controlled by the timely application of appropriate fungicides either to protect fruit, or to eradicate infections and prevent symptom development (Kellerman, 1976; Kellerman & Kotzé, 1977). The effectiveness of fungicide applications is particularly reliant on the number and timing of applications (Kellerman, 1976). In South Africa, control of CBS has mostly relied on continuous protection of young citrus fruit during the potential infection period when the host is most susceptible and pathogenic spores are present (McOnie & Smith, 1964).

The earliest method of controlling CBS was by applying a Bordeaux mixture (as preventative measure)(Benson, 1895; Cobb, 1897; Kiely, 1948b), which was later found to result in copper toxicity (Kotzé, 1964). In 1964, dithiocarbamates were introduced as preventative control measures by first applying Zineb (active ingredient zinc ethylene bisdithio-carbamate) and later Mancozeb (active ingredient manganese ethylene bisdithio-carbamate)(Kotzé, 1964). These proved superior to copper based products (Kellerman, 1976; Kellerman & Kotzé, 1977), as they did not retard fruit coloration or result in dark rind injuries (McOnie & Smith, 1964). This group of chemicals were replaced by Benomyl [active ingredient methyl-1-(butylcarbamoyl)-2-benzimidazole carbamate] — a preventative and curative approach (Kellerman & Kotzé, 1973, 1977) — in 1971 (Kiely, 1971). However, by 1984 the CBS fungus had developed resistance to the frequent spraying of Benomyl (Herbert & Grech, 1985). Current research suggests that strobilurins hold some potential for the control of CBS (Kotzé, 1996; Miles et al., 2004; Schutte et al., 1996; Tollig et al., 1996).

3.8.3 Post-harvest control

A water-wax emulsion can be applied to harvested fruit to reduce the development of CBS during storage at 16-27°C (Seberry et al., 1967). Since light and temperature affect the development of symptoms on fruit (Smith, 1962), it may also be transported in dark coloured wrappers to reduce light intensity (Brodrick, 1969). Furthermore, low temperature storage and shipment of fruit will inhibit symptom development in latently infected fruit (Calavan, 1960; Kiely, 1970).

3.9 Economic importance

Before the implementation of phytosanitary barriers against the import of citrus fruit from areas where the disease occurs to disease-free regions (European Union, 1977), all losses as a result of CBS were attributed to injured fruit not fit for marketing. The CBS lesions on fruit significantly lower the market value of fruit and result in the product being re-directed for processing (Calavan, 1960; Cobb, 1897; Kellerman & Kotzé, 1977; Wager, 1945).

Already in 1895, CBS caused significant losses throughout Australia (Benson, 1895) and in 1939, the industry suffered a major economic setback due to a severe CBS epidemic in New South Wales (NSW). This resulted in an oversupply of unwanted CBS infected fruit on the local market. In 1945, 90% of citrus fruit produced from unsprayed orchards in the northern provinces of SA (today Limpopo and Mpumalanga), were rendered unfit for export (Sutton & Waterson, 1966). During the 1960s, numerous citrus growing areas in SA reported similar major losses in production, as up to 60% of fruit intended for the export market was unsuitable for export (Brodrick, 1969). Within the 1960s it was speculated that world-wide losses due to this disease amounted to millions of dollars (Calavan, 1960). By 1970, losses due to CBS were so severe in NSW that it was seen as the most serious disease affecting citrus production in Australia (Kiely, 1970).

Pre-harvest CBS losses arise when severely affected fruit drop prematurely in the orchard and go to waste (Wager, 1945; Wager 1952; Kotzé, 2000). Post-harvest CBS losses are not always apparent as latent, asymptomatic export fruit may develop CBS symptoms while in transit to the harbour (Brodrick, 1969; Kiely, 1948b; Loest, 1958; Smith, 1962). Furthermore, CBS control programmes are costly (Cobb, 1897; Kotzé, 1961). However, if not controlled CBS may cause total loss of the crop (Seberry et al., 1967) and therefore in some areas, citrus production will be impossible without effective CBS control programs (Smith, 1996). Finally, CBS affects international trade in citrus. The EU and the USA reject consignments of fruit containing CBS infected fruit, with economic implications to the citrus industry of the country of origin.

3.10 Phytosanitary barriers to trade & inspection and detection methods

Currently the EU and the USA enforce phytosanitary regulations that restrict the import of citrus from CBS infected areas (Anonymous, 1986; Baayen et al., 2002). These regulations aim to prevent CBS entering and establishing in the EU and the USA (European Union, 1998, 2000c). Imports of citrus from CBS affected regions are not entirely prohibited, but fruit may only be imported if evidence can be provided that effective pre-harvest spray programs exist and no disease symptoms were observed in official inspections of export consignments at packinghouses and at ports (European Union, 2000c). Shipments of imported fresh citrus fruits are also inspected at the ports of entry into the EU (Bonants et al., 2003) and USA (USDA/APHIS, 2002) by phytosanitary services of the importing countries. Any consignments that do not meet requirements may be refused, and they will also be rejected if they are found to contain CBS infected fruit (Bonants et al., 2003).

Methods for the pre-harvest and post-harvest detection of CBS include visual inspection of fruit and the isolation of the pathogenic strain from fruit lesions (Fogliata, 2000; Whiteside, 1967). Citrus Black Spot may be diagnosed visually by the readily recognisable CBS fruit symptoms, such as hard spot. However, speckled blotch and freckle spot may be confused with symptoms of other citrus diseases such as true melanose (*D. citri*) and greasy spot (*Mycosphaerella citri* Whiteside) (Baayen et al., 2002). In such cases, the fungus is cultured by removing lesions from the peel and incubating it for five days (Bonants et al., 2003). However, the two biotypes of *Guignardia* are morphologically similar and this test may be an unreliable method of detecting the pathogen. In addition, *Guignardia* may take up to 14 days before forming mature pycnidia in culture, during which time the value of a consignment will decrease significantly (Baayen et al., 2002). To speed up the process, Bonants et al., (2003) developed a rapid PCR detection method for the diagnosis of CBS lesions originating from speckled blotch or freckle spot symptoms. The primer set of the PCR-detection method (GCF3/GCR7) is selective for *G. citricarpa* and does not amplify any other fungi present within citrus peel (Bonants et al., 2003).

Spread of CBS to countries that do not have the disease can be prevented by appropriate quarantine measures. The potential future spread of the disease will rely on the effective application of these measures (Kotzé, 1981; Kotzé, 1996). However, the pathogen has not established in some areas despite repeated introductions of suitably infectious material. Areas where CBS has not established include the inland citrus growing areas of NSW, Australia (Barkley, 2003, Personal Communication; Whiteside, 1967), and the Western Cape region in South Africa (Mabiletsa, 2003; Smith, 1962). Therefore, the introduction of diseased material does not necessarily imply that it will eventually cause a CBS disease epidemic, especially if climatic conditions are not suitable for disease development. This should be taken into consideration when enforcing phytosanitary barriers to trade.

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Chapter 4 — Analysis of the suitability of European climate for establishment of Citrus Black Spot disease caused by *Guignardia citricarpa* Kiely

4.1 Abstract

Citrus Black Spot (CBS), caused by *Guignardia citricarpa* Kiely*,* is an economically important fungal disease of citrus. The disease is widespread in some citrus producing countries, occurring in Southern Africa and Australia but not in Europe. To prevent the disease from spreading to Europe, the EU has placed phytosanitary barriers on the importation of fruit from areas infected with CBS. The aim of this study is to evaluate whether the European climate is conducive to the development of the disease. This is done using the Match Climates function of the software package CLIMEX. The climate of 16 locations in South Africa with known CBS presence are compared with the climate of other locations in South Africa, Europe and Australia. The model successfully predict areas of CBS presence and absence in South Africa and Australia, and results suggest that the climate in Europe is not suitable for the establishment of the CBS pathogen.

4.2 Introduction

Citrus Black Spot (CBS) caused by *Guignardia citricarpa* Kiely, is a foliar and fruit disease of citrus. It occurs, amongst other countries, in parts of South Africa (SA) and Australia (Sutton & Waterson, 1966; European Union, 1998; Kotzé, 2000; Baayen et al., 2002), but it has not been reported in European countries (European Union, 1998). The disease affects the rind of the fruit, causing superficial lesions (Kotzé, 1981; Snowdon, 1990). Most commercial citrus cultivars are susceptible, especially lemons.

South Africa is the third largest exporter of fresh citrus fruit after Spain and the United States of America (FAO, 2002). The South African Citrus Industry is dependent on these exports, particularly to European countries (Mabiletsa, 2003). However, European Union (EU) quarantine regulations restrict the import of fruit from areas where CBS occurs (European Union, 1998, 2000), the implication being that there may be a risk of CBS establishing in Europe.

As for all plant pathogens, an outbreak of CBS requires at least the presence of an active strain of the pathogen, a susceptible host, and favourable climatic conditions (Booth et al., 2000). The inability of a pathogenic species to establish in an area where both the species and susceptible host are present may usually be attributed to unfavourable climatic conditions.

Robust examples where the effect of climate on the risk of establishment of potentially invasive plant pathogenic species has been estimated include rice blast disease, hop powdery mildew and hop downy mildew in Australia [caused by *Magnaporthe grisea* (Hebert) Barr, *Podosphaera macularis* Braun, and *Pseudoperonospora humuli* (Miyabe et Takahashi) respectively] (Lanoiselet et al., 2002; Pethybridge et al., 2003).

These studies were done using the Match Climates Function of CLIMEX (Hearne Scientific, Melbourne, Australia). CLIMEX is a dynamic simulation model that allows researchers to estimate the geographic distribution of a species as determined by climate (Sutherst et al., 2003). The Match Climates function enables the user to compare meteorological data from different places. It therefore allows an initial rough assessment of the likelihood of a species establishing in a new area based solely on the similarity of climate between the current range and the potential range (Sutherst et al., 2003).

The objective of this study is to estimate the potential risk of the disease occurring in European climates - the premise being that the pathogen can only persist in climates similar to those where it is currently found. If climatic conditions are unfavourable for the growth and survival of the pathogen, then it may be unable to establish in Europe. In this case, current phytosanitary barriers should be reconsidered.

4.3 Methodology

4.3.1 Data on the geographical distribution of Citrus Black Spot

Six field specialists with extensive knowledge of CBS carefully mapped areas of CBS presence and absence onto a map of South Africa (1:1 000 000, 2 x 2 m, Department of Geography, University of Pretoria). All areas in South Africa where *G. citricarpa* was either known to have been isolated from fruit or leaf surfaces or where symptoms of the disease have been observed by the field specialists, were indicated as areas with CBS presence. In the same manner, areas where no symptoms of the disease have ever been observed and no isolations of *G. citricarpa* were known to have been made from fruit or leaves were indicated as areas with CBS absence. Information obtained from recent surveys in which farms were investigated for CBS presence was also included. The areas of CBS presence or absence included commercial citrus production areas and areas of "garden" citrus, for instance scattered citrus trees on the experimental farm of the University of Pretoria. Some, but not all, areas were confirmed from literature (Wager, 1949, 1952).

Polygons, representing either CBS presence or absence as drawn on the map, were then transcribed by hand onto a smaller map (A3 –29.7 x 42 cm in size). The smaller map was scanned into a computer and information on the geographical occurrence of CBS was digitized using ArcView GIS 3.3 (Environmental Systems Research Institute)(Figure 4.1).

Copies of this map were made available to participants at the Citrus Growers' Association biennial Symposium (July 2002, Stellenbosch, South Africa). At the meeting, about 200 citrus growers and researchers from all over the country had the opportunity to confirm areas of presence and absence. Therefore, this distribution data was considered to be reliable, and of a resolution suitable for input into CLIMEX.

4.3.2 Outline of the CLIMEX model

CLIMEX provides three major functions:

1. Compare Locations — used to predict the potential geographic distribution of a species based on its climatic requirements.
2. Compare Years — used to examine the effect of climatic variation on the potential abundance of a species over consecutive years at the same location.
3. Match Climates — used to compare climates at different locations.

The present study focussed on Match Climates. CLIMEX for windows Version 1.1 was used throughout.

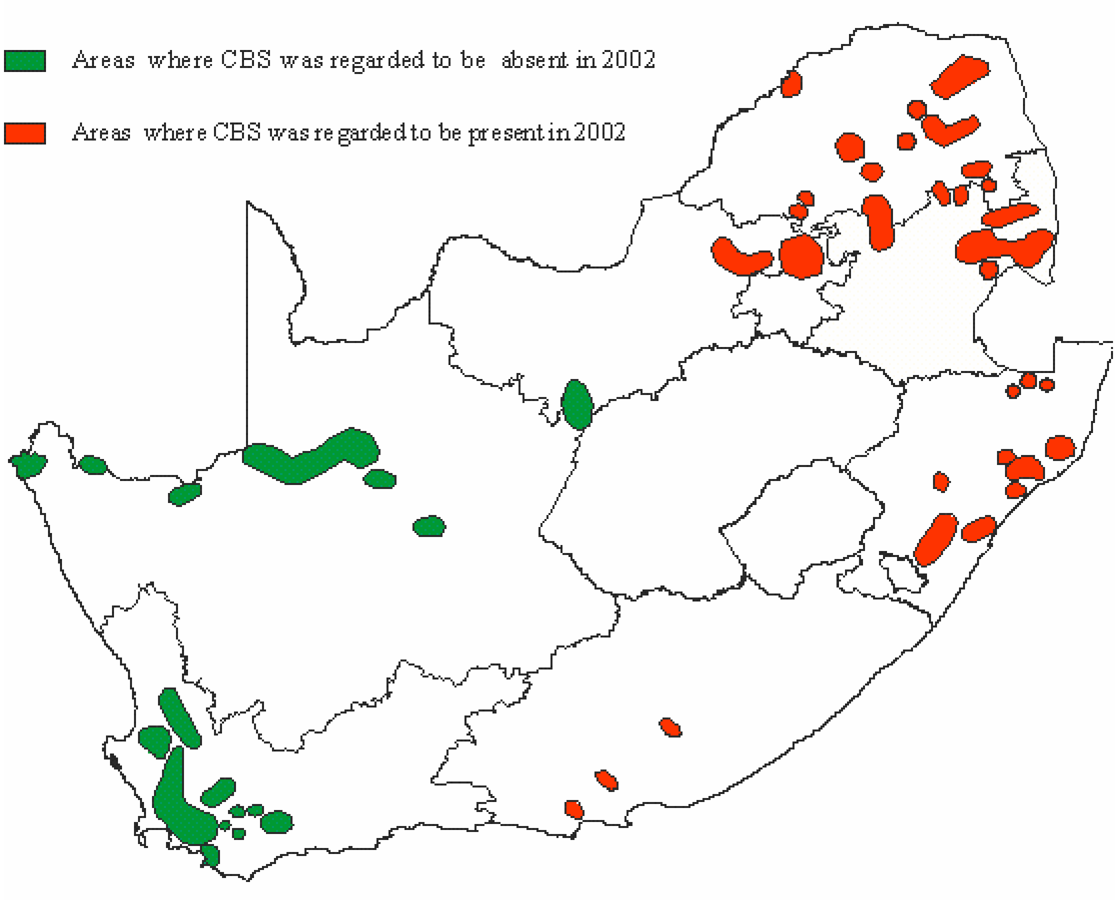

Figure 4.1 — The occurrence of Citrus Black Spot in South Africa in 2002 as determined by visual confirmation of symptoms and/or positive identification of the pathogen *Guignardia citricarpa*.

The Match Climates function in CLIMEX allows the prediction of the climatic similarity of a target location to another specified location by exploring long-term meteorological data for locations with climates similar to those of a chosen location (Sutherst et al., 1999). If locations in different hemispheres are being compared, CLIMEX shifts the data of the target location by six months to match that of the location selected by the user.

A similarity index lists the percentage similarity of the target locations to the nominated site. The index is a product of five parameters, which indicate the similarity for average monthly maximum daily temperature, average monthly minimum daily temperature, average monthly rainfall, rainfall pattern and relative humidity values at 9 a.m. and 3 p.m. These variables were selected because they have been shown to be the most meaningful when dealing with biological questions. Minimum and maximum temperature allow the user to identify extremes, while information about rainfall, relative humidity and rainfall pattern identifies differences in availability of moisture and assists in matching zones with similar seasonal rainfall (Sutherst, 2002, Personal Communication).

The user may decide how closely each of these parameters should be matched by assigning to each parameter a weighting between zero and one. If this value is set at one it will indicate, for example, that the average monthly rainfall value has to be the same at both locations for a similarity of 100%. If the weighting is set to 0.8, then the rainfall can be slightly different at the two locations but the similarity index will be close to 100%. CLIMEX also allows the user to set an importance level for the climate stations. Choosing an importance level of five will include all the climate stations and provide a highly detailed result. Setting the importance level lower will result in the selection of only the most important locations, resulting in a less specific result (Sutherst et al., 1999).

In the present study, the weighting for all parameters was set to one. Moreover, so as to obtain the most detailed results possible, all climate stations in South Africa, Europe and Australia within the CLIMEX meteorological database were included.

To estimate the similarity between European climates and those where CBS occurs, an index of similarity sufficient for disease establishment was determined based on CBS distributions in South Africa. This similarity index was tested against the known distribution of CBS in Australia, and was subsequently applied to determine the likelihood of establishment in European countries.

4.3.3 Determination of an index of similarity sufficient for disease establishment

CLIMEX has a database of climates from more than 2 400 meteorological stations world-wide, 127 of which are in South Africa (Figure 4.2). For this study, 16 meteorological locations that occurred within, or very close to, the range of CBS presence in South Africa were selected (Figure 4.3). For each of the 127 locations in South Africa, the climate was compared to that of each of these 16 locations. From this, the maximum similarity between each of the 127 locations and a CBS locality was calculated. All CBS localities had maximum similarities of 100%, as they were compared to themselves, thus, CBS localities were only compared to each of the other 15 CBS localities [e.g. the climate of Johannesburg was allocated a maximum similarity index of 81.7% (to Pretoria), and not 100% (to Johannesburg)]. Matching CBS localities in this manner provides an upper limit on the maximum similarity required for the establishment of CBS.

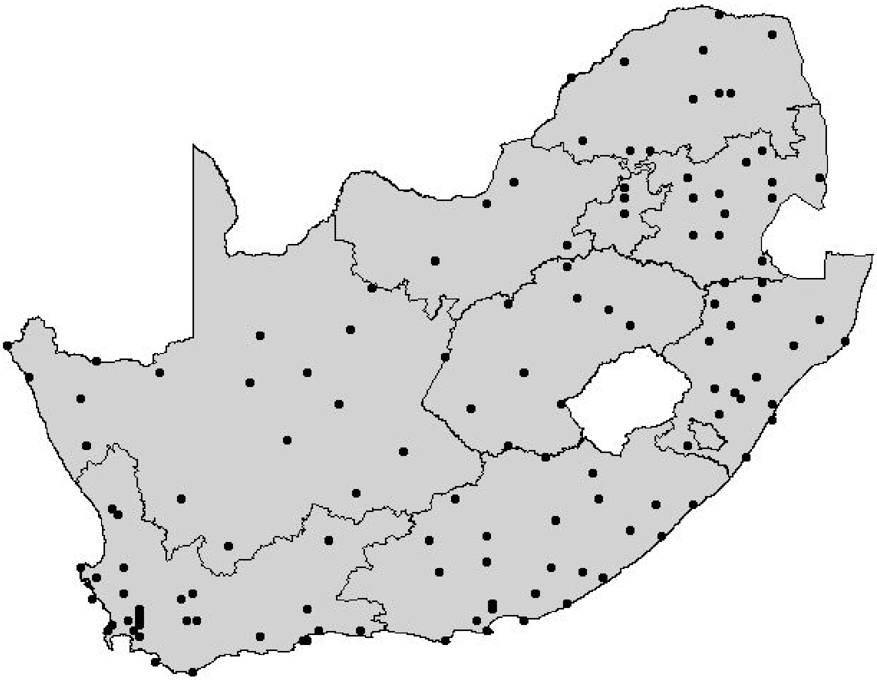

Figure 4.2 — The location (•) of the 127 climate stations in South Africa.

Figure 4.3 — Climate data locations in South Africa falling within the ranges of confirmed Citrus Black Spot presence. The spelling of locations used here is as in CLIMEX.

Prior to the implementation of the restriction on the movement of citrus propagation material by the Agricultural Pest Act of 1983 (Act no 36), CBS infected citrus fruit were moved freely to Western Cape harbours (Loest, 1958) and nursery trees originating from diseased areas (potentially carrying latent infections) were transported to, and planted in, the citrus growing areas of the Western Cape. Additionally, citrus fruit is presently marketed throughout the country irrespective of its source, and there are no restrictions on the movement of citrus fruit by the public (Kotzé, 2002, Personal Communication). Thus, sources of inoculum of *G. citricarpa* have been repeatedly introduced into the Western Cape.

Venter et al. (1995) conducted a survey of citrus producing regions of the Western Cape for the presence of *G. citricarpa*. A total of 17,200 microbial isolations were made from citrus fruits and leaves from the magisterial districts of Bredasdorp, Clanwilliam, Caledon, Heidelberg, Hermanus, Ladysmith, Montagu, Paarl, Piketberg, Robertson, Somerset West, Stellenbosch, Swellendam, Strand, Wellington, and Worcester. Results indicated that the citrus cultivation areas within these magisterial districts were all free of CBS.

As the absence of the disease in the Western Cape cannot be attributed to the absence of the host or pathogenic organism, it may be ascribed to the specific climate of this region. Furthermore, the disease-free status of the Western Cape region is currently recognised by the EU (European Union, 1998), and the United States Department of Agriculture (USDA) (USDA/APHIS, 2002).

Guignardia citricarpa has also not been detected in the Vaalharts district of the Northern Cape Province of South Africa (Anonymous, no date). Additionally, in an exercise to map the distribution of CBS in South Africa (section 4.3.1, page 69), all the citrus production regions in the Northern Cape were mapped CBS free. However, this disease-free status has not been recognised by the European nor North American authorities (at the time of assessment).

A disease matrix was subsequently drawn up that grouped all provinces in South Africa as potentially positive to CBS, except for the Northern Cape Province (CBS not detected) and the Western Cape (official disease-free status) (Figure 4.4).

In order to determine a maximum similarity index sufficient for disease establishment, it was assumed that the climate should match all those localities where CBS occurs. Conversely, a maximum similarity index that fails to match all the localities that are in the proximity of diseased areas would not be suitable for determining disease establishment in other parts of the world.

In New South Wales (NSW), Australia, CBS remains restricted to coastal citrus production regions (Barkley, 2003, Personal Communication; Whiteside, 1965), where it was first described in 1895 (Benson, 1895). Fruit and nursery trees infected with CBS have been introduced to the inland citrus production areas of NSW (e.g. Riverina in the south west, and Bourke and Narromine in the north west), but it has not become established (Kiely, 1970). However, the climate of this region is very dry. This again suggests that climate is responsible for limiting the distribution of CBS.

Figure 4.4 — The potential Citrus Black Spot status of provinces in South Africa indicating the Western Cape as a province where the disease was officially considered to be absent in 2002 (European Union, 1998) and the Northern Cape where the disease was not detected in 2002.

4.3.4 Application of the disease similarity index to Australia and Europe

4.3.4.1 Climatic matches with Australia

To confirm that the chosen maximum similarity index is sufficient to describe the potential for establishment of CBS, the 16 South African CBS locations were individually compared to each of 676 locations in Australia (Figure 4.5). According to an official document of the European Community, three states in Australia, namely South Australia, Western Australia and the Northern Territory, have been declared CBS free (European Union, 1998). A matrix, similar to that for South Africa, was drawn up for Australia to indicate the areas where CBS is considered to be present and those areas where CBS is considered to be absent (Figure 4.6). The maximum climatic similarities deemed to be sufficient for the establishment of CBS, as determined in 4.3.3, were mapped onto this matrix to test the validity of the model.

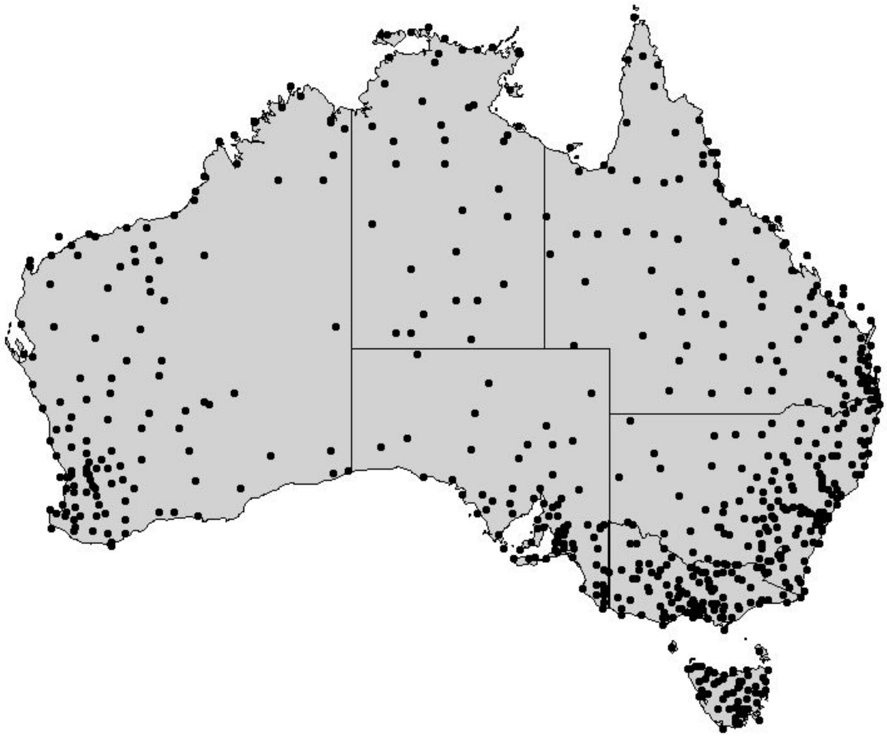

Figure 4.5 — The location (•) of 676 climate stations in Australia.

Figure 4.6 — The potential Citrus Black Spot status of states in Australia.

4.3.4.2 Climatic matches with Europe

The climates of 16 CBS locations in South Africa (Figure 4.3) were compared to 285 locations in Europe (Figure 4.7). Maximum climatic similarity was separately determined for each of the 285 locations.

4.3.5 Mapping the disease similarity index

Results from the Match Climates function are returned as a map, graph or table. All results were exported from CLIMEX to ArcView GIS 3.3 (Environmental Systems Research Institute) following instructions in http://www.ento.csiro.au/climex/climex.htm and are presented as maps. In ArcView, locations were separated into those that had maximum similarity indices ≥60% (which included all localities where CBS was found) and those that had maximum similarity indices <60%.

4.4 Results

4.4.1 Determination of an index of similarity sufficient for disease establishment

All areas where CBS is found in South Africa had maximum similarity indices ≥60% (Figure 4.8). Five localities that fall within provinces with CBS absence, namely Boegoebergdam (62.7%), Kimberley (62.9%), Kuruman (62.3%) (Northern Cape), Riversdale (61.4%) and George (60.3%) (Western Cape) had maximum similarities in climate of ≥60%. This suggests that these localities may be climatically suitable for the potential establishment of CBS. The majority of localities with maximum similarity indices below 60% are from CBS free provinces (Figure 4.9). However, eleven localities with indices below 60% fall within provinces with an official CBS presence, but these include sites where no citrus is produced (southern coastal areas, and areas at very high elevations, e.g. Belfast, Mapumalanga, the highest point in South Africa). Therefore a maximum similarity index of greater than 60% can be considered sufficient for disease establishment and a maximum similarity index of 60% or less can be considered as a climate probably unsuitable for CBS.

4.4.2 Validating the climate similarity index using Australian locations

At maximum similarity indices above 60%, all of the locations from Australia that were considered to be CBS positive at the time of assessment were successfully mapped (Figure 4.10), and no locations were mapped in areas considered CBS free.

4.4.3 Application of the disease similarity index to determine the likelihood of establishment of the disease in European countries

As maximum climatic similarities ≥60% were found to represent the level of similarity that would be suitable for CBS establishment, this similarity level is used to test the potential establishment of CBS in Europe. At this level, none of the 285 locations analysed from Europe had a climate similar to the 16 South African locations (Figure 4.11).

Figure 4.7 — The location (•) of 285 climate stations in Europe.

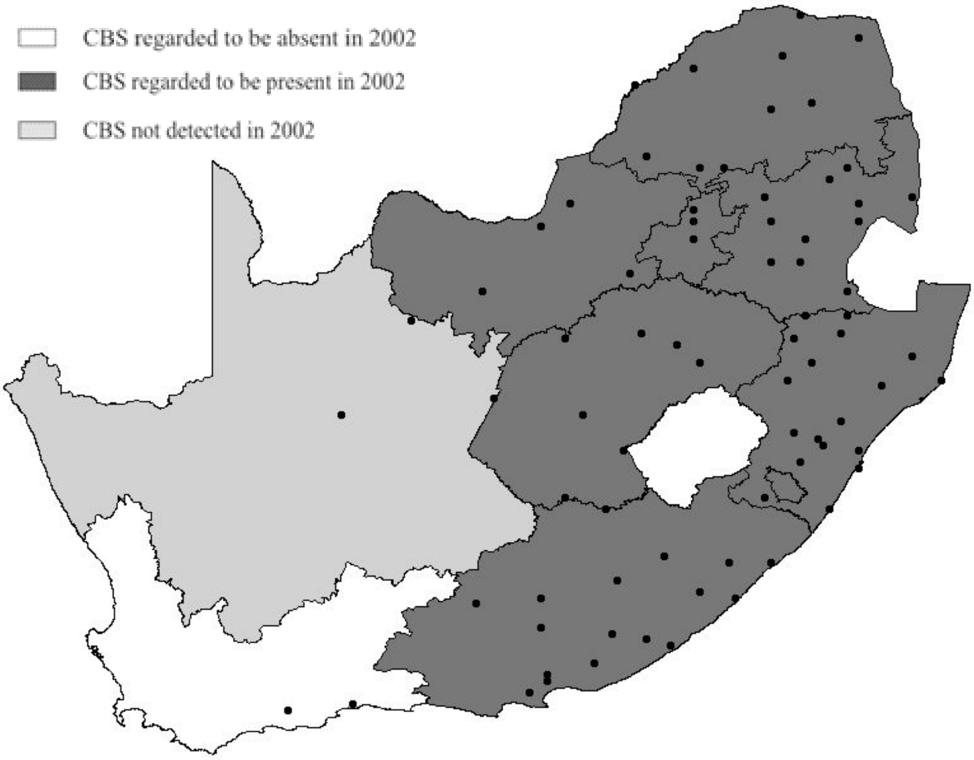

Figure 4.8 — Locations (•) in South Africa that have a maximum climatic similarity of ≥60% to the 16 South African locations which fall in the proximity of areas where CBS is found (see section 4.3.3). Provinces are colour coded to indicate the observed occurrence of CBS at a provincial level.

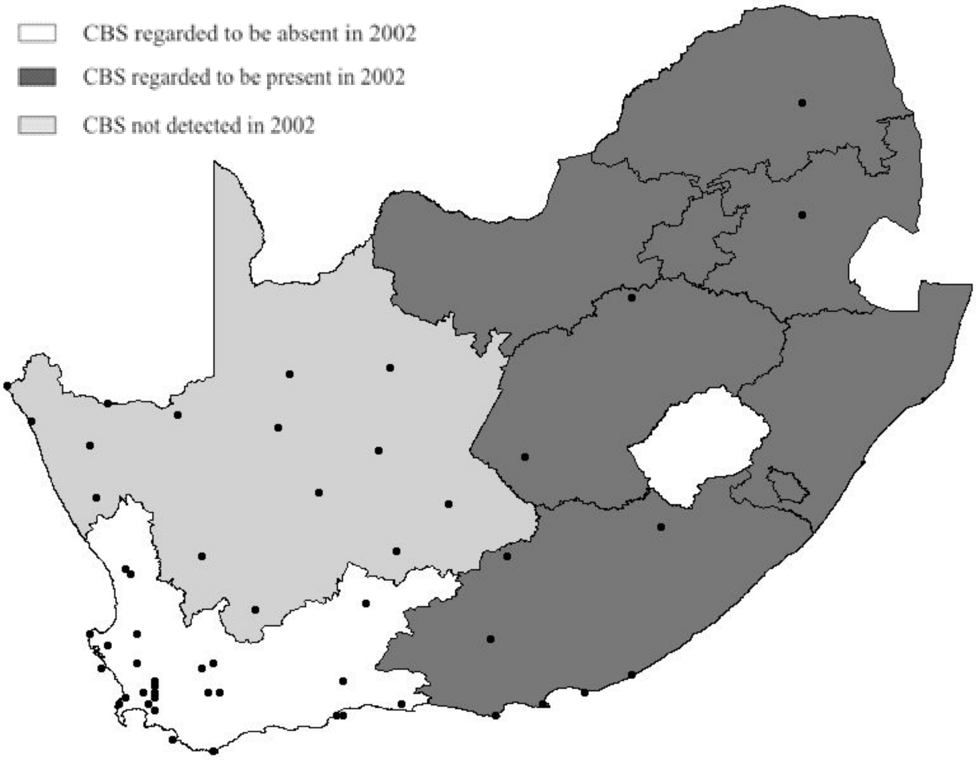

Figure 4.9 — Locations (•) in South Africa that have a maximum climatic similarity of <60% to the 16 South African locations which fall in the proximity of areas where CBS is found (see section 4.3.3). Provinces are colour coded to indicate the observed occurrence of CBS at a provincial level.

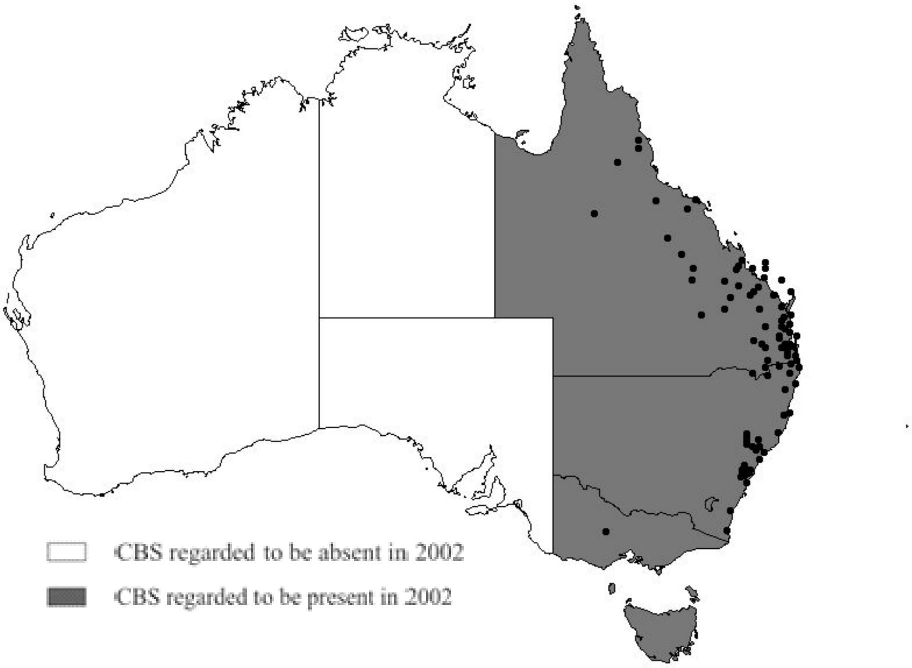

Figure 4.10 — Australian locations (•) with a maximum similarity index ≥60% to 16 South African locations which fall in the proximity of areas where CBS is found.

Figure 4.11 — None of the 285 locations in Europe had a maximum climatic similarity ≥60% to the 16 South African locations which fall in the proximity of areas where CBS is found.

4.5 Discussion

In this study it was found that a similarity index of ≥60% is sufficient to circumscribe a high potential for the establishment of CBS. These results are comparable to those found by Bennett et al. (1998), who used the Match Climates function to determine where certain plant species useful as genetic resources for plant breeding may occur. These authors selected a similarity index of 65% as the minimum level of similarity required for the successful establishment of plant species.

Results obtained in the present study support the absence of CBS in the Western Cape and Northern Cape Provinces, with the majority of weather data localities having a maximum similarity in climate of <60% to the chosen localities in South Africa.

Locations within the two Australian states with known CBS presence, New South Wales (Cobb, 1897; Kiely, 1960; Bertus A.L., 1980) and Queensland (Wager, 1945), are consistently included in the potential distribution of the disease when using a similarity level ≥60% to model the potential for establishment of CBS. Regions of Australia known to be free of CBS were not modelled as areas of potential occurrence at this similarity level. It is interesting to note that the inland localities of NSW (Bourke and Narromine), where the pathogen has been introduced and where it has not been able to establish, are not mapped as localities where the disease might occur. This verifies the hypothesis that a similarity index of ≥60% discriminates between localities where the climate is conducive for the establishment of the disease and those localities where the climate is not suitable for CBS establishment.

None of the 285 locations in Europe had a similarity of ≥60% when compared with any of the 16 chosen locations circumscribing positive CBS occurrence in South Africa. Consequently, it appears that the disease will not be able to establish itself in Europe. The knowledge that the disease does not currently occur in Europe supports these findings (European Union, 1998). Moreover, South Africa has been exporting citrus to Europe since 1906 (Oberholzer, 1969) and CBS has been present in South Africa from 1929 (Doidge, 1929). However, restrictions on the import of citrus from South Africa to the EU were first enforced in 1977 (European Union, 1977) and specific restrictions on imports from CBS infected areas were only introduced in the 1990s (European Union, 1992). Presumably CBS infected fruit entered the European Union over the 48-year period of free trade in citrus from CBS infected areas. During this time CBS did not establish in Europe. In practice, this situation is similar to that experienced in South Africa in terms of free-trade of citrus fruit between the rest of the country and the Western Cape region, where the disease has similarly not established to date.

Finally, it should be taken into consideration that the Match Climates Function in CLIMEX only considers the similarity in the meteorological data. The species requirements and interactions are not taken into consideration. Therefore outputs from this model should be interpreted with caution, and only serve as a rough first estimation for the potential establishment of a species.

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Chapter 5 — The potential global geographical distribution of Citrus Black Spot caused by *Guignardia citricarpa* (Kiely), with emphasis on the likelihood of disease establishment in the European Union

5.1 Abstract

This study represents a climatic modelling approach towards assessing the risk that Citrus Black Spot (CBS) will spread to regions of the world where the disease does not occur. Globally, CBS is widespread, but is absent within countries of the European Union (EU). Thus, barriers to the trade of citrus fruit have been put in place to restrict the possible introduction of the pathogen *Guignardia citricarpa* Kiely. The objective of this study is to evaluate the climatic suitability of the European climate for the establishment of the pathogen and persistence of the disease. For this purpose, the CLIMEX model was used which allows for the prediction of the potential geographical distribution of a species using its observed geographical distribution. In this study, the climatic requirements of CBS were inferred from the distribution thereof in South Africa and Australia. The model output reflected the current known distribution of the pathogen around the world and indicated that climate provides a barrier to the establishment of the disease in Europe. The potential distribution of CBS was mainly limited by cold conditions. A global map was produced which indicates localities where the climate is suitable for the potential establishment of the pathogen.

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5.2 Introduction

Citrus Black Spot (CBS), caused by *Guignardia citricarpa* Kiely [anamorph *Phyllosticta citricarpa* (McAlpine) van der Aa], is a foliar and fruit disease of citrus. The disease affects the rind of the fruit, causing superficial lesions (Kotzé, 1981; Snowdon, 1990). Most commercial citrus cultivars are susceptible to CBS to some degree, with lemons and Valencia oranges being highly susceptible (Kiely, 1948b; Kotzé, 2000). The disease may also cause significant losses on grapefruit and limes (Brodrick, 1969), and has been reported to occur on citron, pomelos and mandarins (Brodrick, 1969; Kiely, 1948b, 1970). Rough lemon is tolerant (Wager, 1952) and Persian limes (Timmer, 2005, Personal Communication) and sour orange are not susceptible to the pathogen (Kotzé, 1981).

The earliest official description of CBS was by Benson, (1895), from diseased fruit originating from citrus growing areas within New South Wales (NSW), Australia. He published drawings of diseased fruit, but did not study the causal organism. Subsequently, CBS was recorded from orange orchards near Sydney, NSW (Cobb, 1897). The first record of CBS in South Africa (SA) was in 1929 from areas around Pietermaritzburg (Doidge, 1929). The disease has also been recorded in other countries, including Argentina (Garran, 1996), Bhutan (European Union, 1998), Brazil (European Union, 2000a), China (European Union, 1998), Ghana (Timmer, 2005, Personal Communication), Indonesia, India (Brodrick, 1969), Kenya, Mozambique (European Union, 1998), Nigeria (Baayen et al., 2002), Philippines, Swaziland, Taiwan, Uruguay (Kotzé, 2000), West Indies (Calavan, 1960), Zambia and Zimbabwe (European Union, 1998).

Reports on the occurrence of CBS in New Zealand and Japan are conflicting and it is uncertain if the disease occurs in these countries (CABI/EPPO, 1998; Sutton & Waterson, 1966). Although a pathogen of citrus, *P. citricarpa* does occur in Japan, it causes fruit decay and not rind spotting (Kuramoto, 1981). Additionally, an isolate of *Guignardia* (PPRI 1567) from Japan, previously thought to be the pathogen *G. citricarpa*, was identified as the endophyte *G. mangiferae* (A.J. Roy) by Baayen et al. (2002). Citrus Black Spot symptoms have never been seen on citrus fruit in New Zealand (Everett & Hale, 2002; Dawson, 2003, Personal Communication; Tyson, 2003, Personal Communication).

The disease has not been recorded in citrus-producing Mediterranean and European countries (European Union, 1998; Kotzé, 2000) including Greece, Israel, Italy, Spain, Portugal, France and Turkey (Baayen et al., 2002; Bonants et al., 2003). It does not occur in Chile or the citrus growing areas of the USA (Baayen et al., 2002; Cook, 1975; European Union, 2000b; Kotzé, 1981).

Various citrus growing areas, within countries where the disease has been recorded, have remained free of CBS. In China, the disease has only been recorded in the provinces of Sichuan, Yunnan, Guangdong, Fujian and Zhejiang (European Union, 1998). In Brazil, it was first recorded in 1980 in the state of Rio de Janeiro and also in Rio Grande do Sul (in 1986) and São Paulo (in 1992) (European Union, 2000a). In SA, the Hartswater (USDA/APHIS, 2002), Vaalharts and Warrenton citrus production regions in the Northern Cape (Mabiletsa, 2003) and all the citrus production regions within the south-western Western Cape are free of CBS (European Union, 1998; Mabiletsa, 2003). Despite movement of CBS-infected citrus fruit and potentially infected nursery trees [prior to the implementation of the restriction on the movement of citrus propagation material in 1983 (Agricultural Pests Act, 1983)] into this region (Kotzé, 2002, Personal Communication) it has remained free of CBS (European Union, 1998; Mabiletsa, 2003). Similarly, CBS infected fruit have been introduced to the inland citrus producing areas of NSW in Australia and the disease has also not been able to establish in this region (Barkley, 2003, Personal Communication; Whiteside, 1965). Other parts of Australia reported to be free of CBS are the Sunraysia and mid-Murray areas of Victoria and NSW, and the entire states of Western Australia and South Australia (including the Riverland region) (Barkley, 2003, Personal Communication; European Union, 1998). This suggests that climate plays an important role in the potential distribution of the disease.

World-wide, South Africa is the third largest exporter of fresh citrus fruit. Approximately 50% of South African citrus was exported during the 2001/2002 season (FAO, 2002). However, the export of fruit from regions infected with CBS to the European Union (EU) is restricted through quarantine regulations (Bonants et al., 2003; European Union, 2000c). Similar phytosanitary restrictions affect the export of citrus from Argentina (European Union, 2001a), Australia (European Union, 1998) and Brazil (European Union, 2000a) into the EU.

A Pest Risk Analysis (PRA) for the export of fresh citrus fruit from CBS-infected production regions in SA to the EU was conducted (Hattingh et al., 2000). This PRA included a review of the disease and results of studies conducted to determine the survival of conidia on fruit in the packinghouse. In addition, there was a need for a predictive climate matching study (European Union, 2001b). Therefore, the main objective of this study was to evaluate the suitability of European climates for the establishment of CBS. The premise of this approach was that CBS only occurs in areas with a climate suitable for disease development. Consequently, there would be no risk of inadvertently introducing the disease into regions where climatic conditions are unfavourable for disease development.

For this purpose, the Compare Locations function in CLIMEX (Hearne Scientific, Melbourne, Australia) was used. This function compares the relative potential for growth and persistence of a species in different localities and allows prediction of the potential geographic distribution of that species based on its climatic requirements (Sutherst & Maywald, 1985; Sutherst et al., 2003). The model is based on the assumption that organisms are efficient integrators of climate and other environmental variables. The seasonal phenology, geographical distribution and relative abundance of the population reflect the integration processes. It is difficult to capture these complex processes in experiments or in process-based simulation models. CLIMEX is especially useful in cases where there is a lack of process-related data. The aim of this model is therefore to describe the core responses of a species to climate by providing a single number to indicate the climatic favourability of a location for a specific species (Sutherst & Maywald, 1985; Vera et al., 2002).

There have been examples where climatic modelling approaches have been used to determine the risk of potential establishment of plant pathogenic species. These include: leaf blight [*Cylindrocladium quinqueseptatum* (Boedijn and Reitsma)] of Eucalyptus in mainland Asia and globally (Booth et al., 2000a); Eucalyptus rust [*Puccinia psidii* (Winter)] in the Neotropics and Australia (Booth et al., 2000b); and *Sphaeropsis sapinea* [(Fr.) Dyko and Sutton] and *Cryphonectria cubensis* [(Bruner) Hodges] (pathogens of *Pinus* and *Eucalyptus* spp.) in South Africa (Van Staden et al., 2004). The risk of establishment of plant pathogens has also been successfully defined a priori using climatic modelling with CLIMEX, for example oak decline [*Phytophthora cinnamomi* (Rands)] in southern Europe (Brasier, 1996) and soybean rust [*Phakopsora pachyrhizi* (Sydow)] throughout the world (Pivonia & Yang, 2004).

CLIMEX aims to provide answers to practical problems about the control of invasive species and provides a modelling technique that allows the incorporation of new information as it becomes available. CLIMEX model outputs can assist in estimating the risk of introducing novel species. This will allow preventative or adaptive disease management approaches (Booth et al., 2000a) and can support decision-making with regards to quarantine issues, particularly when existing information is sparse (Worner, 1988).

Since citrus is a high value fruit crop and CBS is economically important and currently a technical barrier to trade for certain countries, the potential global distribution of this disease is of interest to all citrus producing countries of the world. Climate plays a key role in the epidemiology of this disease, especially since relatively high temperatures and the availability of moisture promote pathogen establishment, and high temperatures increase disease severity (Kotzé, 1971, 1996). The objective of this study is to explore the influence of climate on the potential for disease establishment in areas where CBS has previously not been recorded.

5.3 Methodology

5.3.1 Epidemiology of Citrus Black Spot

Two types of spores may cause infection of citrus, namely windborne ascospores (contained in perithecia) and waterborne conidia (contained in pycnidia) (Kiely, 1948b; Kotzé, 1963, 1996). Both kinds of fruiting bodies may be found on a single leaf, but only pycnidia occur on infected fruit (McOnie, 1965). In wet weather, conidia ooze from pycnidia. These conidia then require running water for dissemination and specific conditions for germination (Kiely, 1948b; Korf et al., 2001).

Ascospores are seen to be the most important source of inoculum (Kiely, 1948b; Kotzé, 1963, 1996). Successful maturation of perithecia is determined by prevailing weather conditions, as optimal maturation requires alternate wetting and sun drying of leaves, and fluctations in temperature (Kiely, 1948a, 1948b, 1949; Kotzé, 1981; McOnie, 1967). Discharge of ascospores relies on wetting of the perithecia. Germination of ascospores and infection then requires the presence of free surface water and suitable microclimatic conditions (Kiely, 1948b).

The critical period for infection of fruit is from fruit set until up to five months later when the fruit becomes resistant to further infection (Kotzé, 1981). Mature fruit is not infected (Wager, 1949). Therefore, the onset of rain, ascospore release and infection period are strongly correlated (Kotzé, 1963; McOnie, 1964; Whiteside, 1967). Where these three factors do not coincide, no epidemic will develop (Kotzé, 2002, Personal Communication).

5.3.2 Outline of the CLIMEX model

The CLIMEX model integrates the weekly responses of a population to climate into a series of annual indices. A hydrological model is used to calculate weekly soil moisture from rainfall and estimated evaporation. Responses to temperature and moisture are combined into a weekly population Growth Index (GIw) for that species. The annual Temperature Index (TI) and annual Moisture Index (MI) summarize the response of the species to temperature and moisture respectively. Responses to detrimental conditions are reflected by a series of "stress indices" that estimate the harmful effects of either extreme or prolonged exposure to hot, cold, dry or wet weather. These stress indices may be applied on their own or in combination with each other, so the stress accumulated may include hot and dry, or, cold and wet stress. These growth and stress indices are combined into an Ecoclimatic Index (EI). The EI indicates the suitability of a certain geographical location for the multiplication, infection and persistence of the species on a scale from 0 to 100. Generally, an EI value greater than 30 can be considered very favourable for population growth and persistence, while an EI value equal to zero suggests that the species will be unable to persist under average climatic conditions (Sutherst et al., 2003). However, EI values are based on the species occurrence and abundance and EI values indicating a highly favourable climate will differ per species based on the requirements of the species. So for instance, Vera et al. (2002) use EI values of higher than 25 as highly favourable for the establishment of mediterranean fruit fly in Argentina and Australia, and D'Amamo et al (2002) use an EI of 20 and higher to circumscribe a highly favourable climate for the establishment of german wasps in Argentina.

The values of the CLIMEX model parameters, which reflect the climatic requirements of the species, are inferred from information on the currently known distribution of the species. The procedure is referred to as inverse, or inferential, modelling. In CLIMEX, this involves developing hypotheses as to which factors limit the distribution, and then manually adjusting parameter values until the simulated geographical distribution coincides as closely as possible with the observed distribution (Sutherst & Maywald, 1985). A specific parameter set should describe the climatic responses of the species. Once the parameter values have been estimated, the parameter set may be used to predict the potential occurrence of the species in other locations (McFadyen & Skarratt, 1996). Sutherst and Maywald (1985) describe the system in full and give details on the theoretical background and application of the program.

5.3.3 Data

5.3.3.1 The geographical distribution of Citrus Black Spot in South Africa and Australia

In 2002, six field pathologists, with extensive knowledge of CBS, mapped the geographical distribution of the CBS in SA (as described in 4.3.1, page 69) and this resulted in a map of the actual presence of the disease in SA at the time of assessment (Figure 5.). Information on the presence of CBS in Australia as obtained from the Australian Plant Pest Database (APPD), was provided by Patricia Barkley (formerly NSW Agriculture, Camden, Australia) and Andrew Miles (Queensland Department of Primary Industries, Indooroopilly). A map of the known occurrence of CBS in Australia was drawn up from these data (Figure 5.2).

5.3.3.2 Climate data

The meteorological database within CLIMEX Version 2. consists of values for monthly long-term average maximum and minimum temperature, rainfall and relative humidity for 3092 locations. Of these localities, 129 are in SA, 676 are in Australia and 285 are in Europe. The model was run for all localities.

5.3.4 Predicting the distribution of Citrus Black Spot

The CLIMEX parameter values were estimated using the known current distribution of the disease in SA (Figure 5.) and in Australia (Figure 5.2), also taking into consideration the officially recorded absences of CBS in the Western Cape of South Africa and the inland parts of NSW in Australia. The values were iteratively adjusted until there was a close visual match between the current known distribution and the predicted potential distribution. Particular attention was paid to areas around Nelspruit in SA, where the disease has been known to occur in serious epidemic proportions. The final parameter values were applied to predict the potential distribution of CBS on a global scale.

5.3.5 Validation

The EI values for the occurrence of CBS, as predicted by the model, were split into three categories: EI ≤ 4, climate unfavourable for the persistence of the species; EI ≥ 5 and EI ≤10, climate marginally suitable for disease development; EI ≥ 11, climate favourable for disease development (locations with EI values above 20 had climates highly favourable for CBS).

To test the validity of these categories, data on the presence or absence of CBS, as obtained from literature or through personal communication were collected for 537 meteorological localities. These localities were from the CLIMEX program, but were independent of those used to build the model. These localities were predominantly from Australia, as the most accurate data was available for Australia, but some localities were from South Africa, Brazil, Zimbabwe, Indonesia and Argentina. The localities were divided into sites where a citrus host was probably present (70 localities) and those where the presence of a citrus host was not known (467 localities). At each locality, EI values greater than 4 were counted as predicted presences, while EI values equal or smaller than 4 were counted as predicted absences. The predicted presences and absences were then compared to the observed presences and absences at those same localities using the Kappa statistic (κ). κ is used to measure the agreement between two sets of categorical data while correcting for chance agreements between the categories. This statistic based on a confusion matrix which relies on both presence and absence records (Robertson & Palmer, 2002) (Table 5.1). The absolute counts for the localities where citrus was probably present is presented in Table 5.2 and the absolute counts for the localities where the presence of a citrus host was not known are presented in Table 5.3.

Table 5.1 — A confusion matrix used to calculate the Kappa statistic (κ). The paramaters a, b, c, and d represent absolute counts.

		Observed	
		presence	**absence**
Predicted	**presence**	a	b
	absence	c	d

Table 5.2 — The confusion matrix used to calculate the Kappa statistic (κ) for the localities where citrus is probably present.

		Observed	
		presence	**absence**
Predicted	**presence**	13	0
	absence	0	57

Table 5.3 — The confusion matrix used to calculate the Kappa statistic (κ) for the localities where the presence of a citrus host was not known.

		Observed	
		presence	**absence**
Predicted	**presence**	0	0
	absence	0	476

The value for κ lies between zero and one. A value of greater than 0.75, indicates an excellent agreement beyond chance, a value smaller than 0.4 indicates poor agreement, and a value close to zero would indicate agreement that is no better than random (Landis & Koch, 1977; Monserud, 1990).

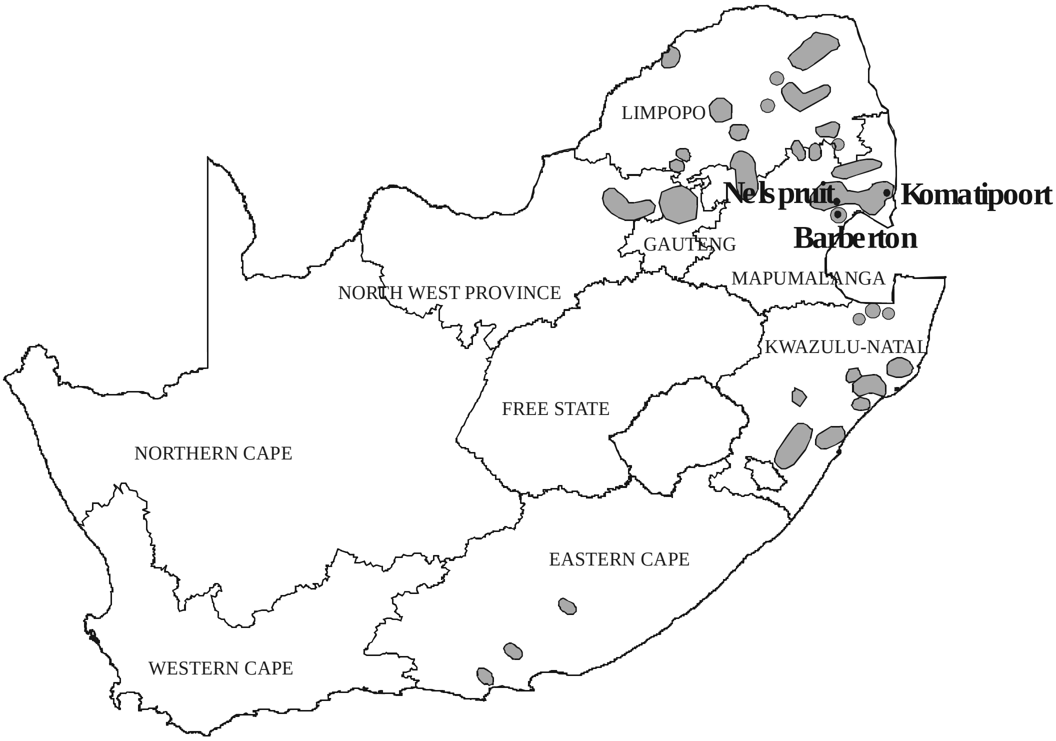

Figure 5.1 — The distribution of Citrus Black Spot in South Africa

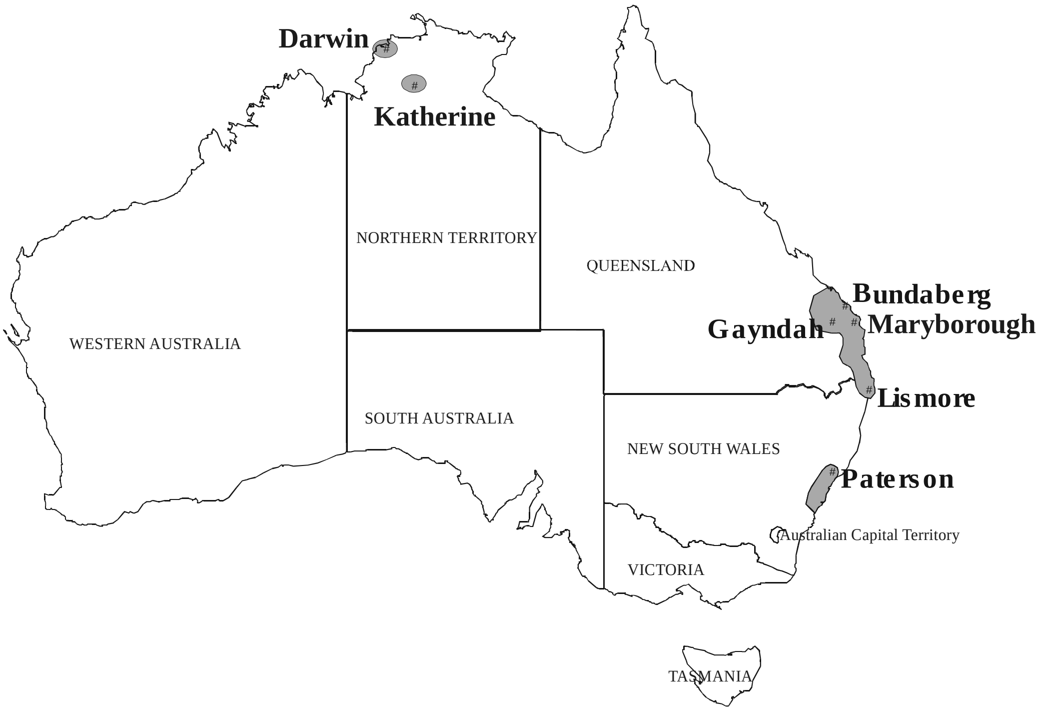

Figure 5.2 — The distribution of Citrus Black Spot in Australia

5.4 Results

5.4.1 Potential distribution of Citrus Black Spot

The parameter values that best describe the observed distribution are provided in Table 5.4. The predicted areas of occurrence of the disease in SA (Figure 5.3) and Australia (Figure 5.4) closely fit the observed distributions of the pathogen in these countries. The radii of the circles on the maps are proportional to the calculated EI values and give an indication of the climatic suitability for persistence of CBS.

Within SA, the model predicted EI values of above 30 at all the localities where the disease occurs abundantly, such as Barberton (EI=36), Komatipoort (EI=33) and Nelspruit (EI=37) (Figure 5.3), indicating that the climate at these localities is highly suitable for the establishment of the disease. Similarly, the model predicted EI values of higher than 20 for localities in Australia known to have a high occurrence of CBS, namely Lismore (EI=24) and Paterson (EI=21) in NSW, and Maryborough, (EI=25), Gayndah (EI=25) and Bundaberg (EI=24) in Queensland (Figure 5.4).

Interestingly, the EI values of several localities within SA where the disease has not been reported to occur are highly suitable for the occurrence of CBS. These localities include East London (EI=30) and Umtata (EI=21) in the Eastern Cape, and Ladysmith (EI=28) and Dundee (EI=20) in Kwazulu Natal. Similarly, in Australia, the model indicated a potential for establishment in localities where CBS has not yet been recorded, in coastal NSW (Casino, EI=31; Grafton, EI=30; Taree, EI=23; Kempsey, EI=23), and in Queensland (EI values above 25 — Charters Towers, Gladstone, Mount Morgan and Rockhampton).

The indices describing cold stress were crucial in explaining the distribution of the disease in SA, Australia and around the globe. The main factor limiting the distribution of the disease was found to be cold stress in the form of continuous winter days with temperatures too low to allow the survival of the pathogen. All southern inland areas of Australia (including the citrus growing areas of Sunraysia, Riverland, Riverina) were excluded due to cold stress, but also as a result of a lack of sufficient moisture for growth, and the EI values in these areas never exceeded a value of one. Additionally, the EI values for localities within the inland parts of NSW (Bourke and Narromine) were smaller or equal to four mainly due to a lack of moisture. In the coastal and inland areas of the south-western Western Cape in SA, where all localities had EI values smaller or equal to four cold stress was the main limiting factor for occurrence of the disease. Although cold stress accumulated in the Northern Cape region of SA, the main factor limiting the distribution of the disease was insufficient moisture for growth.

Table 5.4 — CLIMEX parameter values giving the best fit to the distribution of Citrus Black Spot caused by *Guignardia citricarpa*.

Parameter Description	**Value**
Temperature parameters	
Lower threshold of temperature for population growth°C (DV0)	17
Lower optimal temperature for population growth°C (DV1)	24.5
Upper optimal temperature for population growth°C (DV2)	32
Upper threshold temperature for population growth°C (DV3)	40
Moisture parameters	
Lower threshold of soil moisture (SM0)	0.18
Lower limit of optimal range of soil moisture (SM1)	0.45
Upper limit of optimal range of soil moisture (SM2)	0.85
Upper threshold of soil moisture (SM3)	1.0
Stress indices	
Cold stress	
Cold stress temperature threshold°C (TTCS) (below which cold stress accumulates)	11
Cold stress temperature rate (THCS)	-0.0001
Cold stress degree-day threshold (DTCS)	6
Cold stress degree-day rate (DHCS)	-0.00025
Dry Stress (not used)	
Heat stress	
Heat stress temperature threshold°C (TTHS) (above which heat stress accumulates)	40
Heat stress temperature rate (THHS)	0.001
Heat stress degree-day threshold (DTHS)	25
Heat stress degree-day rate (DHHS)	0.001
Wet stress	
Wet stress threshold (SMWS)	1.45
Wet stress rate (HWS)	0.0001

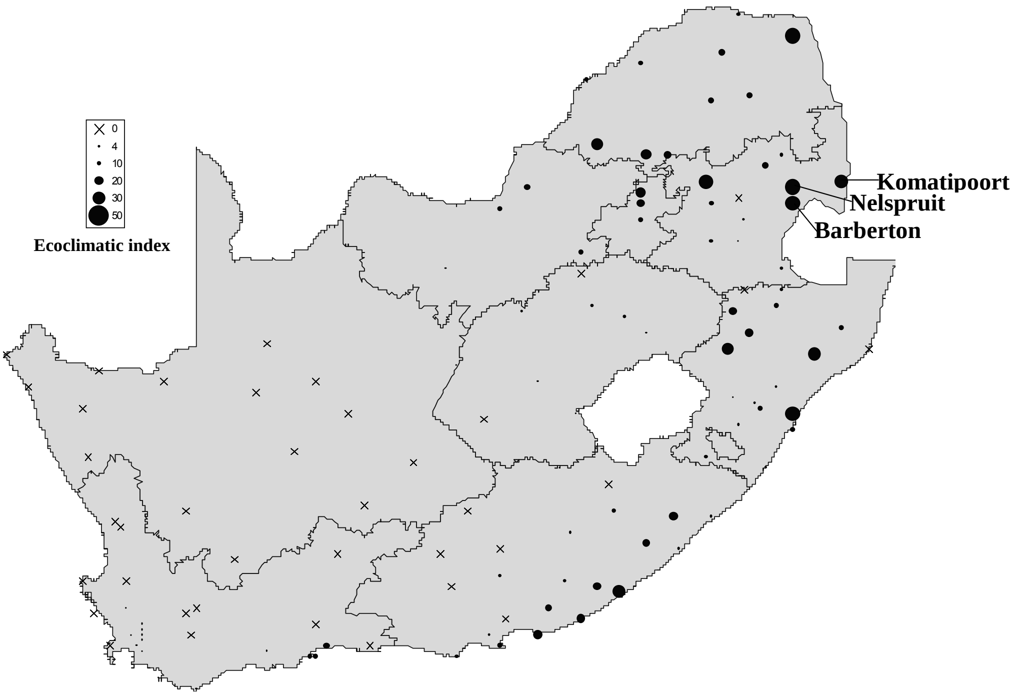

Figure 5.3 — The potential geographical distribution of Citrus Black Spot in South Africa as fitted by the CLIMEX model. The Ecoclimatic Index (EI) is proportional to the radii of the circles. Locations indicated with an x represent those with an EI of 0.

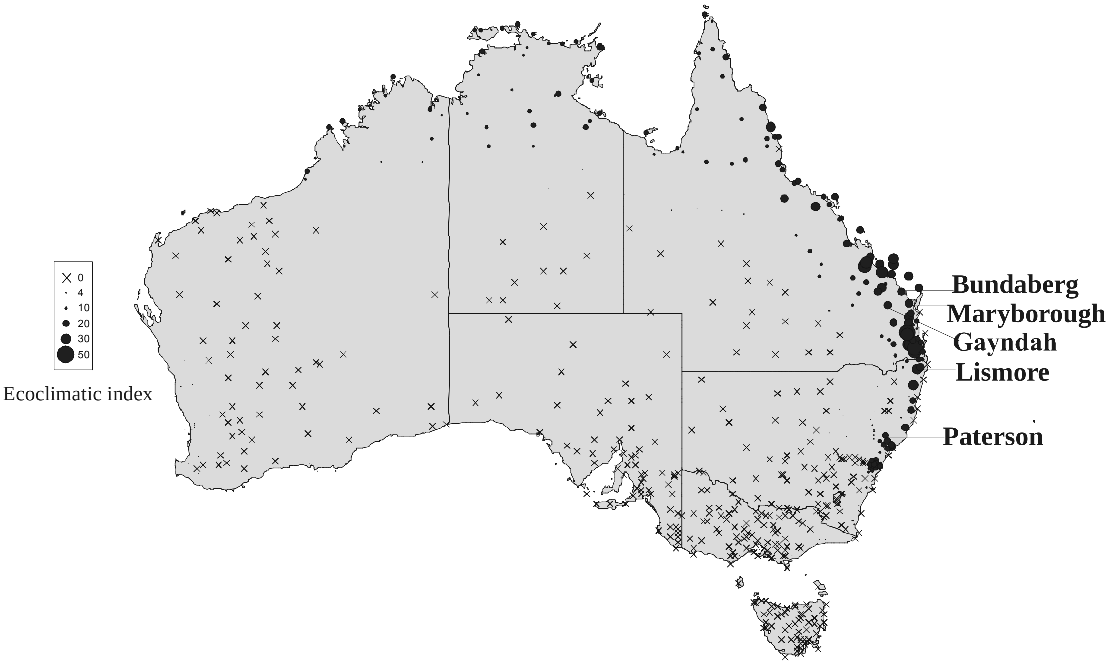

Figure 5.4 — The potential geographical distribution of Citrus Black Spot in Australia as fitted by the CLIMEX model. The Ecoclimatic Index (EI) is proportional to the radii of the circles. Locations indicated with an x represent those with an EI of 0.

Globally the distribution, especially in the northern hemisphere, was limited by cold stress, whereas heat stress limited the distribution in Northern Africa and parts of India, Pakistan, Iraq and Saudi Arabia.

Currently, the disease does not occur in Europe (Baayen et al., 2002). The CLIMEX model indicated that of the 285 localities in Europe 228 had an EI=0, indicating that the species will be unable to establish or persist at those localities. An EI=0 was found at all the localities in Austria, Belgium, Denmark, Finland, Germany, Ireland, Luxembourg, The Netherlands, Sweden and the United Kingdom (Figure 5.5). Furthermore, another twenty-one localities had an EI=1, thirteen had an EI=2, ten had an EI=3, seven had an EI=4, three had an EI=5, one locality an EI=6, and one had an EI=7. The highest EI obtained was EI=8 for the Las Palmas Island of Spain (Figure 5.6).

On a global scale the model mapped the potential distribution of the disease in all the countries where CBS has been reported, except for Taiwan and Bhutan (Figure 5.7). In all of these countries, the EI values were favourable for the establishment of CBS with values higher than 20 (at least at one locality), except for China (maximum EI=19) and Swaziland, (maximum EI=13). The model also reflected the lack of climatic suitability of some areas where the disease is currently known to be absent. All of the localities in Chile, had an EI=0, with the exception of one locality with an EI=1. Likewise, all the localities in California had an EI=0, with the exception of one locality with an EI=1.

5.4.2 Validation

The EI values of 537 meteorological localities within CLIMEX were statistically compared to the known occurrence of CBS at that locality. This was done using the Kappa statistic, a value that measures the agreement of categorical data (Landis & Koch, 1977). The 537 localities included 70 localities where the citrus host was probably present and 437 localities where the presence of the citrus host is not known. When the kappa value was caluculated for these groups of localities it was equal to one for both groups, indicating that the CLIMEX model was in exact agreement with the current true occurrence of CBS at those localities.

Figure 5.5 — The potential geographical distribution of Citrus Black Spot in Europe as predicted by the CLIMEX model. The Ecoclimatic Index (EI) is proportional to the radii of the circles. Locations indicated with an x represent those where the EI amounts to 0.

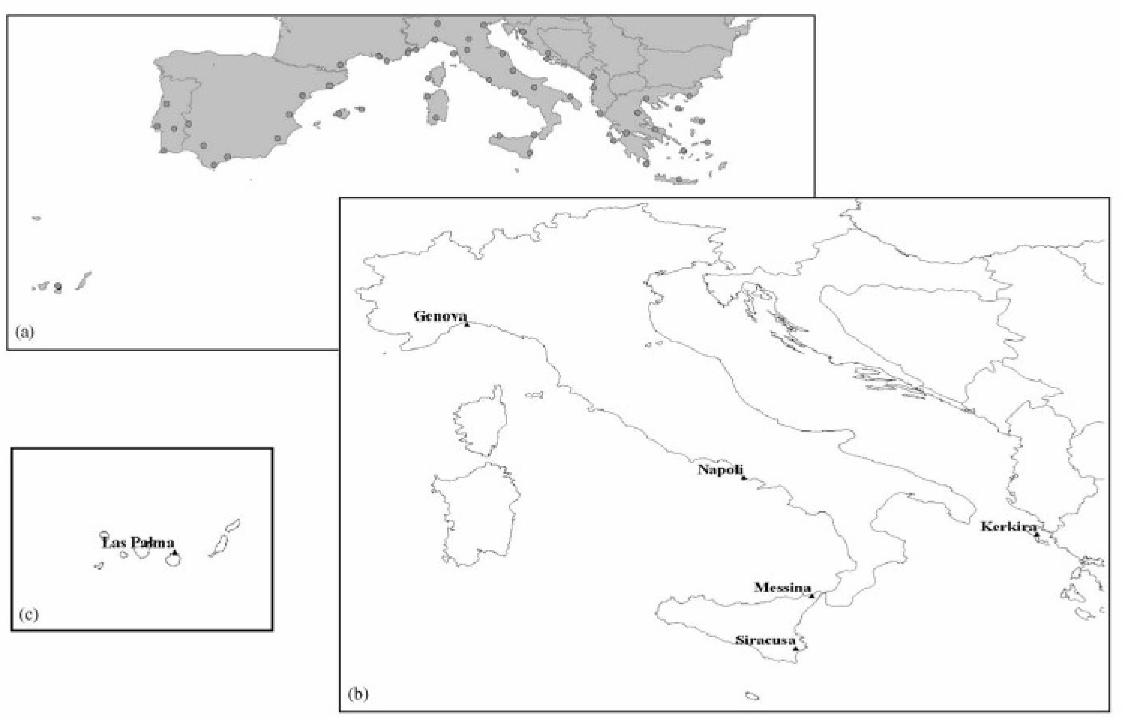

Figure 5.6 — Localities in Europe indicating: a) All localities with Ecoclimatic Index (EI) values lower than eight, b) Those localities with an EI value greater than four and c) The Las Palmas Island of Spain (EI=8).

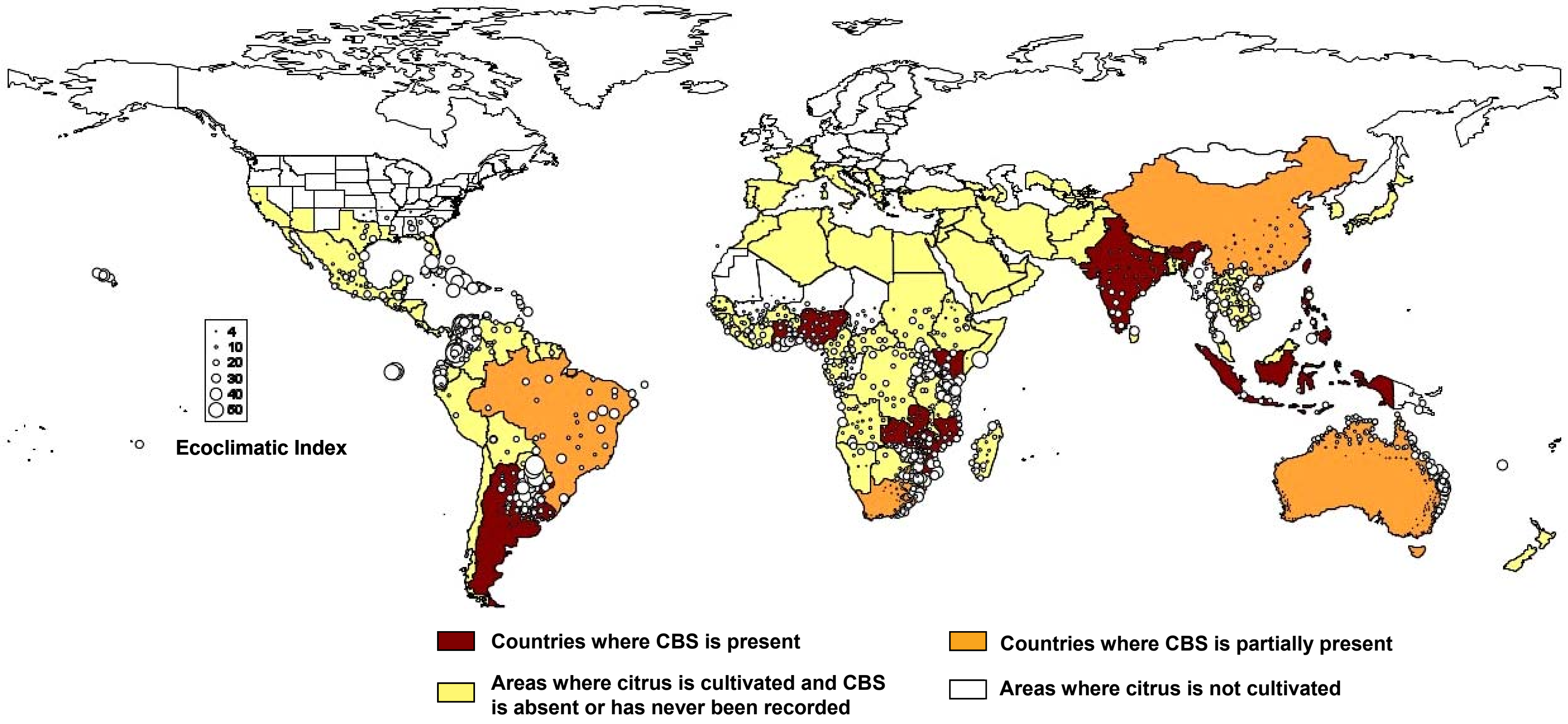

Figure 5.7 — The potential geographical distribution of Citrus Black Spot world-wide as fitted by the CLIMEX model. The Ecoclimatic Index (EI) is proportional to the radii of the circles.

5.5 Discussion

The model successfully describes the current known distribution of the pathogen around the world and indicates that climate appears to provide an effective barrier to CBS establishment. However, in SA (Figure 5.3) and Australia (Figure 5.4), some localities where CBS has never been recorded were predicted to have climates suitable for the occurrence of CBS. This may be because the host and/pathogen are absent or the presence of the disease has not been reported in the literature. In any event, the climates at these localities may be suitable for the establishment of CBS, and these results should serve as an early warning for the expansion of citrus production into the areas demarcated climatically suitable for the establishment of CBS.

On a global scale (Figure 5.7), the model mapped the potential distribution of the disease in all countries where CBS has been reported, with the exceptions of Taiwan and Bhutan. Only two climate data localities for Taiwan were available within the meteorological database of CLIMEX. Thus, the exclusion of Taiwan by the model may be because specific weather data points did not fall within citrus production regions of the country, where CBS may potentially occur. There were also no weather data localities for Bhutan within the meteorological database of CLIMEX (See Appendix A). Furthermore, these results support reports on the absence of CBS in Japan (Kotzé, 1996) and New Zealand (Sutton & Waterson, 1966), since there were no localities in either of these countries with favourable EI values.

All localities in the south-western Western Cape and inland parts of NSW where CBS is absent, despite the introduction of the pathogen, had EI values smaller than or equal to four. Since the outbreak of a plant disease requires the presence of a pathogen, a susceptible host and favourable climatic conditions (Booth et al., 2000a), the inability of a pathogenic species to establish in an area where both the pathogenic species and susceptible host are present may be attributed to unfavourable climatic conditions. Therefore, it is reasonable to conclude that an EI value equal to, or lower than four reflects climatic unsuitability for establishment of the CBS.

This study suggests that the climate of EU countries is unsuitable for establishment of the CBS disease-causing organism. However, five localities in Europe had an EI value higher than four (Figure 5.6). Three of these localities had an EI=5, namely Kerkira (Corfu) in Greece, and Napoli and Siracusa (Sicily) in Italy. One locality had an EI=6, namely Messina (Sicily, Italy), one locality, Genova had an EI=7 and the Las Palmas Island of Spain had an EI=8. Kerkira, Siracusa, Messina (Sicily) and the Las Palma Islands are island localities. Napoli and Genova are the only sites with an EI value greater than four that are on the European mainland and citrus is not cultivated at either of these localities (Anonymous, 1992), so the risk of introduction of CBS to commercial citrus growing operations appears to be very low. Furthermore, citrus trees require minimum temperatures above 7°C to survive (Davies & Albrigo, 1994; Spiegel-Roy & Goldschmidt, 1996; Srivastava & Singh, 2002). At both these localities, average temperatures below 7°C are experienced for two to three months of the year, indicating that citrus trees, the hosts of CBS, are unlikely to survive at these localities.

Whereas climatic unsuitability alone can provide a good indication that the risk of an organism establishing in a region is low, evaluating the phytosanitary risk posed by trade must combine the climatic suitability of a given region with a multitude of other risk mitigation considerations through a PRA. Standardized guidelines for PRAs have been developed by the International Plant Protection Convention (1996).

The importation of citrus into the EU is restricted to fruits and seeds and excludes any other vegetative citrus material such as leaves. Fruit are thus required to be free of peduncles and leaves (European Union, 2000c). It is known that only conidia and no ascospores (primary inoculum source) are associated with CBS-infected fruit, and together with the outcomes of this climatic modelling exercise, the risk of CBS introduction and establishment in the EU as a result of commercial trade in fresh citrus fruit, even from CBS infected areas, appears negligible.

The climate in some citrus producing countries near Europe such as Egypt and Turkey are also unsuitable for the establishment of CBS. Dry conditions restricts the survival of the species in Egypt while, in Turkey, cold temperatures are detrimental to the persistence of the species. Likewise, the EI values in Israel and Morocco were always ≤ 4 except for one locality in Morocco, Larache (EI=5) and two localities in Israel namely Gaza (EI=5) and Haifa (EI=6). Availability of moisture restrict the potential occurrence of the species in Israel and in Morocco climatic conditions are mainly too cold and too dry.

Several important citrus producing countries where the disease has not yet been reported have climates suitable for the establishment of CBS. This is especially true for the USA (Florida and Texas), which is second only to Brazil in citrus production, and Mexico, the world’s largest producer of limes. Localities in these two countries frequently had EI values of above 20 with the highest values obtained in Tampa, Florida, USA (EI=28), at Brownsville, Texas, USA (EI=34) and at Progreso, Mexico (EI=36). Citrus is produced commercially at all of these localities. Other citrus producing countries that had climates suitable for disease establishment included Colombia, Cuba, Ecuador, Vietnam and Thailand.

It is important to realise that the values for the EI as provided by CLIMEX is not an absolute value and should be interpreted in a comparative or relative manner (Worner, 1988). CLIMEX parameter sets are not overly sensitive and small changes in the parameter set do not change the outcome appreciably. Because the total response of the species to climate is of interest, this information is valuable in the absence of more detailed studies and can be derived from relatively incomplete data.

CLIMEX analyses only consider the effects of climate on the species, therefore the output should be interpreted with caution. Decision-making processes should take account of the potential effects of competition from other species and human influences (such as effective control methods and irrigation) within the areas where CBS is predicted to occur (Worner, 1988).

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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.

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.

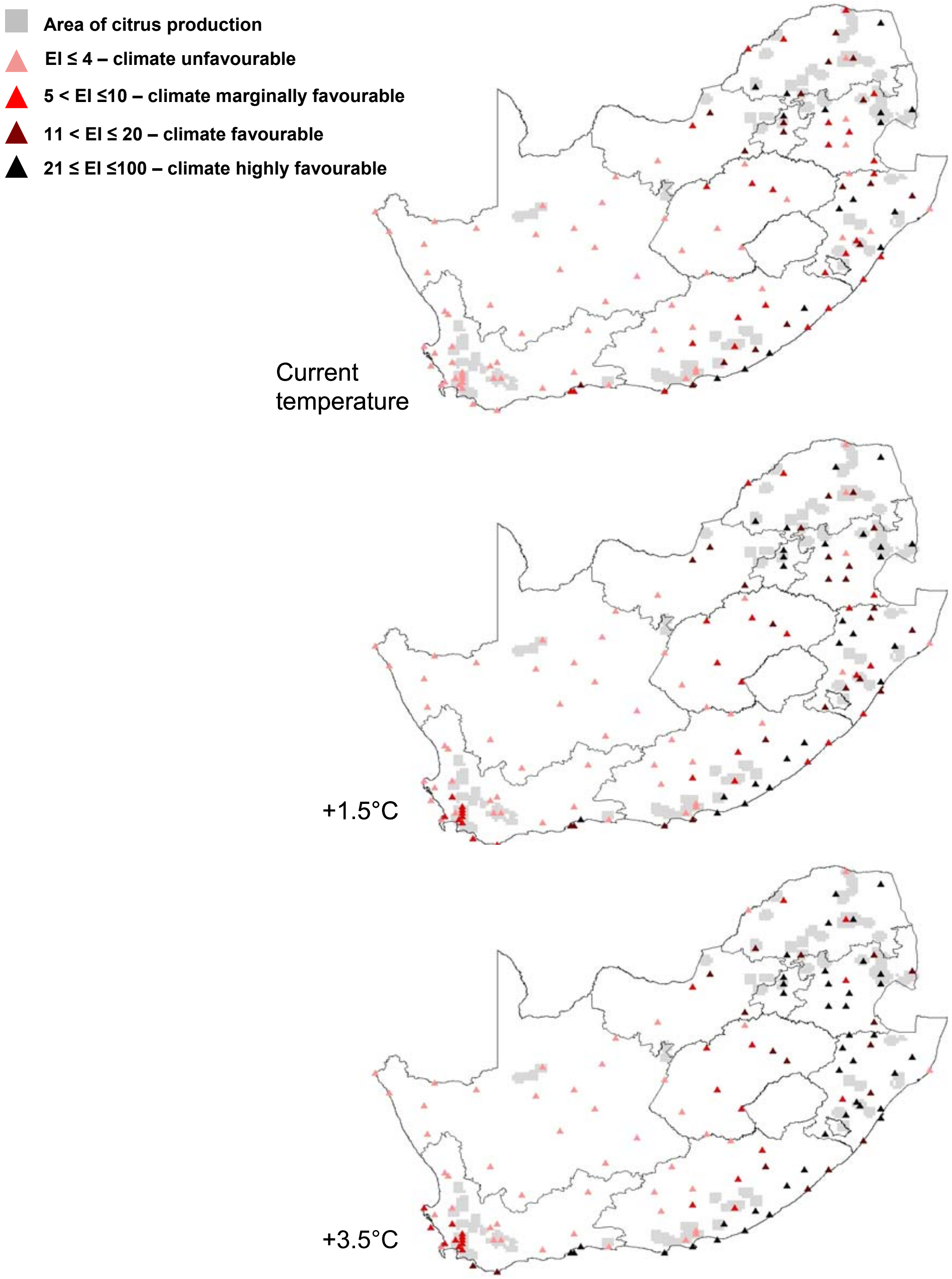

Figure 6.1 — The effect of an increase in temperature on the suitability of South African climate for CBS, indicating the differences in suitability of climate at different localities.

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.

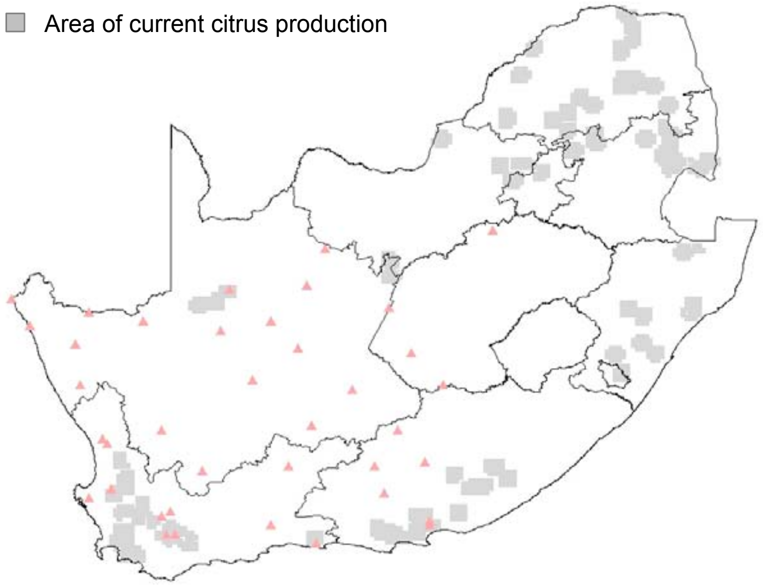

Figure 6.2 — Localities in South Africa, where climate will not become suitable for the establishment of CBS for 17 different climate change scenarios.

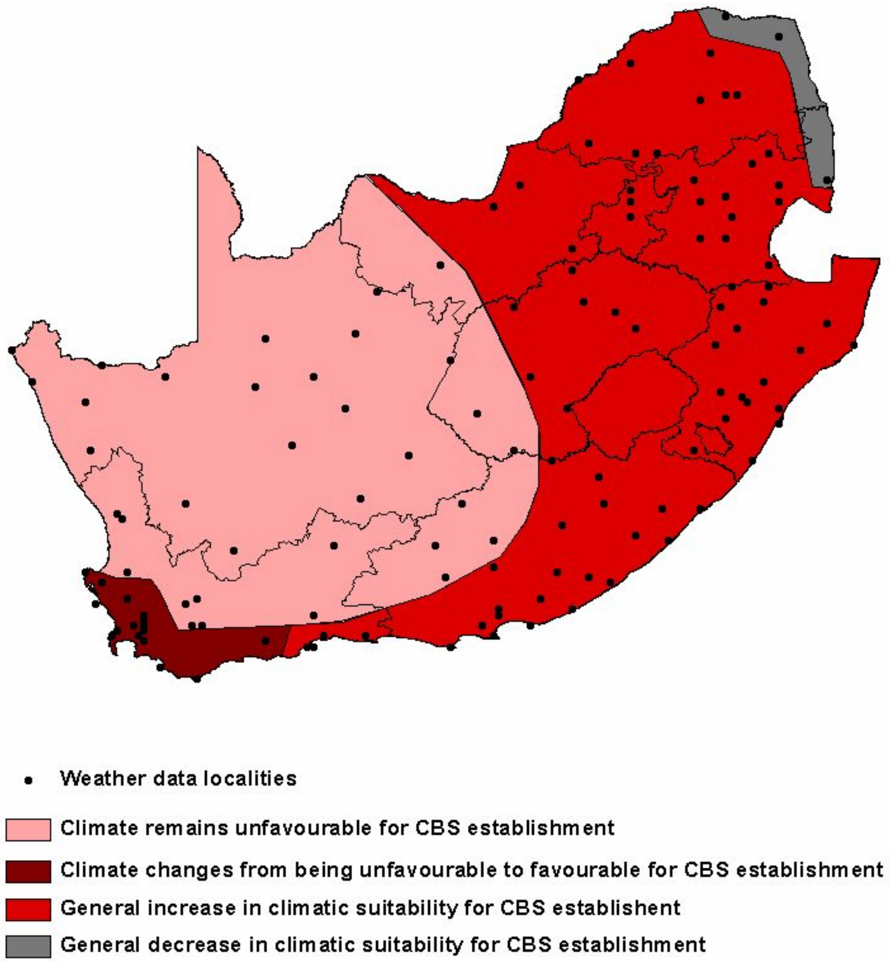

Figure 6.3 — Broad changes in climatic suitability of localities in South Africa for the establishment of Citrus Black Spot under all of the 17 different climate change scenarios.

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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 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, 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).

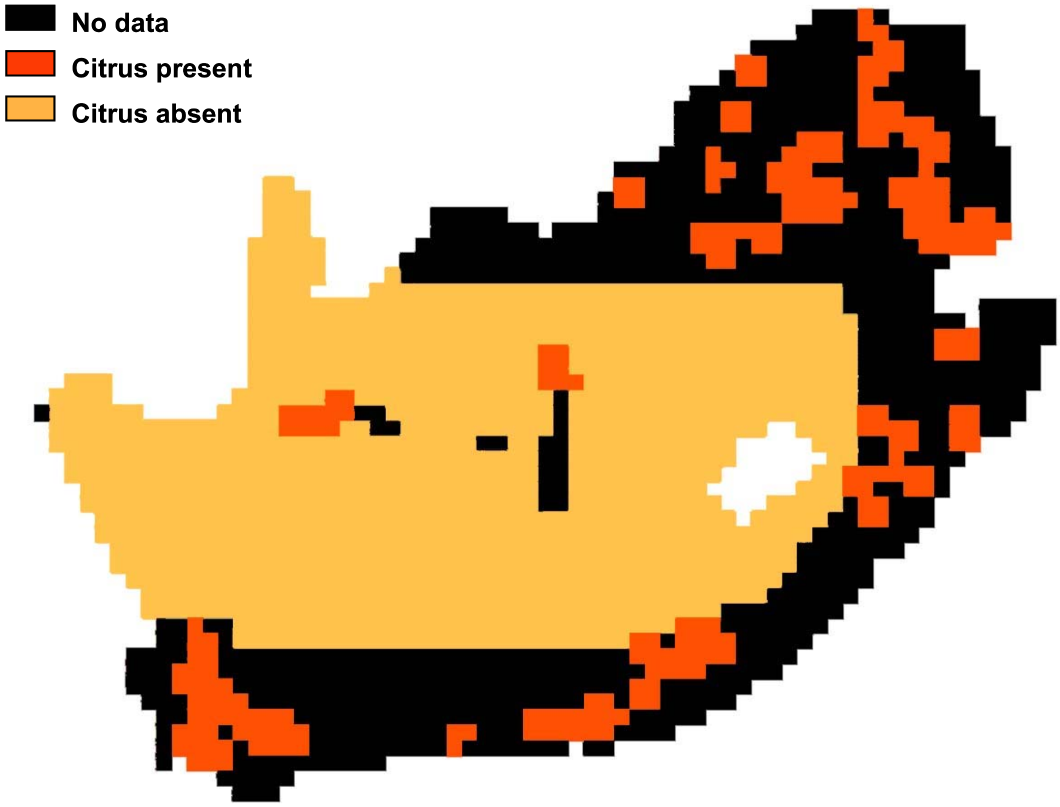

Figure 7.1 — The occurrence of citrus cultivation areas in South Africa in 2004.

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 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 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 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 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.

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 ≤ 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.

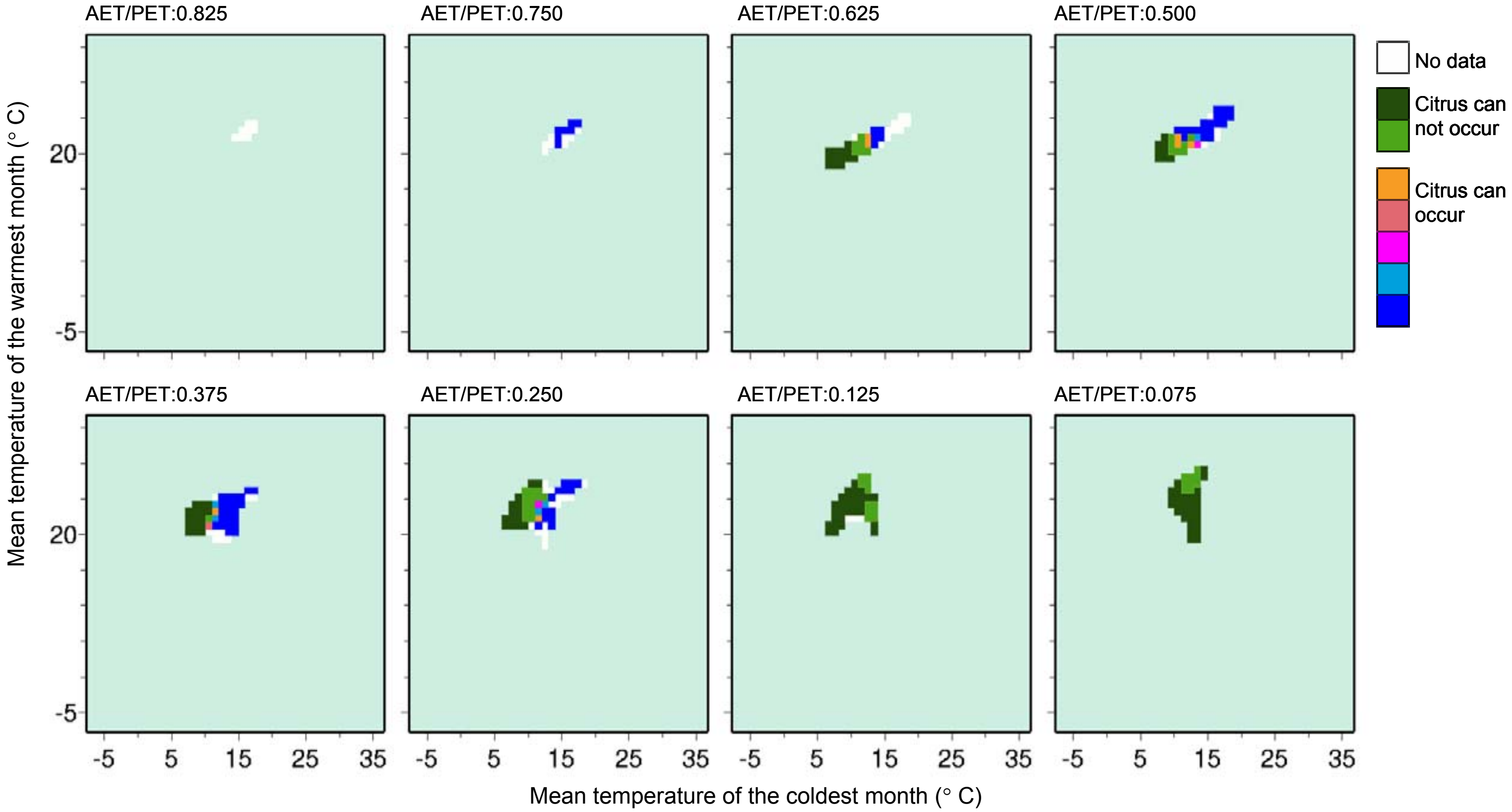

Figure 7.2 — SCT data citrus response surface. Three dimensional climate response surfaces for citrus in South African climates. The response surface is shown as a series of eight slices with respect to the ratio of actual to potential evapotranspiration (AET/PET) axis, with each panel representing a 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.

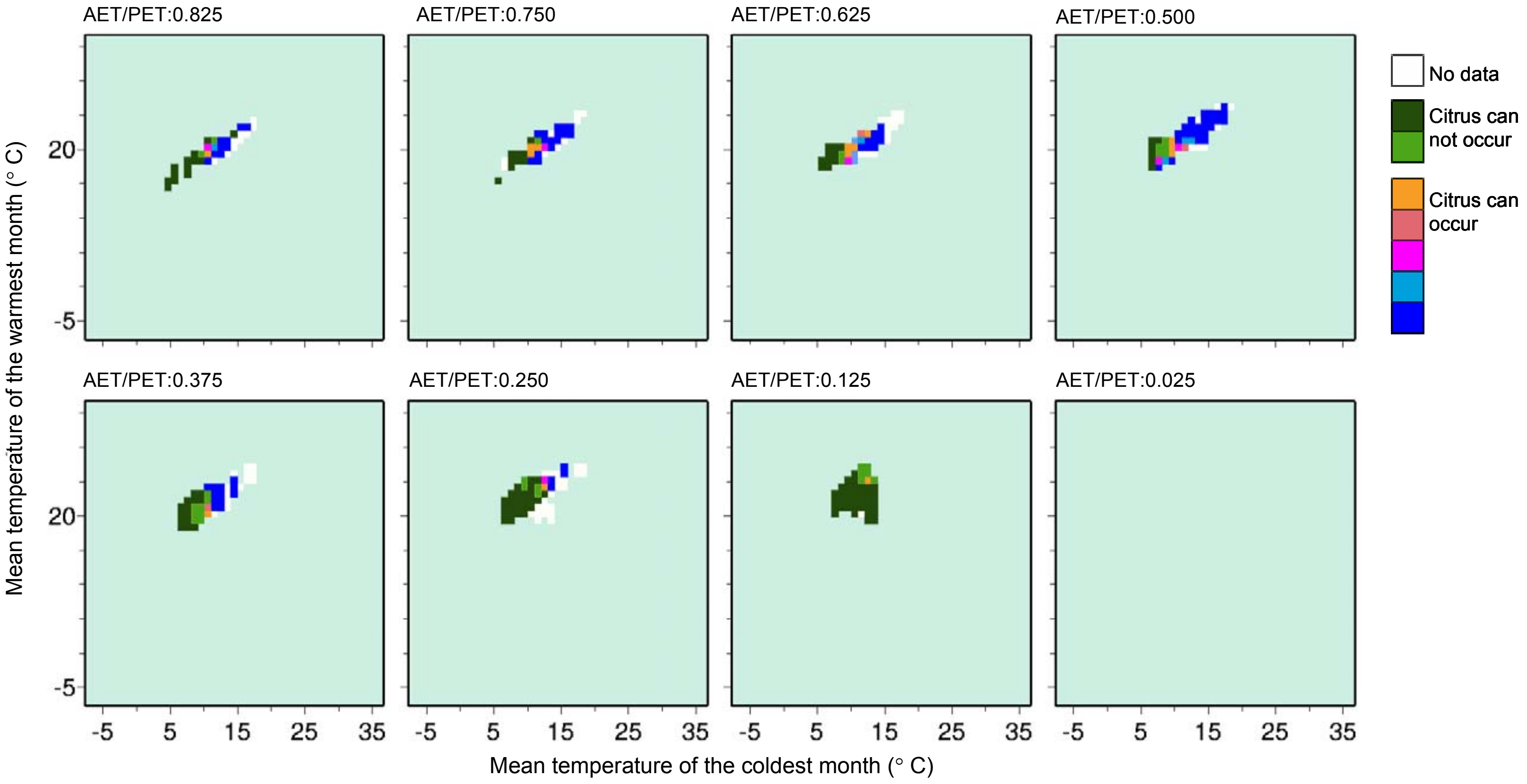

Figure 7.3 — Cramer data citrus response surface. Three dimensional climate response surfaces for citrus in South African climates. The response surface is shown as a series of eight slices with respect to the ratio of actual to potential evapotranspiration (AET/PET) axis, with each panel representing 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.

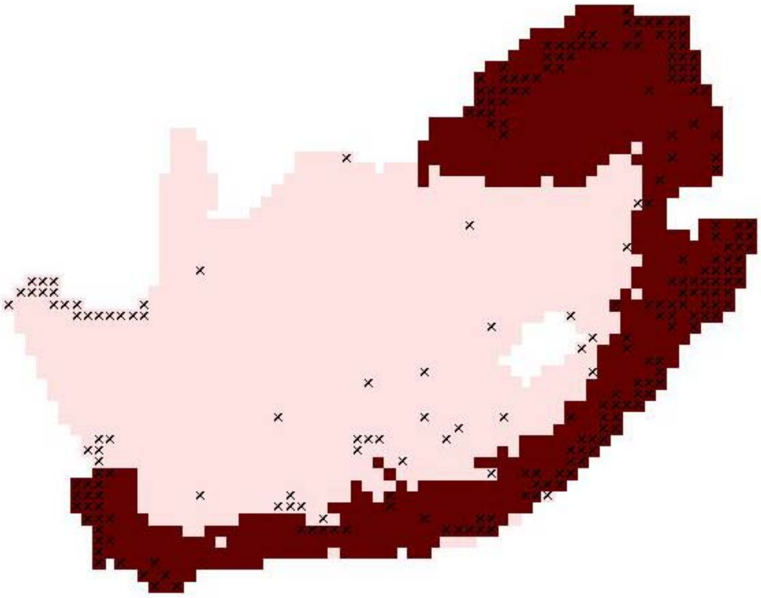

Figure 7.4 — Simulated potential distribution of citrus in South Africa under current climate for the SCT climate data set. κ=0.904, which indicates an excellent fit. Grid cells where the response surface was extrapolated are indicated by an x.

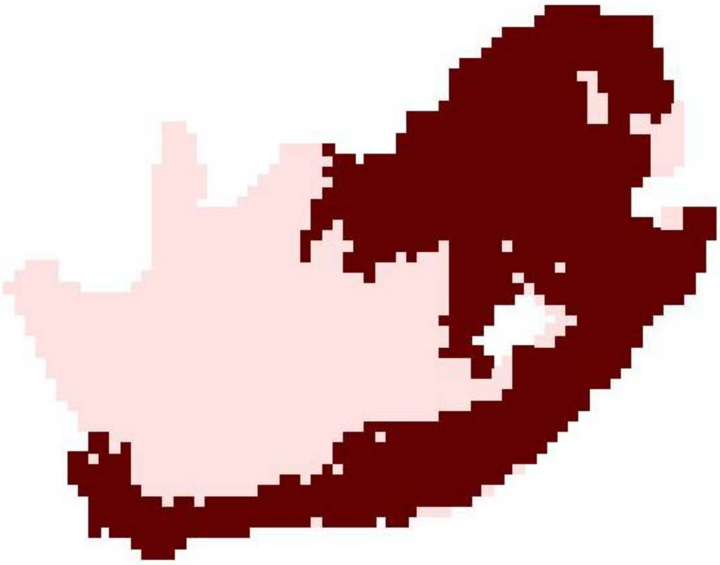

Figure 7.5 — Simulated potential distribution for citrus in South Africa as calculated for the HadCM3 B2 climate change scenario from the SCT climate data set.

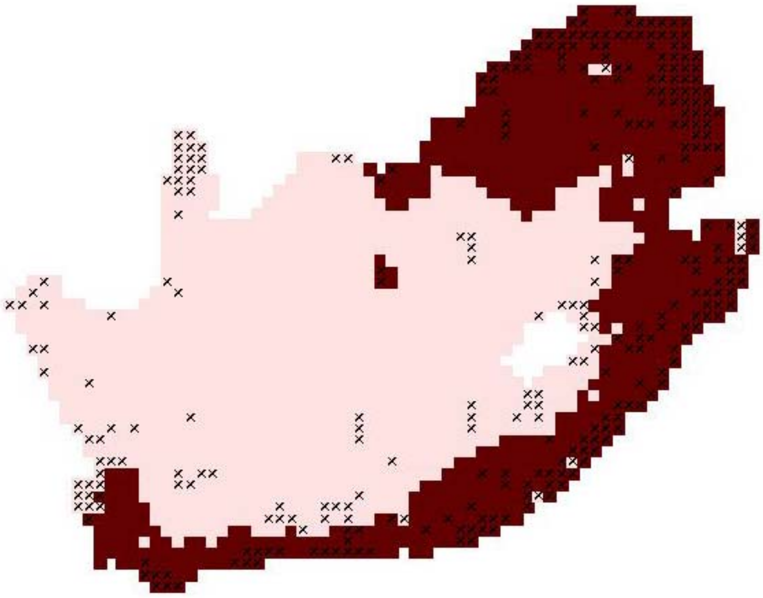

Figure 7.6 — Simulated potential distribution of citrus in South Africa under current climate for the Cramer climate data set. κ=0.91, which indicates an excellent fit. Grid cells where the response surface was extrapolated are indicated by an x.

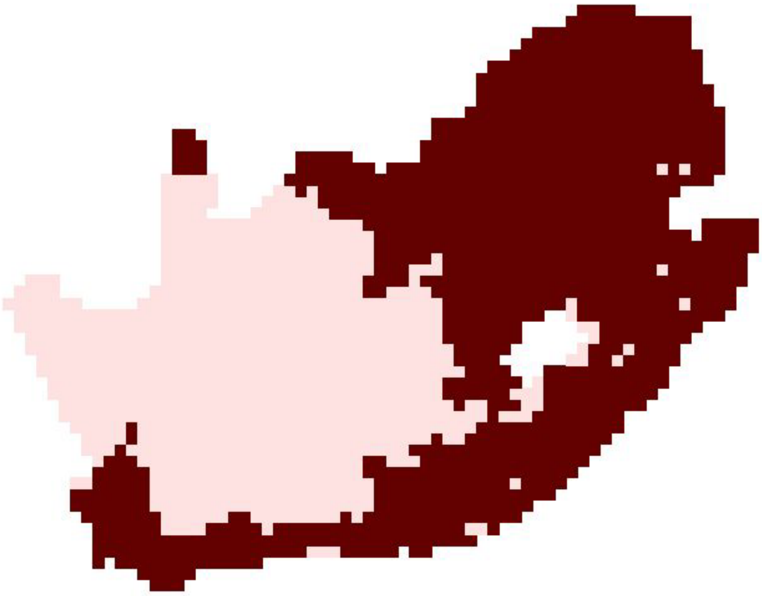

Figure 7.7 — Simulated potential distribution for citrus in South Africa as calculated for the HadCM3 B2 climate change scenario from the Cramer climate data set.

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.

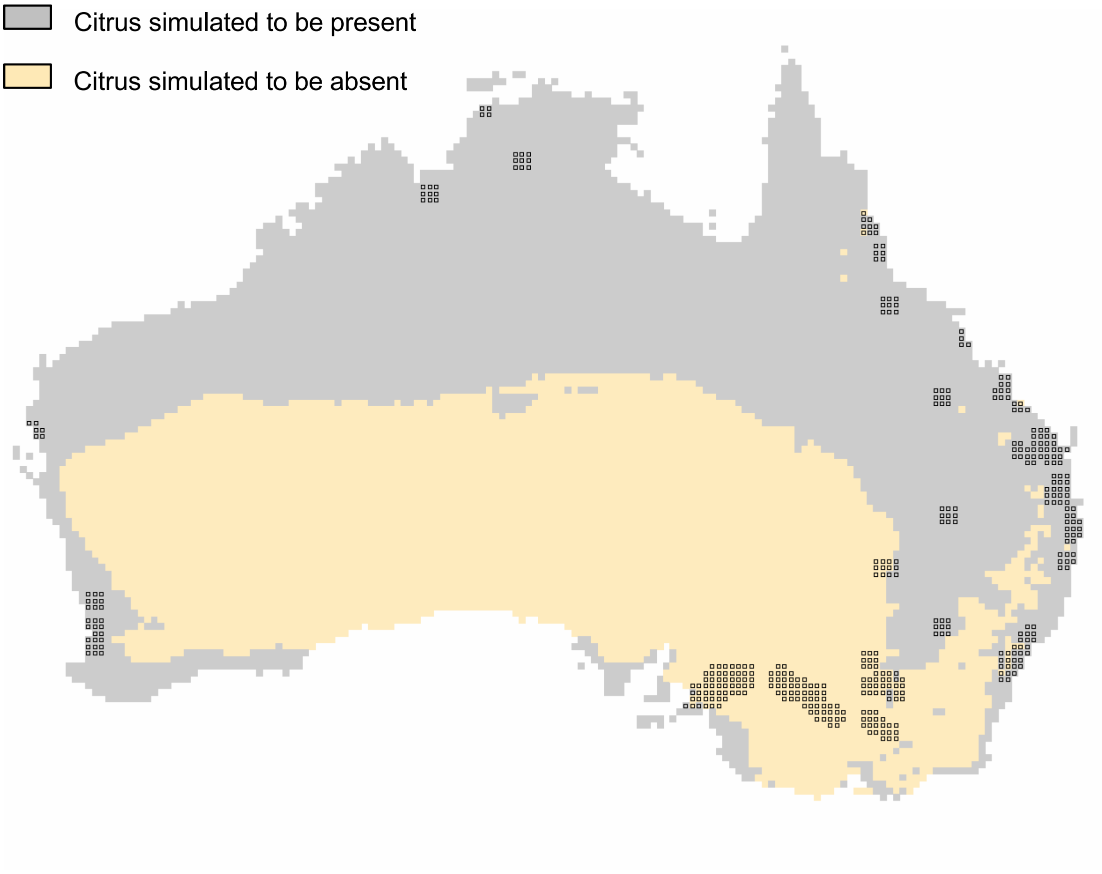

Figure 7.8 — Simulated distribution of citrus in Australia on a 15' grid using the Cramer data response surface and present climate. Grid squares in which citrus is cultivated are marked with small black squares.

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 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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Chapter 8 — Modelling the range of *Guignardia citricarpa* Kiely, the causal agent of Citrus Black Spot, in South Africa: a response surface approach

8.1 Abstract

Citrus Black Spot (CBS), caused by *Guignardia citricarpa* Kiely, is a fungal disease of citrus that occurs in many citrus producing countries, but not in Europe or the United States of America (USA). The export of citrus fruit from CBS infected areas to the European Union and the USA is restricted, and consequently CBS is an economically important disease. In South Africa, CBS occurs in all citrus production areas except those of the Western and Northern Cape Provinces. In this study, the climatic risk of CBS expanding its distribution to uninfected regions in South Africa is assessed for the current climate, and for a future climate scenario. The potential distributions of the pathogen was estimated using response surfaces. The response surfaces were fitted to the observed distribution of the pathogen and two separate climate data sets (SCT and Cramer). For both climate data sets, under current climate, there was a close fit between observed and simulated distributions of the pathogen. Under conditions of climate change, results suggest that citrus production regions of the Western Cape and those of the Vaalharts region of the Northern Cape will become climatically suitable for CBS, however the rest of the Northern Cape and inland parts of the Western and Eastern Cape are unlikely to become climatically suitable for CBS occurrence.

8.2 Introduction

The fungus *Guignardia citricarpa* Kiely causes a disease known as Citrus Black Spot (CBS), the symptoms of which include superficial lesions on the rind of citrus fruit (Brodrick, 1969). Almost all commercial types of citrus are affected by CBS including lemons, oranges (especially the Valencia variety) (Kotzé, 2000), grapefruit and limes (Brodrick, 1969; Kotzé, 2000). However, Persian limes (Timmer, 2005, Personal Communication) and sour orange and its hybrids are not susceptible (Kotzé, 1981).

The disease was first described in 1895 from citrus fruit grown in New South Wales, Australia (Benson, 1895). In 1929, CBS was reported for the first time in South Africa (Doidge, 1929). Diseased citrus material has since been found in Kwazulu-Natal, Limpopo Province, Mpumalanga, North-Western Province (Kellerman, 1976), Gauteng, and the Eastern Cape Province (Kotzé, 2004, Personal Communication). However, it has not been reported from any of the citrus growing areas in the Northern (le Roux, 2004, Personal Communication; Mabiletsa, 2003; USDA/APHIS, 2002) or Western Cape Provinces (European Union, 1998; Kellerman, 1976; Venter et al., 1995).

Citrus fruit exports from CBS infected areas to Europe and other parts of the world are restricted by phytosanitary regulations (Bonants et al., 2003; European Union, 2000). As the South African Citrus Industry is dependent on export (FAO, 2002), CBS is of substantial economic importance to South African citrus growers.

Climate plays an important role in CBS epidemiology and it is an important factor in determining the occurrence, incidence and severity of CBS (Kotzé, 1981; Kotzé, 1996; Whiteside, 1967). The maturation and release of ascospores, the major source of CBS inoculum, are dependent on climatic conditions. Ascospores are contained in perithecia which are produced on dead citrus leaves. The presence and abundance of mature perithecia rely on the frequency with which leaves are moistened and sun dried and on prevailing temperatures (Kotzé, 1996), with low temperatures effectively impeding perithecia development (Brodrick, 1969). Ascospore discharge is also dependent on wetting of the petithecia (Kotzé, 1981).

Infection takes place in the presence of warm, wet and humid conditions (Kotzé, 2000) and occurs in young citrus leaves and fruit. Fruit are only susceptible within the first four to five months of early fruit set (Brodrick, 1971; Kotzé, 1996). After this period, young fruit become resistant to infection (Kotzé, 2000). The full epidemiology of CBS has been reviewed and is described in section 3.6, page 56.

The strong correlation between climate and the occurrence of CBS implies that the climates in which CBS may occur can be predicted from information on the climate where it currently occurs. The influence of climate on the distribution of several other plant pathogens has been explored using bioclimatic models. These studies include investigations on the potential geographical distribution of forest (Booth et al., 2000b; Meentemeyer et al., 2004) and crop pathogens (Hoddle, 2004; Lanoiselet et al., 2002; Paul et al., 2005; Pethybridge et al., 2003; Pivonia & Yang, 2004), and also the estimation of the potential impact of climate change on the geographical distribution of crop (Chakraborty et al., 2002; Chakraborty et al., 1998; Chakraborty et al., 2000; Coakley et al., 1999) and forest pathogens (Booth et al., 2000a; Brasier, 1996; Van Staden et al., 2004).

Response surface modelling is a bioclimatic modelling approach that has been used to study the climates in which species occur and to model the potential distribution of several groups of species, including birds (BirdLife International, 2004), butterflies (Hill et al., 2002; Hill et al., 1999) and plants (Beerling et al., 1995; Huntley et al., 1995; Shafer et al., 2001). In this study, response surfaces are used to study the relationship between the current geographical distribution of CBS and climate. The response surfaces are also used to simulate the potential occurrences of CBS under current climate and a future climate scenario.

8.3 Methodology

8.3.1 The distribution of Citrus Black Spot in South Africa

Data on the occurrence of CBS in citrus production areas of South Africa were obtained from literature and from citrus pathologists (section 4.3.1, page 69). Using this information and a map of citrus production areas (Figure 7.1, page 116), the occurrence of CBS within the citrus cultivation areas of South Africa was mapped (

Figure 8.1). Areas where no citrus is produced were classified as areas of no CBS distribution data.

To calculate a response surface, data about both the occurrence of the species and climate must be available at the same geographical locations. Information on the presence and absence of CBS were transcribed onto a regular grid (referred to as the CBS grid) of 15' resolution and 1974 squares using ArcGIS 8.3 (Environmental Systems Research Institute). Meteorological station data values could then be interpolated onto this grid.

8.3.2 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.

a) CBS Present

b) CBS Absent

Figure 8.1 — The occurrence of Citrus Black Spot in South Africa in 2004

8.3.2.1 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.

8.3.2.2 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.

8.3.3 Bioclimate variables

The response surfaces were fitted using the three bioclimate variables that statistically gave the best fit between the observed and the simulated distributions. As for citrus (Chapter 7), these variables were mean temperature of the coldest month (MTCO), mean temperature of the warmest month (MTWA) and the ratio between actual and potential evapotranspiration (AET/PET). These variables are thought to influence the survival and proliferation of CBS. The two temperature related bioclimate variables — MTCO and MTWA — are used to estimate the temperature requirements of CBS. The ratio of actual to potential evapotranspiration (AET/PET), as described by Prentice et al. (1992), is used to estimate moisture availability. 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).

8.3.4 Fitting the response surfaces and simulating distributions

For each climate data set a response surface was fitted using the presence and absence of CBS in South Africa as the dependent variable (see CBS grid, section 8.3.1, page 136) and the values for the three bioclimate variables, for each climate data set as the independent variables. This was done using unpublished computer programs written by P.J. Bartlein (Department of Geography, University of Oregon, USA) with modifications by B. Huntley (School of Biological and Biomedical Sciences, University of Durham, UK). 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) (section 7.3.4, page 119). 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 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.

8.3.5 Simulated distributions in South Africa and in Australia

The resultant response surfaces were used to simulate the potential occurrence of CBS in South Africa. The ability of the response surface to describe the observed distribution of CBS provides a test of the response surface. (Methodology is the same as in as section 8.3.4 page 139).

Additionally, the predictive capacity of the Cramer data set was tested by simulating the potential distribution of CBS in Australia (section 7.3.6, page 121). Areas of observed CBS presence in Australia were mapped by adding information on the occurrence of CBS to the map of citrus cultivation produced in Chapter 7. Mapped areas of CBS presence were confirmed by P. Barkley (2004, Personal Communication).

A kappa statistic could not be calculated for the simulation of CBS in Australia as CBS absence data were not available. Therefore, to estimate of the reliability of the simulated distribution, the percentage of grid cells where the presence of CBS was correctly simulated was calculated.

8.3.6 Simulated distributions using a General Climate Model scenario

Human activities alter global climate. Increased emissions of radiatively active gasses cause changes in the atmospheric composition which contribute to changes in global climate. Over the next century, global surface air mean temperatures are expected to increase by 1.4–5.8°C, and the intensity and timing of rainfall is expected to become more variable (IPCC, 2001). These climatic changes are apparent (IPCC, 2001), and there is evidence that there has already been noteworthy impacts on ecosystems and species (Hughes, 2000; Parmesan & Yohe, 2003).

Little is known about how climate change may affect the geographic range of citrus pathogens. As CBS is a disease of great economic importance, it is vital that the potential impact of climate change are estimated. The potential future range of CBS under a climate change scenario was simulated using the methodology of section 7.3.5, page 120. The HadCM3 B2 scenario, a middle of the range scenario, was used to calculate the bioclimate scenarios of the future.

8.4 Results

8.4.1 Response surfaces of Citrus Black Spot in South Africa

The response surfaces represent the probability of CBS occurring under any combination of three bioclimate variables. The resultant response surfaces are shown as bioclimate envelopes within which CBS occurs in South Africa on a three-dimensional climate space (figures were drawn using an unpublished computer program written by B. Huntley). Each axis of this climate space represents a bioclimate variable that was used to fit the response surface.

The SCT climate data response surface indicates that the climate space of CBS is limited to MTCO values between 10°C and 19°C and MTWA values of between 20°C and 27.5°C. The highest probability of occurrence is at an AET/PET value of 0.5. No occurrences of CBS are found at AET/PET values of 0.125 and lower (Figure 8.2)

The Cramer data response surface shows a high probability of occurrence in those areas where the MTWA exceeds 18°C. The upper limit for MTWA is 27.5°C and there are no occurrences at MTCO values lower than 9°C. The upper limit of MTCO is 18°C. The probability of occurrence sharply declines at AET/PET values of 0.375 and lower, with no occurrences at AET/PET values of 0.125 and lower (Figure 8.3).

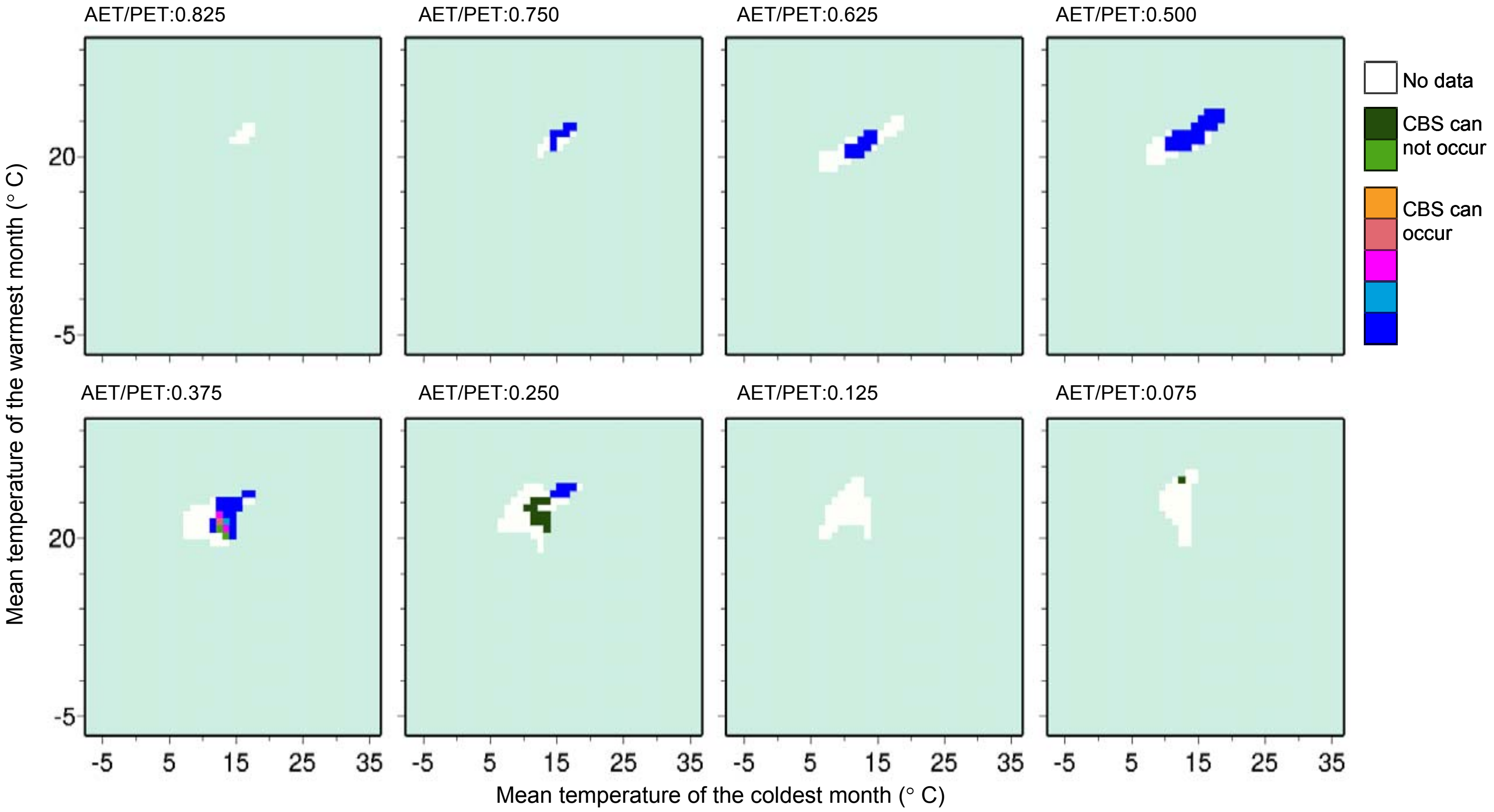

Figure 8.2 — SCT data Citrus Black Spot response surface. Three dimensional climate response surfaces for citrus in South African climates. The response surface is shown as a series of eight slices with respect to the ratio of actual to potential evapotranspiration (AET/PET) axis, with each panel representing 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.

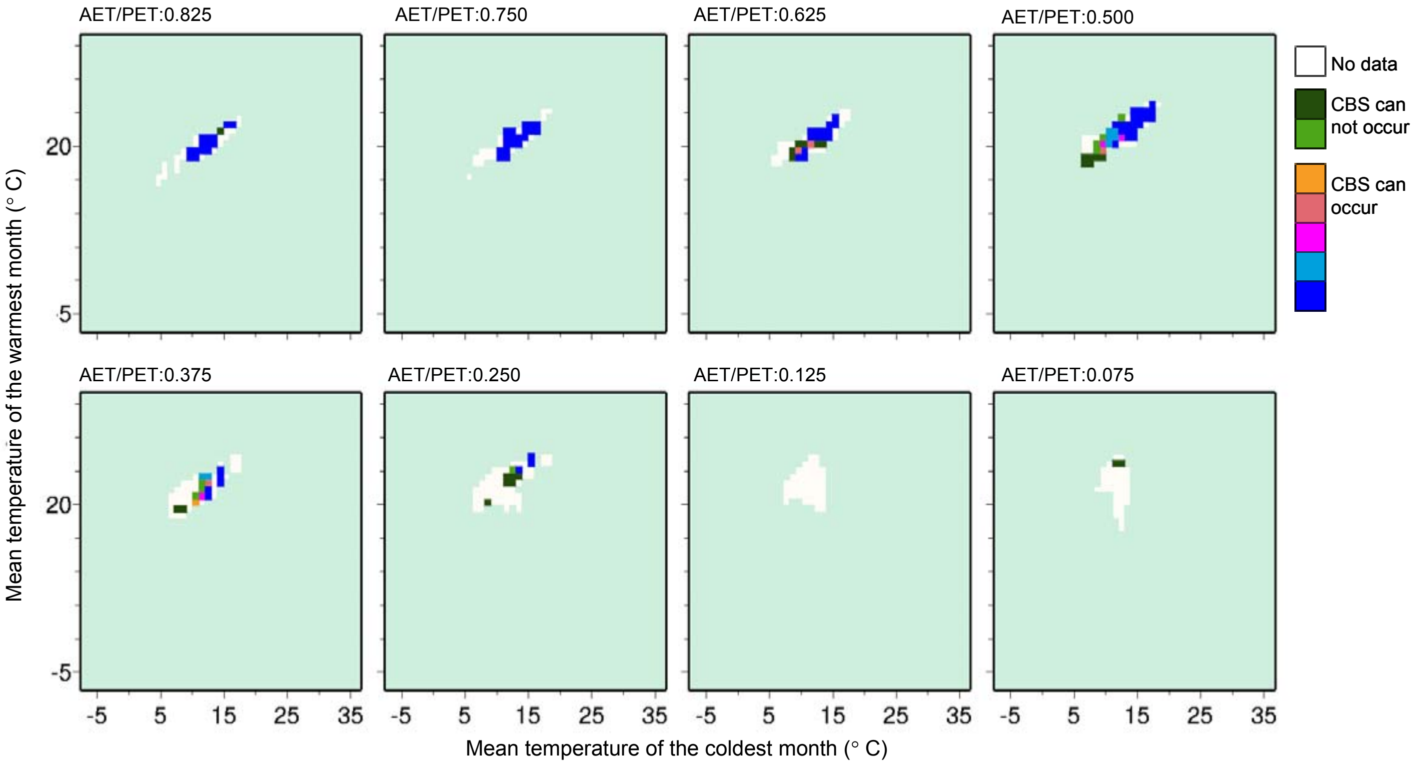

Figure 8.3 — Cramer data Citrus Black Spot response surface. Three dimensional climate response surfaces for Citrus Black Spot in South African climates. The response surface is shown as a series of eight slices with respect to the ratio of actual to potential evapotranspiration (AET/PET) axis, with 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.

8.4.2 Simulated distributions in South Africa under current and future climate

8.4.2.1 SCT Data

At a threshold probability of 0.54, the simulated distribution of CBS includes all the areas where CBS had been observed (Figure 8.4). The simulation indicates climatic potential for the range of CBS to expand almost throughout the whole eastern half of South Africa. Notably, the eastern parts of the Western Cape are simulated to hold climates suitable for CBS establishment. The absence of in the CBS citrus producing areas of the Northern and Western Cape Provinces are accurately simulated.

With the HadCM3 B2 scenario, the simulated range expands to most, but not all of the citrus producing areas in the Western Cape where CBS does not currently occur. Some inland areas of the Western Cape are simulated not to be climatically suitable for CBS. This simulation also suggests that the Vaalharts region of the Northern Cape will become climatically suitable for CBS. The climate of the rest of the Northern Cape's citrus production areas remains unsuitable for CBS (Figure 8.5). Additionally, the climate of a small inland part of the Eastern Cape and parts of the Free State also remains unsuitable for CBS in future.

8.4.2.2 Cramer Data

Using the threshold probability of 0.65, the simulated range of CBS corresponds well with the observed geographical occurrence, but the simulation does not include all of the observed occurrences (Figure 8.6). The model accurately simulates the absence of CBS in the Northern Cape and in the majority of the citrus growing areas in the Western Cape. However, in the Western Cape CBS was simulated to occur in some grid cells where citrus is currently cultivated, but where CBS has been shown to be absent [no CBS isolates were found in tests of citrus material (Venter et al., 1995)]. The climates of some grid cells in Limpopo Province (one grid cell), North West Province (one grid cell) and the Eastern Cape (five grid cells) where CBS is known to be present were also simulated to be unsuitable for CBS.

The simulation for the HadCM3 B2 scenario shows an inland expansion of climates suitable for CBS (Figure 8.7), which includes an expansion of suitable climate to the Vaalharts district in the Northern Cape, but not the rest of this province. Climates of the inland parts of the Western and Eastern Cape, and parts of the Free State are not simulated to be suitable for the occurrence of CBS.

The future climate of South Africa, as projected by the HadCM3 B2 scenario, contains climatic conditions not currently found in South Africa. Therefore, predictions as to the future distribution of CBS in South Africa had to be based on extrapolations of the response surfaces. To gain a better understanding of the nature of projected climate changes in South Africa modern analogues for the future climates, and the future values of the bioclimate variables were mapped (Appendices B and C).

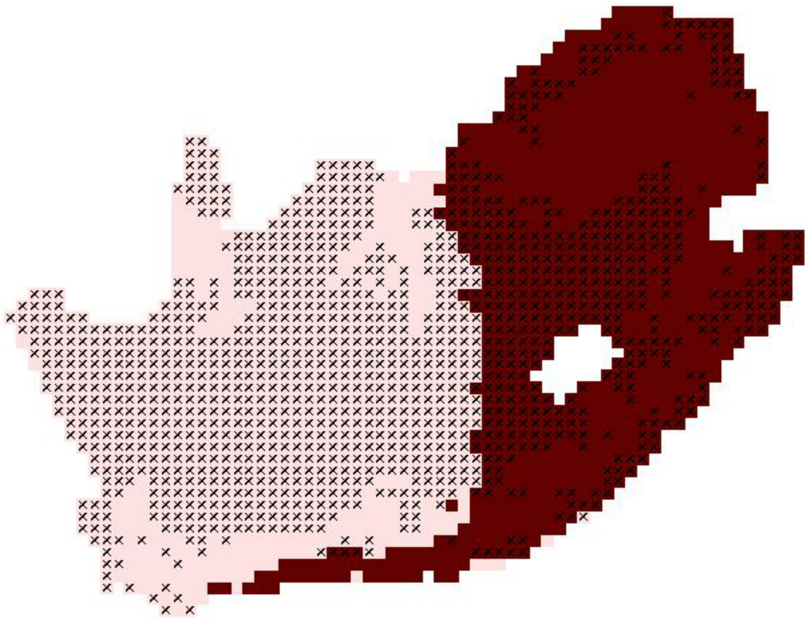

Figure 8.4 — Simulated potential distribution of Citrus Black Spot (CBS) in South Africa under current climate using the SCT data. κ=1.00, which indicates a perfect fit. Grid cells where the response surface were extrapolated are marked with an x.

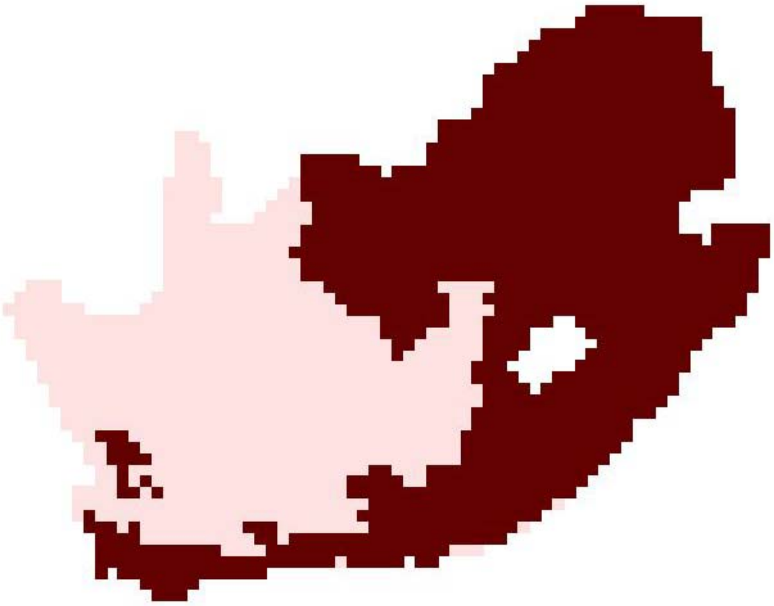

Figure 8.5 — Simulated potential distribution for Citrus Black Spot (CBS) in South Africa as calculated for the HadCM3 B2 future climate scenario using the SCT data.

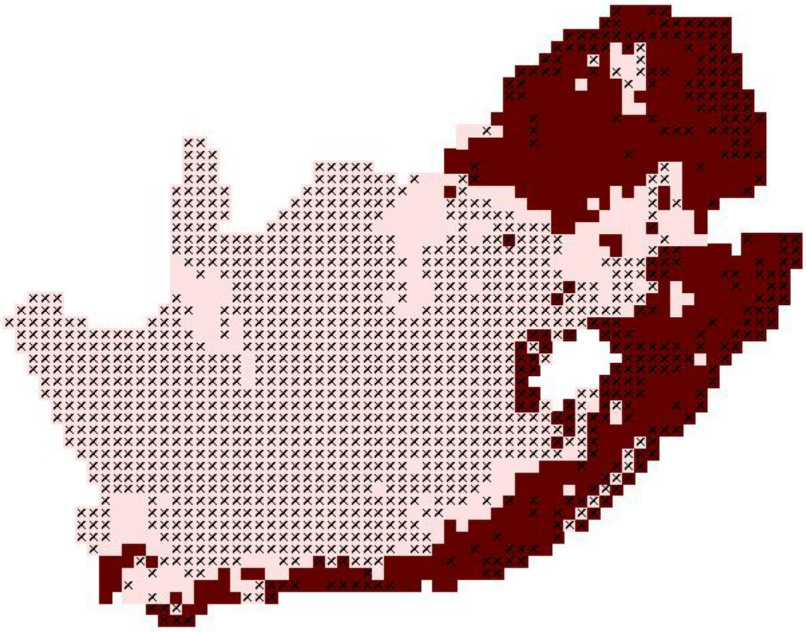

Figure 8.6 — Simulated potential distribution of Citrus Black Spot (CBS) in South Africa under current climate using the Cramer data. κ=0.834 indicating a very good fit. Grid cells where the response surface was extrapolated are indicated by an x.

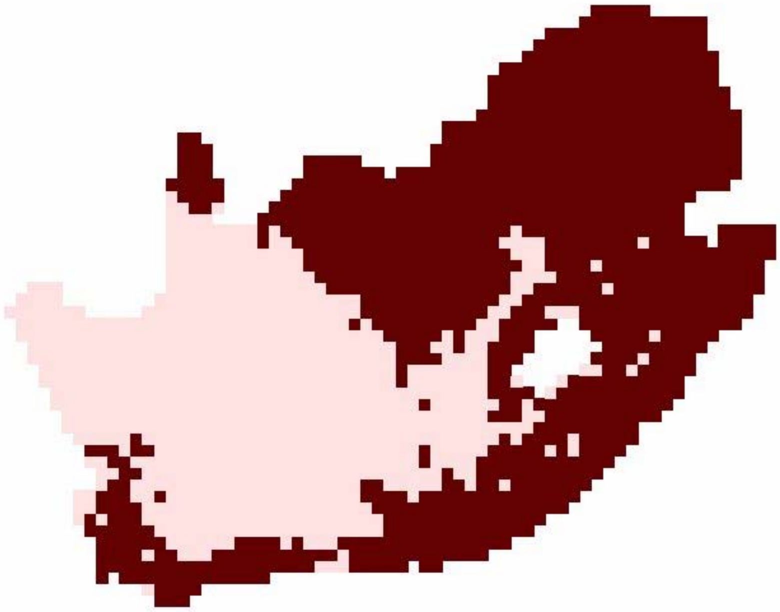

Figure 8.7 — Simulated potential distribution for Citrus Black Spot (CBS) in South Africa as calculated for the HadCM3 B2 climate change scenario using the Cramer data.

8.4.3 Simulated distribution in Australia

The occurrence of CBS was simulated in 95.2% of grid cells where CBS is observed (Figure 8.8).

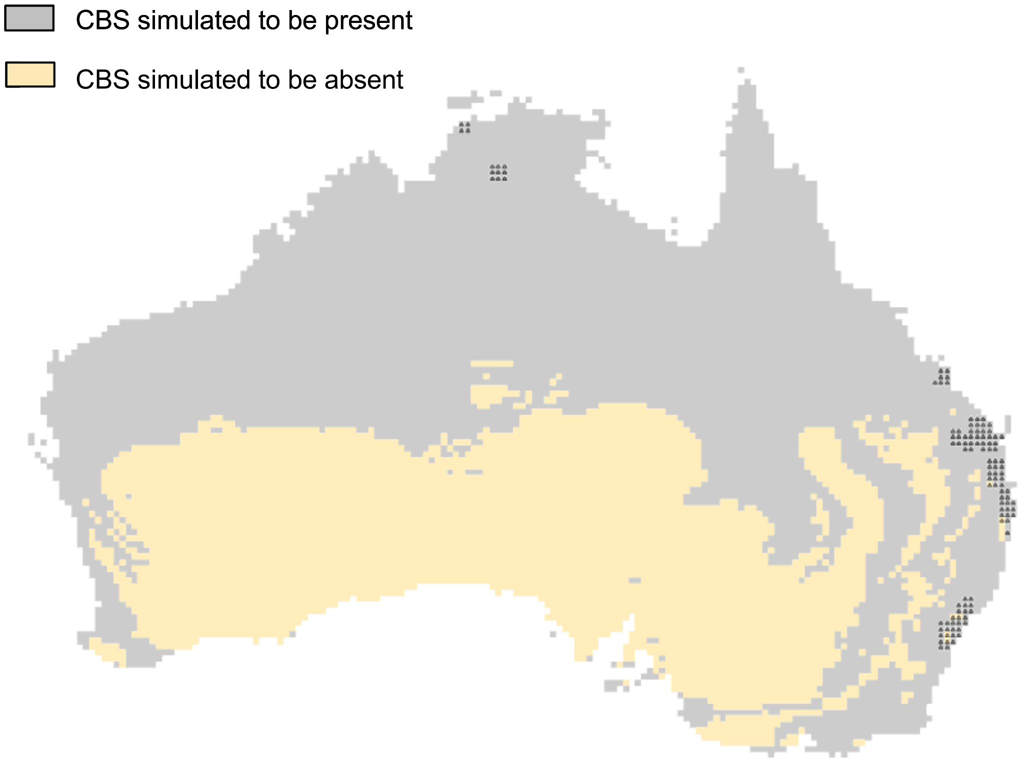

Figure 8.8 — Simulated distribution of Citrus Black Spot (CBS) in Australia on a 15' grid using the Cramer data response surface and present climate. Areas of observed CBS presence are indicated with black triangles representing a single grid square each.

8.5 Discussion

The climate space obtained from the SCT data response surface and that obtained from the Cramer data response surface both suggest that CBS will be restricted to the warmer citrus growing areas of South Africa. This agrees with the epidemiology of the disease in that maturation of the perithecia that hold the ascospores requires warm temperatures (Kellerman & Kotzé, 1977; Kiely, 1969; Kiely, 1970; Kotzé, 1961). The sharp decline in the probability of occurrence of CBS as moisture availability becomes less also corresponds to the epidemiology of the disease as ascospore discharge is reliant on wetting of the perithecia (Kotzé, 1981).

Although the two response surfaces are similar, they are not identical because of differences in the climate data sets. These differences are discussed in Appendix B. The kappa statistic (κ), a measure of agreement between categorical data, was calculated to determine the agreement between the observed and simulated distributions for each simulation. The SCT simulation gave a perfect fit (κ=1.00). The Cramer data simulation also in general gave a good fit, but there were some discrepancies (κ=0.834).

Simulations of the potential occurrences of CBS, as obtained from the response surfaces fitted with both the climate databases, suggest that there is significant climatic potential for CBS to expand its range within the provinces where it is prevalent. However, the disease should remain restricted to the eastern side of the country. Both response surface simulations supported the absence of CBS in the Northern Cape and it seems unlikely that the disease will be able to establish in this region under current climate. Although the simulations agree that the climate of the citrus growing areas of the Western Cape is larglely unsuitable for the establishment of CBS, the Cramer data response surface simulation suggests a few areas are climatically suitable (7 out of the 42 grid squares where citrus is currently cultivated). This response surface, however, also incorrectly simulated the climate of areas where CBS is currently present as to be not suitable for disease establishment. It is therefore likely that results from the SCT data response surface are more reliable (see Appendix B).

In Australia, almost all the observed presences of CBS were accurately simulated when using the Cramer data response surface. This result supports the correlation between the bioclimate variables (MTWA, MTCO and AET/PET) and the geographical distribution of CBS. It also suggests that the climate in which CBS occurs in South Africa is similar to the climates in which CBS is found in Australia (also see Paul et al. 2005).

Under a future climate, represented by the HadCM3 B2 scenario, the simulations of the SCT and Cramer response surfaces indicate a potential range expansion of CBS to most citrus producing areas in the Western Cape. There is also a climatic potential for the disease to expand its range into the Vaalharts district of the Northern Cape, an important citrus growing area in this province. The climates of the inland parts of the Western Cape, and areas surrounding the Orange River, where some citrus is produced, is simulated be unsuitable for CBS establishment under future climates. Also, the inland parts of the Eastern Cape and the Free State and also the rest of the Northern Cape are simulated to be unsuitable for CBS occurrence, but citrus is not currently being produced in these areas.

Projections using response surfaces provide a means to assess the magnitude of the potential impact of climate change upon species distribution within agro-ecosystems. However, these projections only explore the potential impacts of climate change on a single aspect of the species (potential range). Other aspects of a species may be affected by climate change, but these effects may be complex and unpredictable (Dukes & Moony, 1999; Scherm & Coakley, 2003). Experimental results of the impact of climate change on plant pathogens suggest that there will be modifications to host resistance, pathogen developmental stages and rates of development (Scherm & Coakley, 2003). New associations with other species may also arise, in particular new competitors and natural enemies. Plant pathogens may be particularly responsive to climate change (Scherm & Coakley, 2003) as, given their short generation times and efficient dispersal mechanisms, these species may be able to adapt and evolve (Rafoss &

Saethre, 2003)(Some other impacts of climate change on crops and their pathogens are summerised in Appendix D). These factors are not accounted for in forecasts of the potential risk of CBS expanding its distribution under a future climate.

Also, simulations should not be seen as predictions of the way in which CBS will respond to climate, because CBS, being dependent on the citrus host, may be excluded from certain areas because of the absence of the host (Shafer et al., 2001). The potential occurrence of the citrus host has also been modelled using response surfaces. Under current and future climates the simulations of the potential occurrences of citrus corresponds with the simulations of potential occurrences of CBS (Figure 7.4–Figure 7.8). Under current climates most of the areas simulated to be climatically suitable for citrus production in the Western Cape are not at climatic risk of CBS introduction (Paul et al. 2005). The citrus growing areas of the Northern Cape were not successfully simulated by the response surface models. Nevertheless, citrus is produced in these areas and under current climates they will remain climatically unsuitable for CBS. Under future climates, both citrus and CBS is simulated to occur in all the parts of the country where it is currently present and also in the Western Cape and parts of the Northern Cape (Vaalharts Region). Those areas predicted to have climates unsuitable for CBS, namely the greater part of the Northern Cape, inland parts of the Eastern Cape and parts of the Free State were also simulated to hold climates considered unsuitable for citrus production in future.

In general it seems that under both current and future climates there is significant climatic potential for the extension of citrus production within South Africa, although the most areas will have climates suitable for CBS. These preliminary results may support the South African Citrus Industry in making decisions about the strategy for citriculture expansion under conditions of climate change.

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Chapter 9 — General discussion and conclusions

Plant health and quarantine researchers need to make decisions about the potential introduction of exotic organisms. However the information needed to adequately address problems is often unavailable, sparse, and difficult to access (Rafoss & Saethre, 2003). In most cases, bio-climatic modelling may be the only way to synthesise and visualise information on how climate influences the exotic organism (Baker et al., 2000; Kriticos et al., 2003). Especially when considering the potential impact of climate change on the geographical distribution of plant pathogens, the outcomes of these kinds of studies may be invaluable and can contribute to better management of the threat of exotic plant diseases. Results can supplement, but not replace, Pest Risk Assessments (PRA). An evaluation of the phytosanitary risk posed by trade must combine the climatic suitability of a given region with a multitude of other risk mitigation considerations, as described by the International Plant Protection Convention (1996).

To prevent the introduction of Citrus Black Spot (CBS), a fungal disease of citrus, phytosanitary barriers to trade restrict the export of citrus fruit from areas where the disease occurs to areas where it has not been recorded. In this study, the potential geographic distribution of CBS under current and future climates is estimated. The research presented in this thesis offers methods for predicting where citrus can be cultivated and, within these areas, where citrus pathogens can occur. It also investigates whether climatic factors prevent the establishment of CBS in new areas. To improve the confidence in the work, two distinct bioclimatic modelling approaches — CLIMEX and response surfaces — are used. This study is the first of its kind in the field of citriculture, and may serve as an example for future similar applications of bioclimatic modelling.

The bioclimatic models require data on citrus and CBS, specifically the geographical distributions of citrus and CBS and how they interact with climate. Therefore, citrus, citrus growing areas, and CBS are reviewed (Chapter 2 and Chapter 3). The maps of global citrus production areas in Chapter 2 were drawn from the most recent information available, but as the citrus industry is dynamic, some of this information may already be out of date. Nevertheless, this is an important step, particularly as the last global map of citrus production was produced almost forty years ago (Reuther et al., 1967). These maps provide an insight into the scale and diversity of global citrus production and may serve as a reference source for direct surveys and literature searches on the occurrence of citrus diseases within broad citrus growing areas.

Data on the occurrence of the species are an important input for the bioclimatic models. As the success of the bioclimatic modelling approach relies on these data, it should be valid, accurate, adequate, and preferably confirmed by knowledgeable pathologists. Ideally, surveys should be undertaken with the aid of a Global Positioning System in order to geo-reference field data. Such data will allow the development of more reliable predictive models (Robinson, 1998). Although in developing countries inadequate funding and a lack of infrastructure impede the surveillance of plant diseases. If the true range limits of the species are not represented within the recorded distribution, then the bioclimatic models will not reflect the true climatic limits of the species (McKenney et al., 2003).

When modelling the potential distribution of pathogens, it should be kept in mind that the symptoms of the disease may be suppressed by successful chemical control that it could seem asif the pathogen is excluded. However, these areas should still be mapped as areas of presence, as was done in this study. Absence may also mean that the pathogen had simply not been introduced. As CBS had been introduced into the areas that had been recorded as areas of CBS absence, but failed to establish, the absence records are reliable and represent true absences.

The climate data applied in the bioclimatic model can also have a significant impact on the outcome of the study. The weather data localities in CLIMEX are not well represented in all countries around the world, and so the Compare Locations Model failed to model the occurrence of CBS in Bhutan and Taiwan. When the model was run with a global gridded climate dataset, however, the climatic potential for CBS to occur in these two countries was successfully predicted (Appendix A). The response surface models were also run using two separate data sets named the Cramer and the SCT data. The Cramer climate data relate to 1931–1960 and the SCT climate data relate to 1961–1990. In Africa, however the climate has warmed rapidly since the 1970s (Hulme et al., 2001). The Cramer data set does not include the effects of this warming and is thus less representative of current climate. Results using the Cramer data and response surface modelling under current climate predict the absence of CBS in some grid cells where CBS occurs. Moreover, some areas in the Western Cape in South Africa where the disease does not occur were predicted to have climates suitable for CBS. For this study, the SCT data, which are more recent and which predict all the climates of the south-western citrus growing areas of the Western Cape to be unsuitable for CBS, are probably more appropriate.

Current approaches to bioclimatic modelling seldom include formal model comparisons to identify the strengths and weaknesses of the different models. Often only outputs, and not inputs, of models are presented. Ideally, input data on crop and disease occurrence should be archived, updated and shared amongst researchers. International communication networks, can mediate the collaboration of scientists and research efforts can be combined for a single pathogen for instance across continents (Scherm & Coakley, 2003).

Although the models are not formally compared in this study, the general strengths and weaknesses of the modelling procedures applied could be identified. CLIMEX is an ideal approach to use when only presence data is available as this profile technique only requires presence data. Often true absence data, needed for group discrimination modelling techniques like response surface modelling are not available. In such cases CLIMEX can be applied to model species distributions. However, CLIMEX modelling requires an in-depth understanding of the species distribution and the underlying mechanisms, and the skill of the user can greatly influence the outcomes. Response surface models, on the other hand, are fitted by a computer program, and so the process of fitting the model is not affected by user bias. The procedure, however, requires highly specialised computer programs specifically written for the purpose, and it is unlikely that most researchers will have access to this modelling procedure.

An assessment of the suitability of European climates for the establishment of CBS (Chapter 4) demonstrates that European climates are not similar to climates where CBS is currently found in South Africa. Similarly, most of the climates of the Northern and Western Cape Provinces (South Africa) are predicted to be unfavourable for disease establishment (Table 9.1). And indeed CBS is not found in these regions. However, Chapter 4 is simply climate matching (Match Climates Function in CLIMEX). Meteorological data from different localities are compared without considering the climatic preferences of a species. This section of the work is therefore only a rough first assessment of the risk of CBS establishing in a new location.

When species requirements were taken into consideration (Compare Locations Function in CLIMEX, Chaper 5), results confirm that CBS is unlikely to establish in European countries. The CLIMEX model also successfully models the absence of CBS in the Northern and Western Cape Provinces (Table 9.1). CBS presence is accurately modelled in most of the countries where it has been recorded.

In future, partly as a result of human activities, climate will change. These changes will include increases in mean temperatures and variation in the intensity and timing of rainfall (IPCC, 2001). The changes, and their effects, are already becoming apparent (Hughes, 2000; IPCC, 2001; Parmesan & Yohe, 2003). Climate change is expected to have significant impacts on the occurrence of plant pathogens, and many important questions will need to be addressed (Runion, 2003). However, around the world, the effect of climate change on plant pathogens has been poorly studied. In this thesis, the potential distribution of CBS was modelled under a changing climate (Chapter 6). This is one of the first examples of modelling the potential distribution of a crop pathogen under climate change in South Africa.

Results indicate that the climates of the Northern Cape are unlikely to become suitable for CBS, but that the climates of the Western Cape will, in some areas, become suitable for the establishment of CBS (Table 9.2).

Previous bioclimatic models of the potential distribution of plant pathogens do not take the potential distribution of the host into account (Booth et al., 2000a; Booth et al., 2000b; Brasier, 1996; Chakraborty et al., 2002; Chakraborty et al., 1998; Chakraborty et al., 2000; Coakley et al., 1999; Hoddle, 2004; Lanoiselet et al., 2002; Meentemeyer et al., 2004; Paul et al., 2005; Pethybridge et al., 2003; Pivonia & Yang, 2004; Van Staden et al., 2004). However, if the potential distribution of the host is considered, then model outputs and conclusions will be more relevant. Therefore, the potential distributions of the pathogen and the host were modelled using the response surface approach. Results indicate significant climatic potential for the extension of citrus cultivation (Chapter 7), but under current climates CBS may establish in most areas suitable for citrus (Chapter 8). The only areas that were predicted to be potentially suitable for citrus, but were predicted to be climatically unsuitable for CBS, were areas in the south-west of the Western Cape (Table 9.1).

Under the current climate, the Northern Cape is largely predicted to be unsuitable for citrus cultivation and CBS establishment (Table 9.1). In the Northern Cape citrus is only produced very close to rivers, where there is a suitable localised climate (le Roux, 2004, Personal Communication), and these areas may be excluded due to the coarse resolution of the models.

Under climate change, all areas simulated to be suitable for citrus cultivation are also simulated to be suitable for CBS (Chapters 7 and 8). Notably both the SCT and Cramer data response surfaces simulate parts of the Western Cape to become suitable for CBS. Most of the citrus production areas of the Northern Cape are simulated to remain unsuitable for citrus and CBS. These results are in general agreement with the results of modelling the impact of climate change on CBS distributions in CLIMEX (Table 9.2). The only exception is the Vaalharts region of the Northern Cape. This region is simulated by both the response surfaces to be climatically suitable for citrus and CBS. The CLIMEX models could not model the impact of climate change on the Vaalharts district as CLIMEX contains no weather data from this locality.

The response surface modelling unfortunately only includes one climate change scenario. However, this is not necessarily detrimental. Shafer et al. (2001), who used response surface models to investigate potential changes to the distribution of North American tree and shrub species, found that the broad-scale patterns were consistent among three climate change scenarios.

Under current climate, all the areas where CBS is present in South Africa and Australia are successfully simulated by the models (Table 9.1). In South Africa, areas where CBS is currently present are predicted to remain suitable for CBS in future (Table 9.2).

Despite differences in data and methodology, the CLIMEX and response surfaces models give similar results, for instance all the models agree that CBS is intolerant to cold temperatures, and the geographical distribution of the disease appears to be limited by cold. This agreement among the model results increases the confidence in the conclusions of the study.

The climate of the Northern Cape is predicted to be largely unsuitable for CBS under current and future climate (Table 9.1 and Table 9.2). However, European Authorities have not certified this province as CBS-free (European Union, 1998).

Table 9.1 — The suitability of the current climate for CBS to occur in different areas as predicted by the models. Areas predicted to be climatically unsuitable for CBS are marked **-**; areas predicted to climatically suitable for CBS are marked **+**; and areas where climate is predicted to be suitable for CBS in some areas, but not others, are marked **±**. If predictions were not made using a particular technique, that box is blacked out.

	Current Situation	CLIMEX Match Climates Chapter 4	CLIMEX Compare Locations Chapter 5	SCT Data Response Surface Chapter 8	Cramer Data Response Surface Chapter 8
Western Cape Province	-	-	-	-	±
Northern Cape Province	-	-	-	-	-
Areas of South Africa where CBS is present	+	+	+	+	+
Areas of Australia where CBS is present	+	+	+		+
Europe	-	-	-		

Table 9.2 — Predictions of the different models for the potential of CBS to occur under climate change scenarios. Areas predicted to be climatically unsuitable for CBS are marked **-**; areas predicted to climatically suitable for CBS are marked **+**; and areas where climate is predicted to be suitable for CBS in some areas, but not others, are marked **±**.

	Current Situation	CLIMEX Compare Locations Chapter 6	SCT Data Response Surface Chapter 8	Cramer Data Response Surface Chapter 8
Western Cape Province	-	±	±	±
Northern Cape Province	-	-	±	±
Areas of South Africa affected by CBS	+	+	+	+

The preliminary results obtained from the different modelling procedures may also support the South African citrus industry to make decisions with regards to the extension of citriculture and the management of the potential spread of CBS. It may be in the interest of the citrus industry to strongly enforce current measures that restrict the movement of propagation material [Agricultural Pest Act of 1983 (Act no 36)] throughout the country in order to prevent the spread of CBS to the Western Cape and the Vaalharts district in the Northern Cape, as future climates may become suitable for CBS.

A global risk map is also produced that indicated that several citrus producing countries are at risk of CBS establishing. Countries where climates were predicted to be suitable for CBS, but where CBS is not currently found, include the United States of America (only in the states of Florida and Texas), Mexico, Colombia, Cuba, Ecuador, Vietnam and Thailand. All of these countries produce large quantities of citrus (also see Appendix A).

As the South African citrus industry is strongly dependant on export, the phytosanitary barriers which restrict the export of citrus from CBS infected areas to the European Union (EU) and the USA have a great economic impact on the industry. Additionally, the most important citrus product, Valencia oranges (Citrus Growers Association, 2004), is also highly susceptible to CBS (Kiely, 1948; Kotzé, 2000) and losses in both yield and quality of production are significant. The income lost may have a ripple effect and cause decreased land prices, unemployment and loss to industries dependent on citrus production. Social impacts include loss of security as a result of loss of income, political conflicts and management conflicts (Windels, 2000). Ideally, the social and economical impacts of CBS in South Africa should be addressed. However, it is clear that CBS is an issue of importance to South Africa.

After the first record of CBS in South Africa in 1929 (Doidge, 1929), significant quantities of citrus fruit from CBS infected areas were exported from South Africa to the EU. The first general restrictions on the import of citrus from South Africa to the EU were imposed in 1977 (European Union, 1977), and restrictions specifically on the import of fruit from CBS infected areas were only introduced in the 1990s (European Union, 1992). CBS infected fruit presumably entered the EU over the 48-year period of free trade, and during this time CBS did not establish in Europe. In practice, this situation is similar to that experienced within South Africa. Citrus fruit is still traded freely around the country and the disease has not established in the Western or Northen Cape Provinces.

Given the devastating economic and social impacts of invasive species (Pimentel et al., 2001), it is important to take a precautionary approach. However, as more information on the potential for a exotic organism to establish in a new region becomes available, existing trade barriers should be reassessed. The work in Chapters 4 and 5 of this thesis suggests that the European Climate is unfavourable for CBS. Additionally, the import of citrus into the EU is restricted to fruits and seeds (European Union, 2000). As the primary inoculum source (ascospores) is not associated with CBS-infected fruit, the risk of CBS introduction and establishment in the EU as a result of commercial trade in fresh citrus fruit, even from CBS infected areas, is low. Some of the outcomes of this study have been included in a Pest Risk Assessment on CBS that have been presented to the EU. A reply from the EU is pending.

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Appendix A — Maps of the potential global distribution of Citrus Black Spot

Maps of the potential distribution of Citrus Black Spot produced in Chapter 6 (published as Paul et al., (2005)) relied on a climate data base represented by weather data localities. Unfortunately, on a global scale, this database is not comprehensive. For example there were no climate data localities in Bhuthan and only two in Taiwan. In this appendix, the CLIMEX model of Chapter 6 is applied to a 0.5° gridded climate dataset developed by New et al. (1999). The gridded climate dataset includes climate data for Bhutan and Taiwan; and, in line with field observations, the map produced suggests that parts of these countries are suitable for disease establishment.

The gridded dataset represents mean monthly surface climate over land areas of the globe between 1961 and 1990. The data were interpolated from weather station data to a 0.5 degree latitude and longitude grid. Variables are precipitation and wet-day frequency, mean temperature, diurnal temperature range, vapour pressure, sunshine, cloud cover, ground frost frequency and windspeed. The data is fully described in New et al. (1999) and can be obtained from the IPPC Data Distribution Centre (http://ipcc-ddc.cru.uea.ac.uk).

Six maps are presented that indicate the climatic potential for CBS to establish in the main citrus growing regions of the world (compare with the maps of citrus growing regions in Chapter 2). Climatic potential is measured using an Ecoclimatic Index (EI): $EI \leq 4$, climate unfavourable for the persistence of the species; $5 \leq EI \leq 10$, marginally suitable for disease development; $EI \geq 11$, favourable for disease development; and $EI > 20$, highly favourable for the persistence of CBS (Paul et al., 2005).

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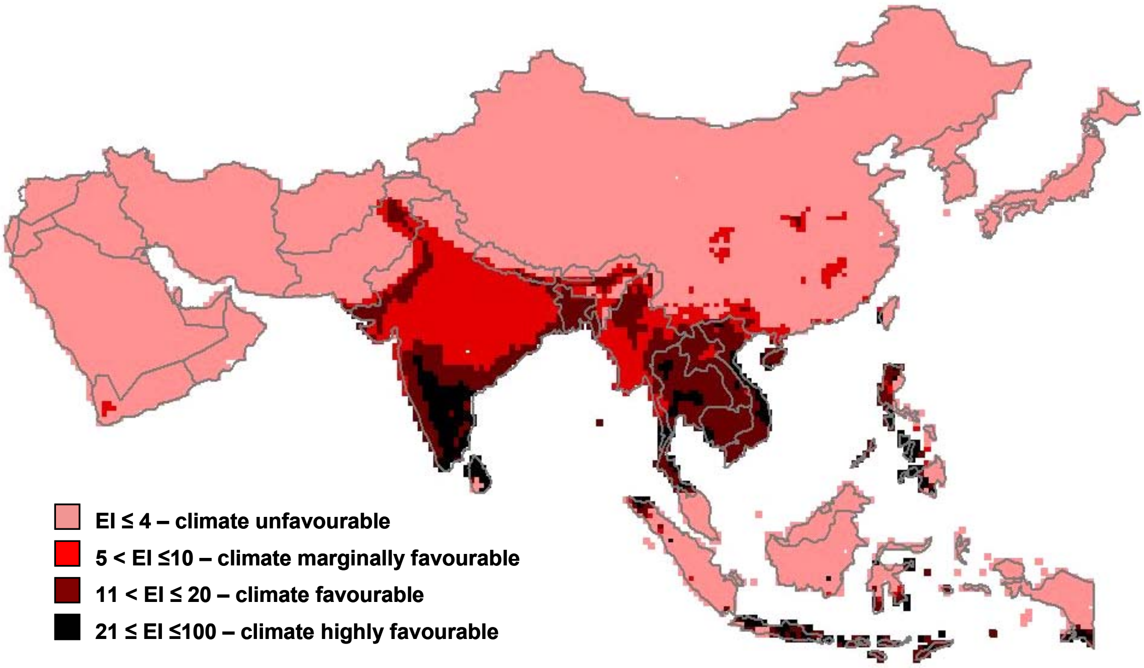


Figure A.1 — The climatic suitability of Asia for the occurrence of Citrus Black Spot.

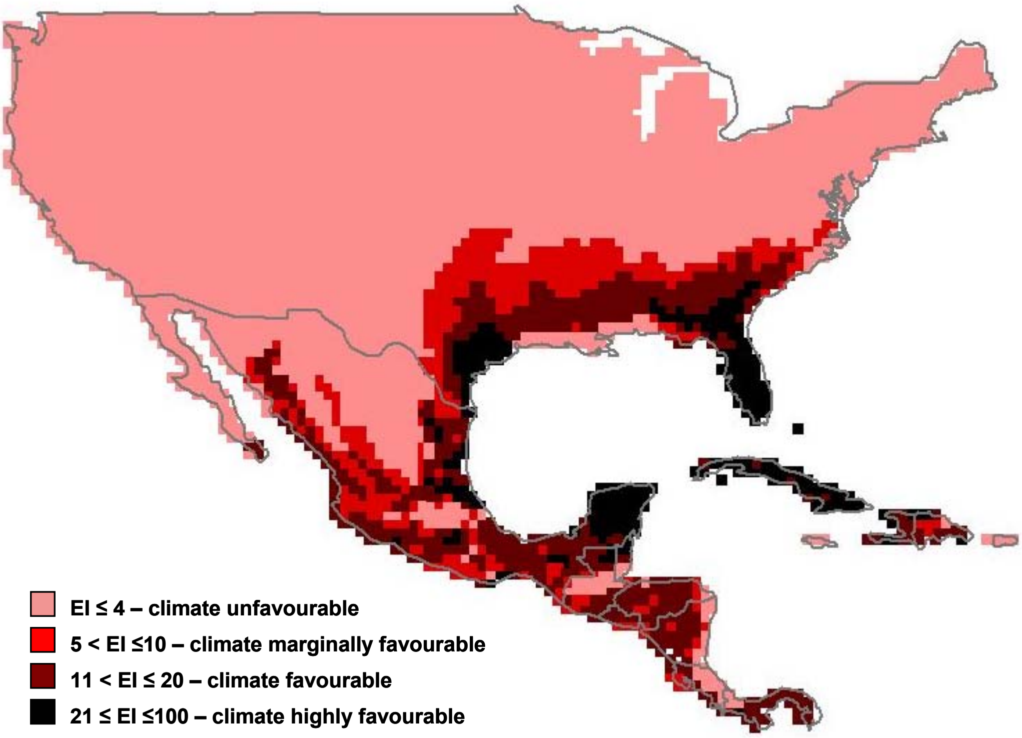


Figure A.2 — The climatic suitability of North and Central America for the establishment of Citrus Black Spot.

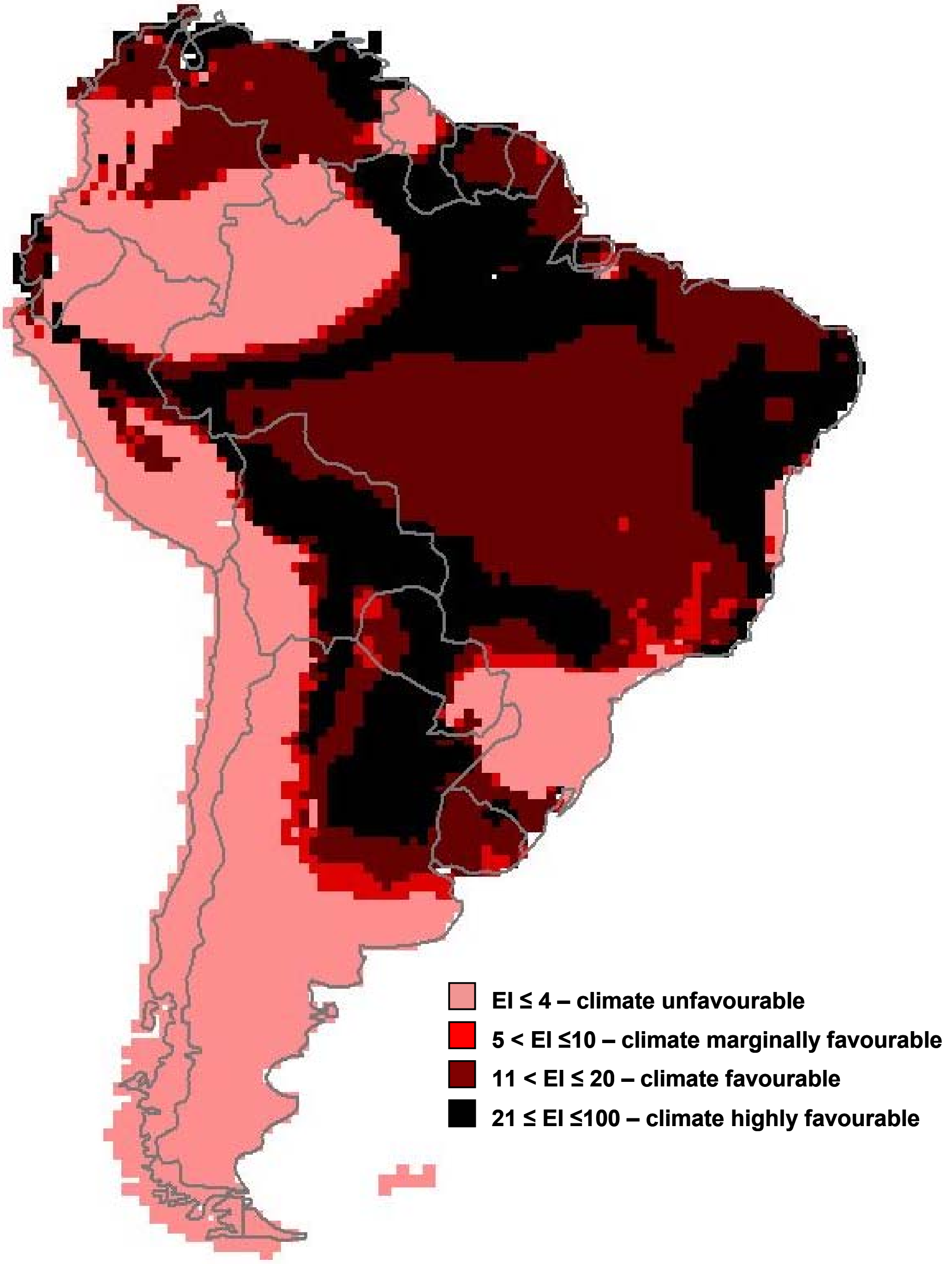


Figure A.3 — The climatic suitability of South America for the occurrence of Citrus Black Spot.

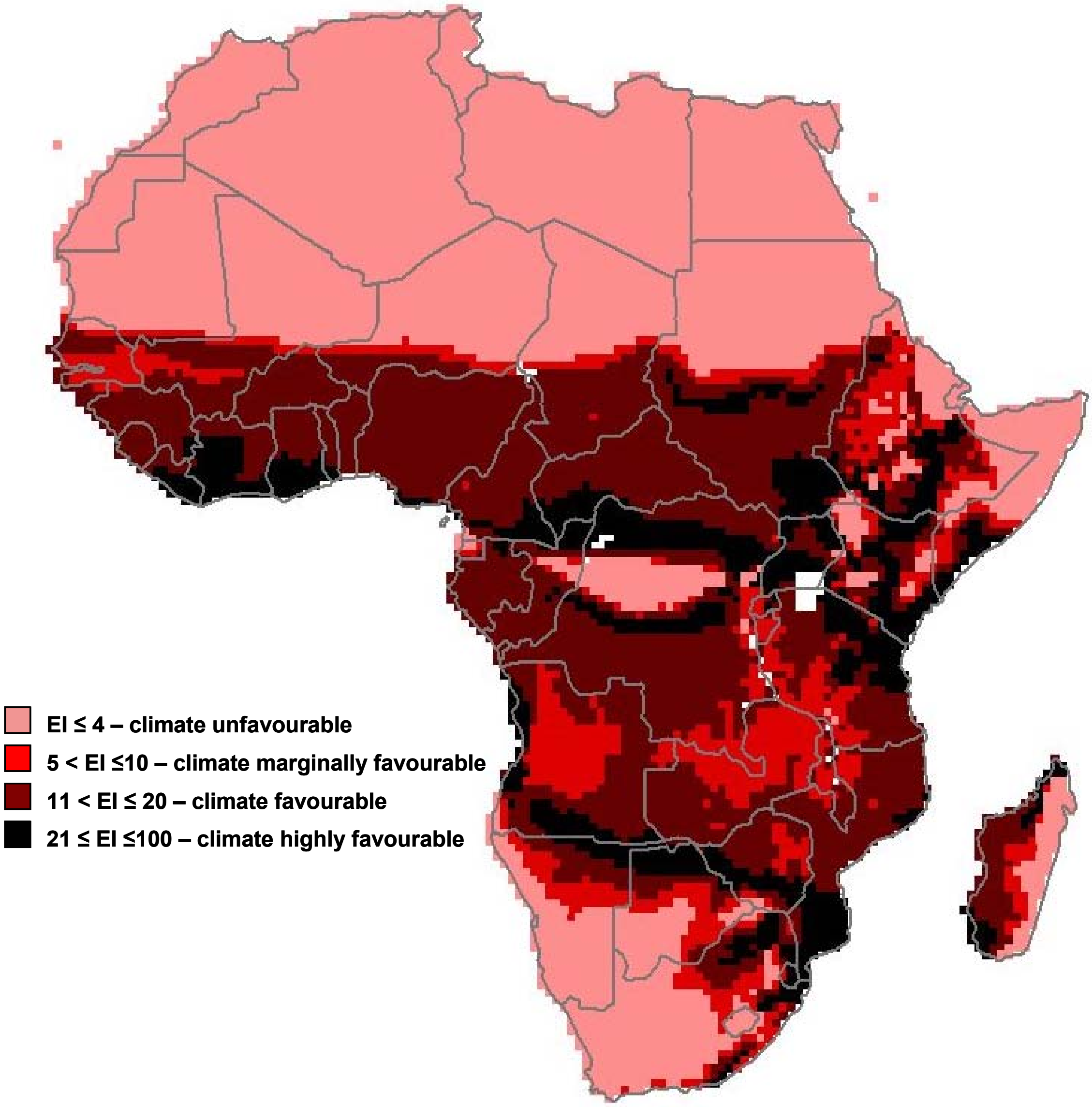


Figure A.4 — The climatic suitability for Africa for the occurrence of Citrus Black Spot.

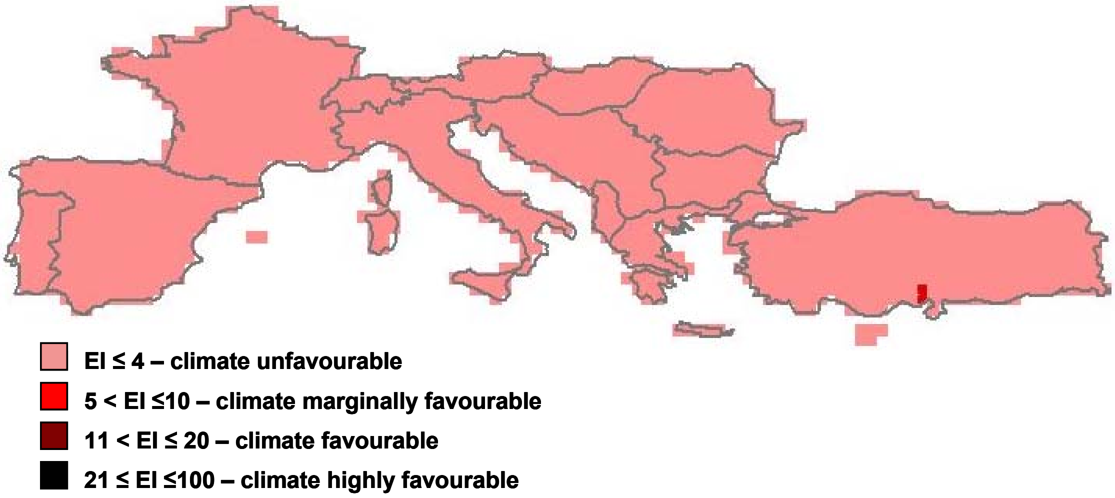


Figure A.5 — The climatic suitability of Southern Europe and Asia minor for the occurrence of Citrus Black Spot.

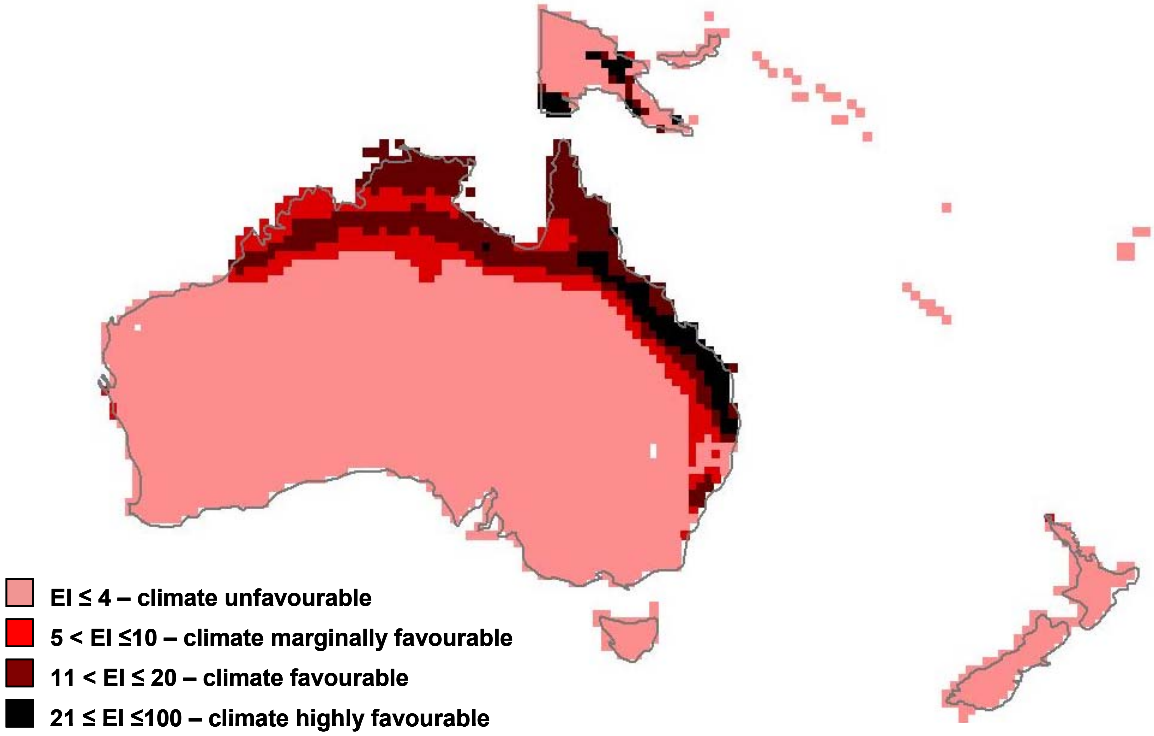


Figure A.6 — The climatic suitability of Oceania for the occurrence of Citrus Black Spot.

Appendix B — Differences between the SCT and Cramer data

Two climate data sets were used in this study. The Cramer data set, for which climate data were collated over the period of 1931–1960, and the SCT data set, for which climate data were collated over the period of 1961–1990. Data for both data sets used originate from direct measurements from weather data stations over the period that the data set relates to. The climate data were spatially interpolated. The Cramer data were spatially interpolated to the mean elevation values (calculated as the mean of the modal elevations) and the SCT data were obtained as values already spatially interpolated to minimum elevation values. Thus the climate data differed in the period in which the data were collated and in the elevation data to which the climate values were interpolated.

These climate data were used to calculate the bioclimate variable values for a 15' grid of South Africa that contained 1974 cells. The bioclimate variables were mean temperature of the coldest month (MTCO), mean temperature of the warmest month (MTWA) and the ratio of actual to potential evapotranspiration (AET/PET). However, differences in the climate data resulted in different values calculated for the bioclimate variables as can be seen from the maps of the bioclimate variable values. Maps of the bioclimate variable under climate change are also presented. Differences between the future climates are analysed in Appendix C.

AET/PET values above 0.9 were calculated from the Cramer data, but not from the SCT data (compare Figure B.1 and Figure B.2). Generally, MTCO and MTWA values from the SCT data are higher than from the Cramer data (compare Figure B.5 with Figure B.6, and Figure B.9 with Figure B.10). The MTCO values for the eastern coastal areas of South Africa are higher when calculated from the SCT data than when calculated from the Cramer data. Similarly, MTWA values for the area of the Kgalagadi Transfrontier Park (Northern Cape) as calculated from the SCT data are higher than those calculated from the Cramer data.

When modelling the potential distributions of species, the most appropriate climate data set should be chosen. The climate of Africa is warmer now than it was 100 years ago, and this warming has been particularly apparent since the 1970s. The six warmest years on record are all more recent than 1987, with 1998 being the warmest (Hulme et al., 2001). This recent rise in temperature is not captured by the Cramer climate data, as these data were collected between 1931–1960. Because of this, although the Cramer data were interpolated from more data localities than the SCT data, the SCT data are accepted to be more reliable for modelling the potential distribution of citrus and CBS.

Hulme, M., Doherty, R., Ngara, T., New, M. & Lister, D. (2001) African Climate Change: 1900–2100. Climate Research, 17, 145-168.

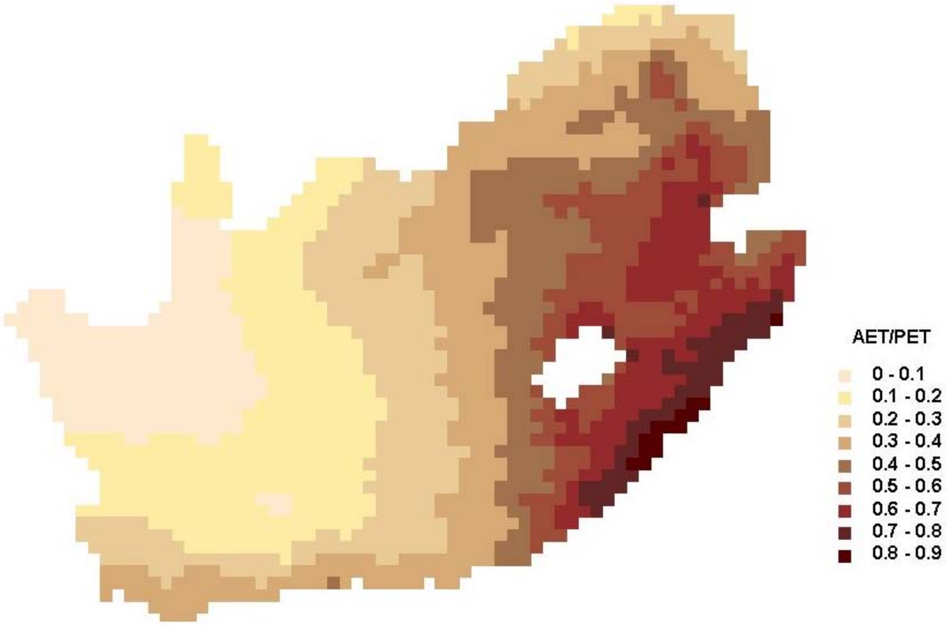


Figure B.1 — The ratio of actual to potential evapotranspiration (AET/PET), SCT data.

Figure B.2 — The ratio of actual to potential evapotranspiration (AET/PET), Cramer data

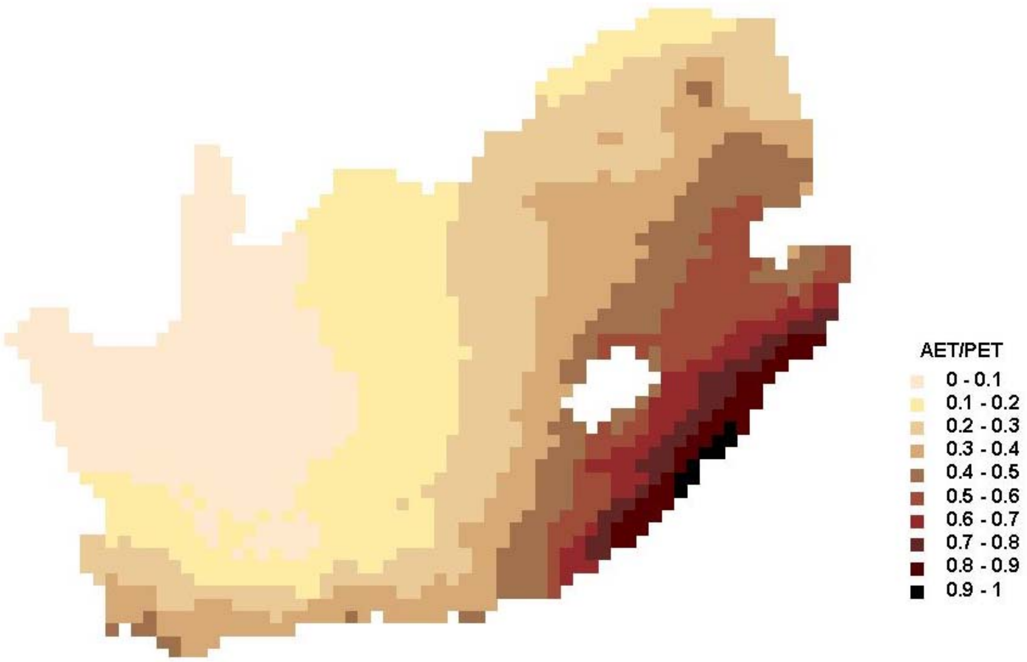


Figure B.3 — The ratio of actual to potential evapotranspiration (AET/PET) values calculated for the SCT data using the future climate represented by the HadCM3 B2 scenario.

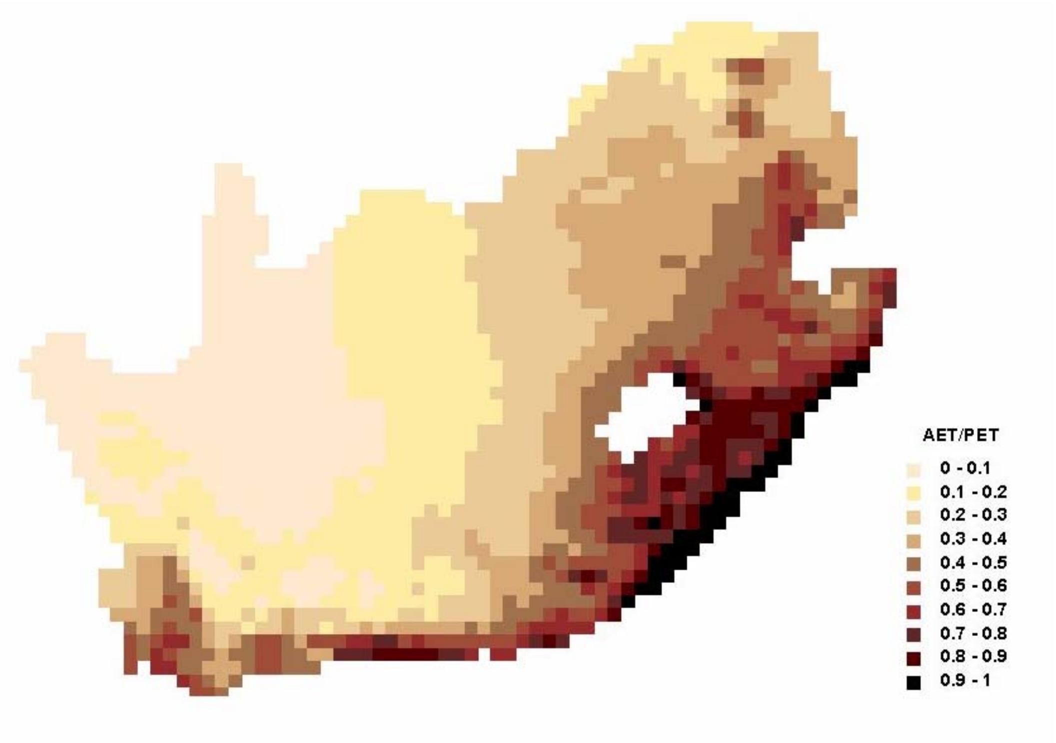


Figure B.4 — The ratio of actual to potential evapotranspiration (AET/PET) values calculated for the Cramer data using the future climate represented by the HadCM3 B2 scenario.

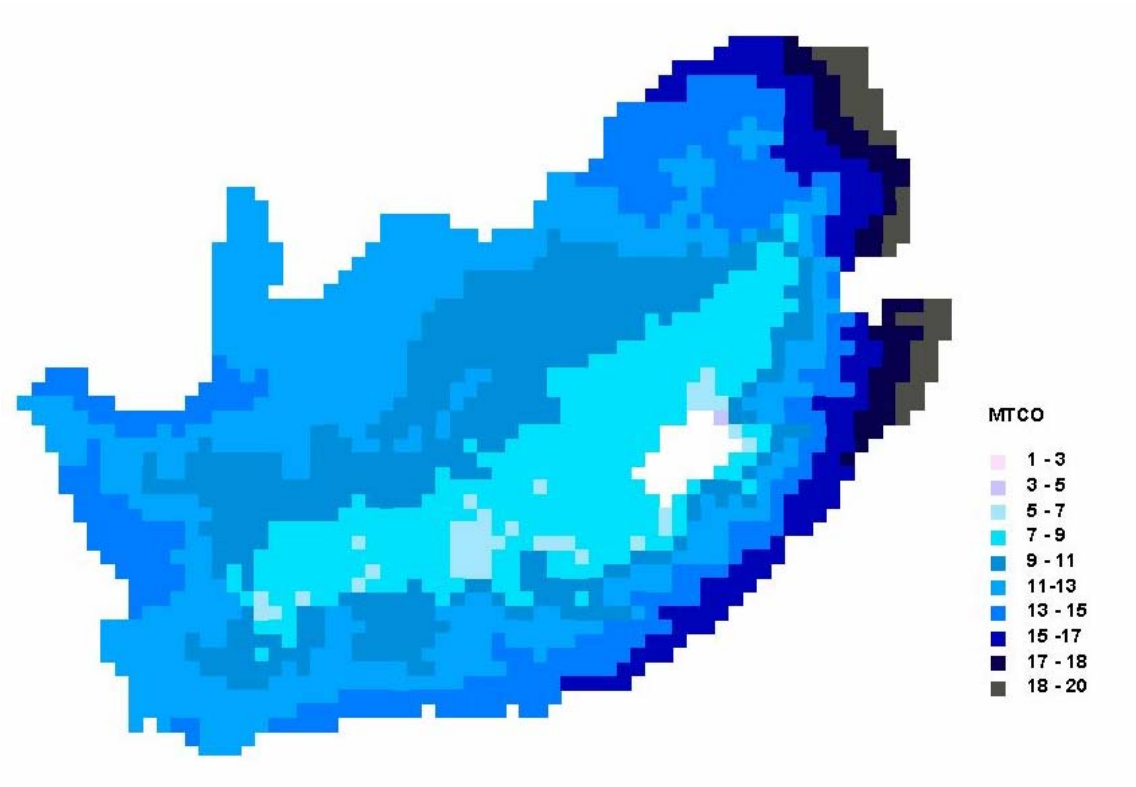


Figure B.5 — Mean temperature of the coldest month (°C), SCT data.

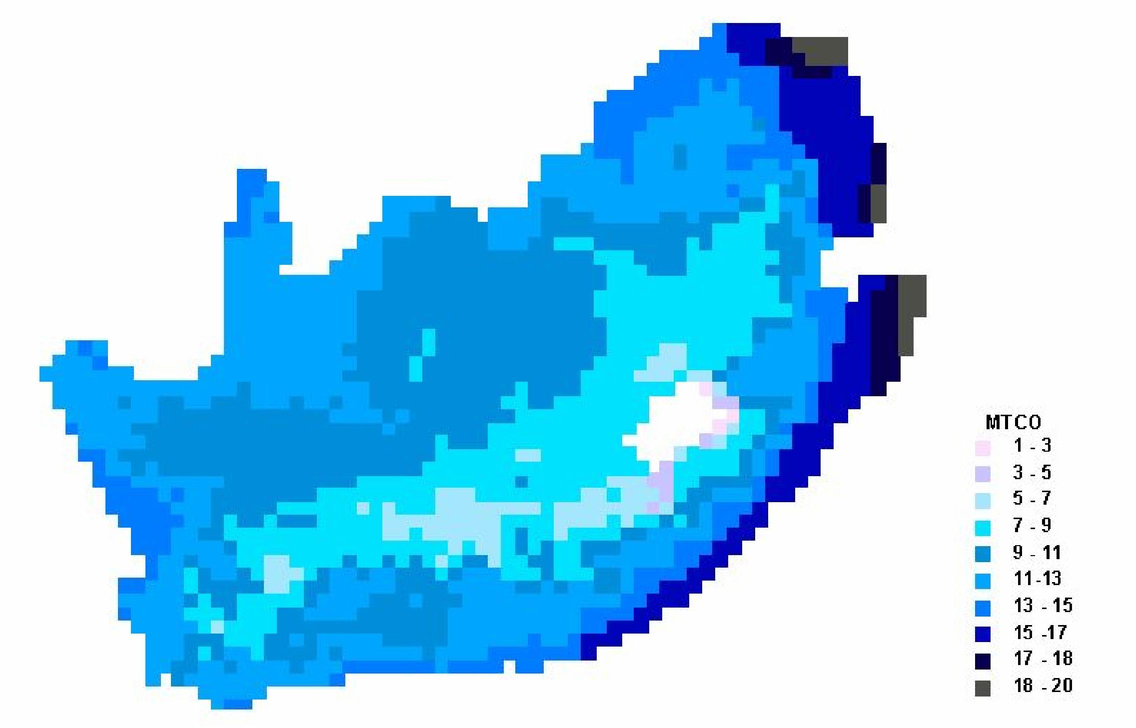


Figure B.6 — Mean temperature of the coldest month (°C), Cramer data.

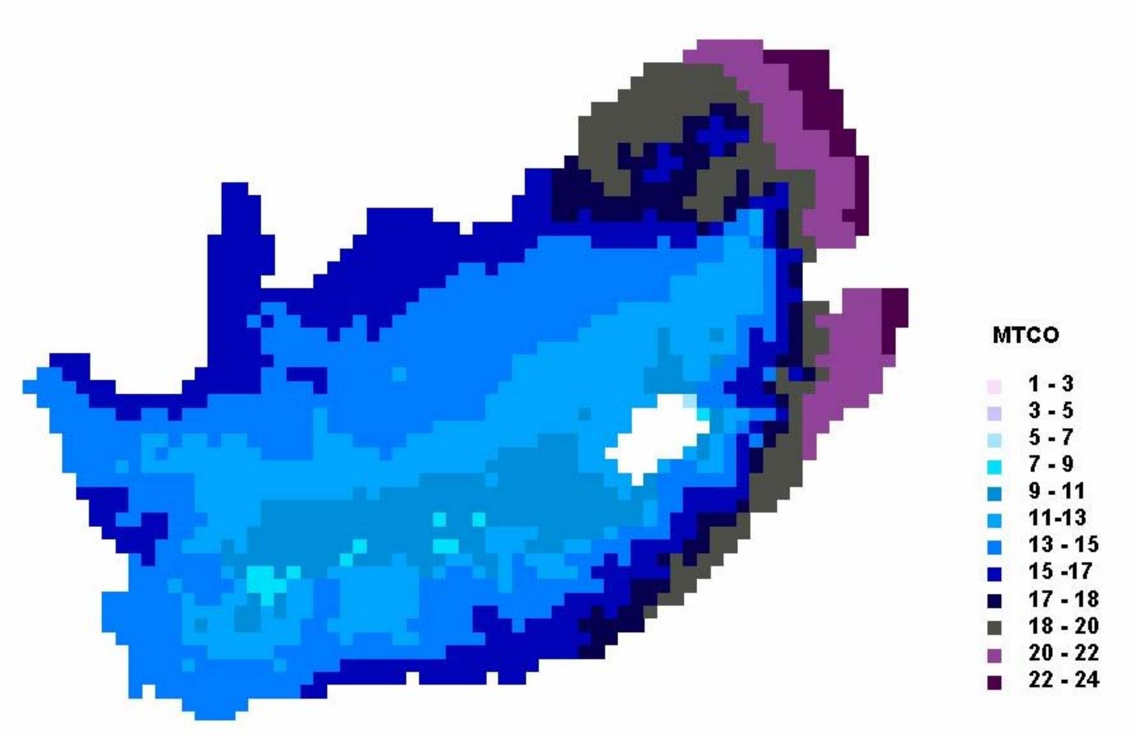


Figure B.7 — Mean temperature of the coldest month values (°C) calculated for the SCT data using the future climate represented by the HadCM3 B2 scenario.

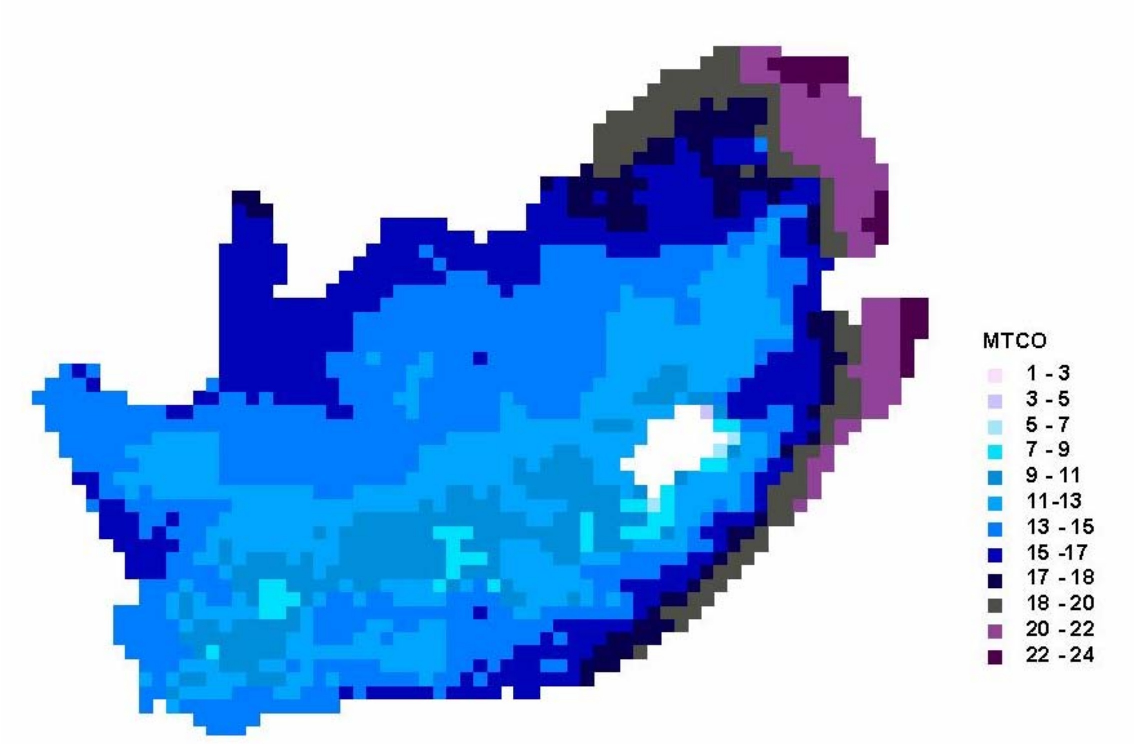


Figure B.8 — Mean temperature of the coldest month (°C) values calculated for the Cramer data using the future climate represented by the HadCM3 B2 scenario.

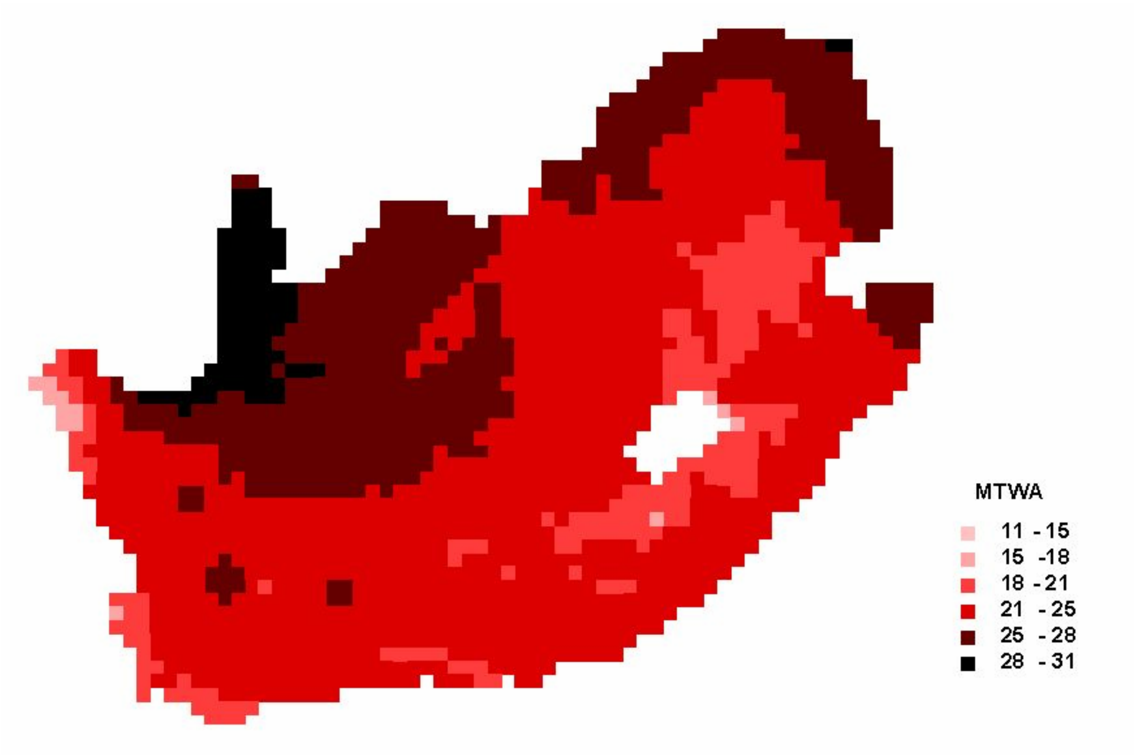


Figure B.9 — Mean temperature of the warmest month (°C), SCT data.

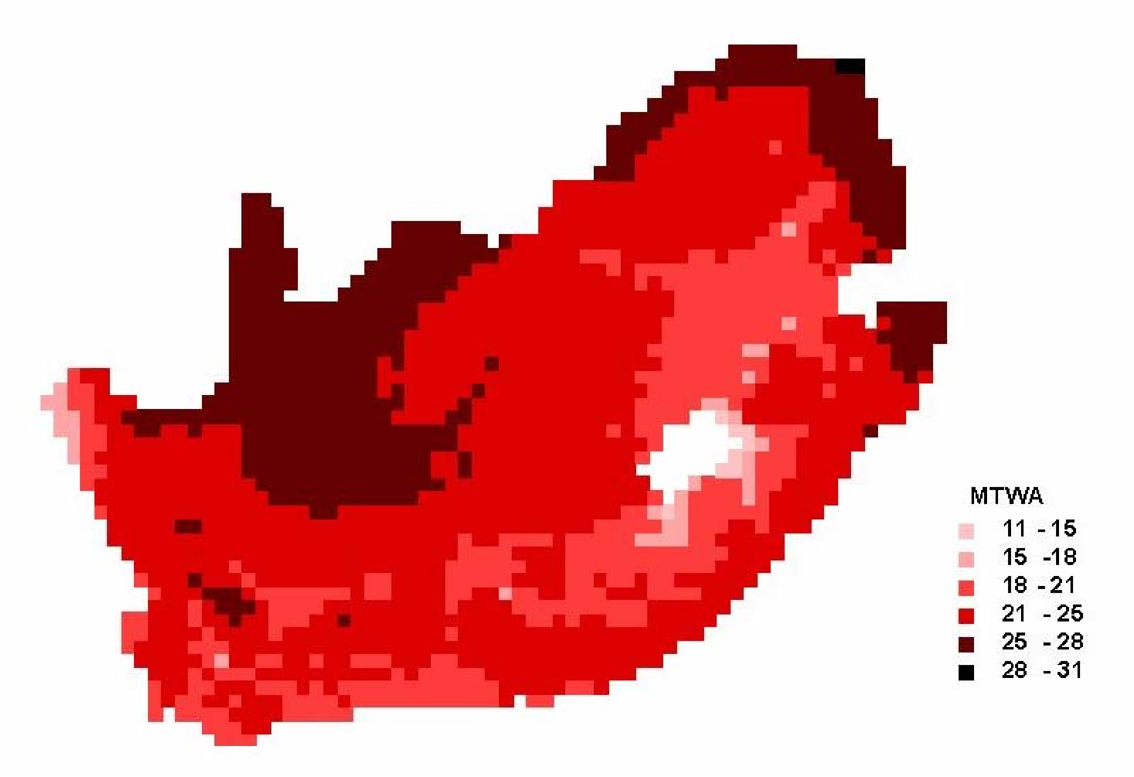


Figure B.10 — Mean temperature of the warmest month (°C), Cramer data.

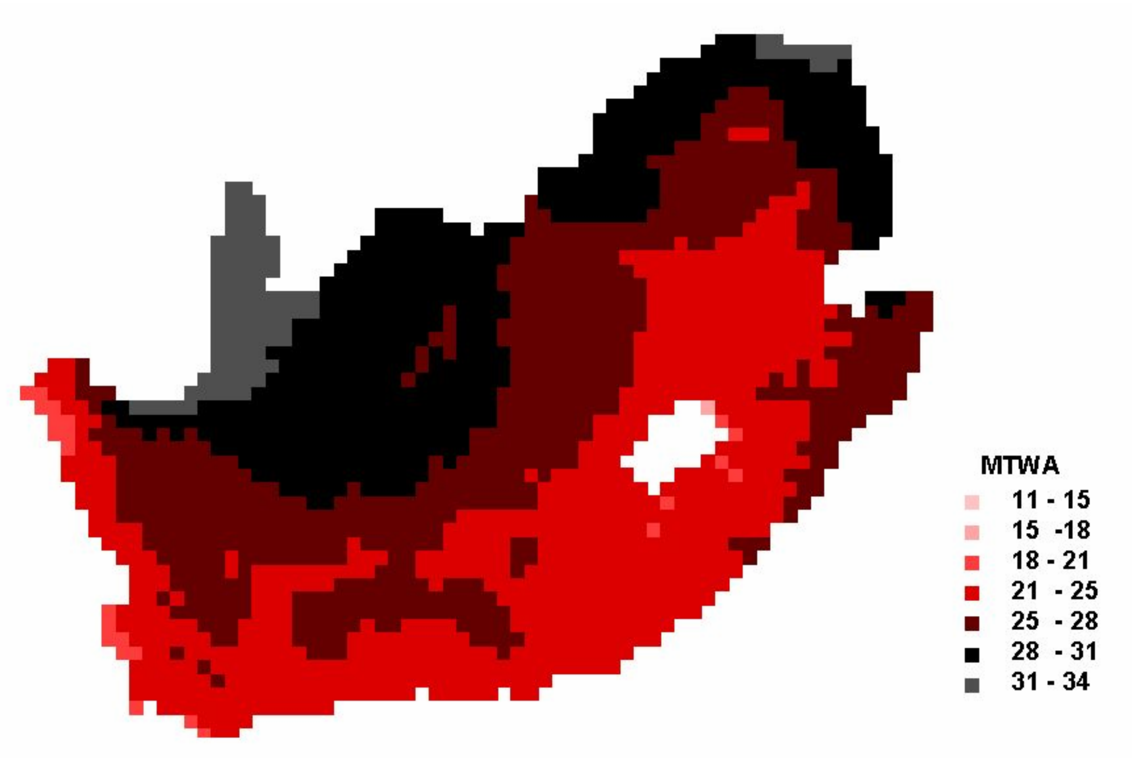


Figure B.11 — Mean temperature of the warmest month values (°C) values calculated for the SCT data using the future climate represented by the HadCM3 B2 scenario.

Figure B.12 — Mean temperature of the warmest month (°C) values calculated for the Cramer data using the future climate represented by the HadCM3 B2 scenario.

Appendix C — Potential future climate of South Africa

The nature of the simulated change in climate for South Africa is illustrated by mapping areas of projected future climates that are analagous to the current climate.

Future climates were compared to records seen as representative of current climate. This was done for both the SCT data (1961–1990) and the Cramer data (1931–1960). Comparisons were based on the values for three bioclimate variables, namely the mean temperature of the coldest month (MTCO); the mean temperature of the warmest month (MTWA); and the ratio of actual to potential evapotranspiration (AET/PET).

So that the variables had equal weight when they were compared, the variables were standardised using the standard normal,

$$A_x' = \frac{A_x - \overline{\overline{A}}}{\sigma_A} \qquad 1$$

where A_x' is the standardised value of a bioclimate variable A at grid cell x; A_x is the value of bioclimate variable A at grid cell x; $\overline{\overline{A}}$ is the mean of all values (current and future) of bioclimate variable A; and σ_A is the standard deviation of all values (current and future) of bioclimate variable A.

As the AET/PET values represent proportions, AET/PET values were linearised using the logit transformation before being standardised. The logit transformation is,

$$x' = \ln\left(\frac{x}{1-x}\right) \qquad 2$$

where x' is a transformed datum, and x is an original proportion datum. So that the logit transformation did not return infinite values, any untransformed AET/PET values of 1 were converted to 0.999.

Visual inspection confirmed that each standardised bioclimate variable approximated the normal distribution, with a mean of zero and standard deviation of one.

The climate at a grid cell could then be compared with the climate at another grid cell using the inversed square Euclidean distance. The Euclidean distance between two grid cells is calculated as,

$$d_{(i,j)} = \sqrt{\left(mtco_i' - mtco_j'\right)^2 + \left(mtwa_i' - mtwa_j'\right)^2 + \left(apet_i' - apet_j'\right)^2} \qquad 3$$

where $d_{(i,j)}$ is the Euclidean distance between the climate at grid cell i and the climate at grid cell j; A_i' is the value of environmental variable A at grid cell i (standardised using equation 2); and A_j' is the value of environmental variable A at grid cell j standardised using equation 2).

To measure how similar the projected future climate is to the current climate the minimum Euclidean distance between a grid cell of the future climate and all the grid cells of the current climate was calculated. This calculation was done for all the grid cells within the future climate data. This comparison reveals where climates similar to the future climate may be found in South Africa today.

To quantitatively assess the minimum distances calculated for future grid cells, current climate was also compared by calculating the minimum Euclidean distance between at a grid cell of the current climate and all the other grid cells of the current climate. The minimum Euclidian distances obtained from these calculations were well described by a log-normal distribution. Therefore, the likelihood that the climate at a future grid cell would be similar to the current climates could be calculated from the expected distribution of the calculated minimum distance values. Figure C.1 (SCT data) and Figure C.2 (Cramer data) show the degree of similarity between the future climates and the observed current climates in South Africa.

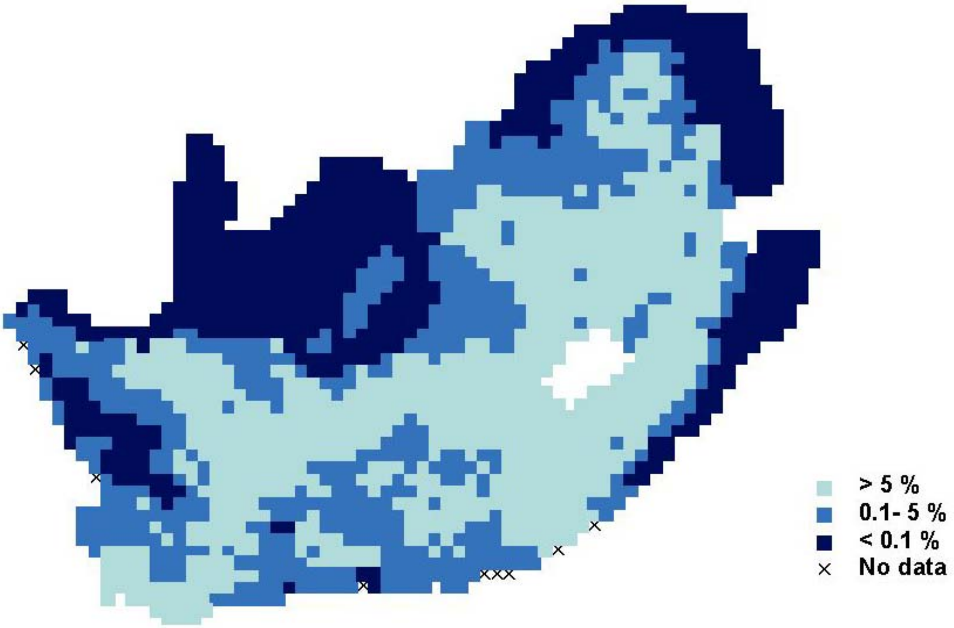


Figure C.1 — A grid of South Africa indicating the similarity between future and current climate using SCT data. The liklihoods that the future climate at grid cells are represented somewhere in the current climate of South Africa are shown.

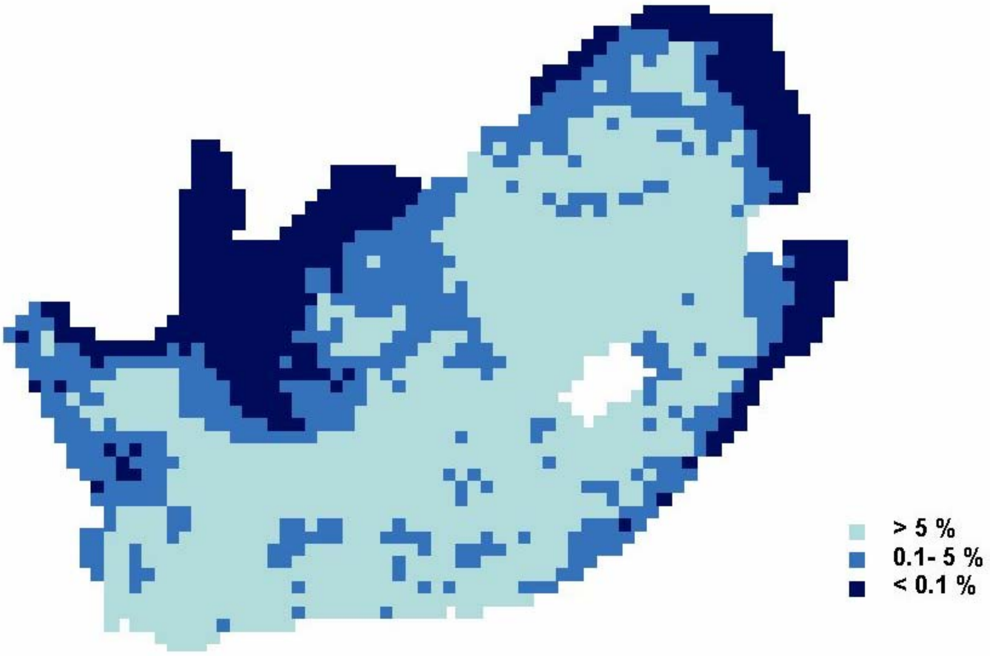


Figure C.2 — A grid of South Africa indicating the similarity between future and current climate using Cramer data. The liklihoods that the future climate at grid cells are represented somewhere in the current climate of South Africa are shown.

For the SCT data and the Cramer data a future climate analogous to the current climate in South Africa is predicted for most of the interior of the country. Climates along the Eastern and Western coastlines and also against the Northern borders of the country and notably the greatest parts of the Northern Cape are calculated to be different from present climates.

Figure C.1 and Figure C.2, however, do not show which current areas in South Africa are most similar to the future climates, or which currently observed climates are no longer represented in the future climates. This is shown in Figure C.3 and

Figure C.4, where the frequency with which the observed climate at a grid cell was found to be closest (most similar) to future climate was plotted for the SCT and the Cramer data respectively. For both the SCT and Cramer data the pattern shows that future climates are not well represented by inland climates. Particularly high frequencies of future aligned climates were found along the northern borders of the country.

To verify that these patterns are not an artefact of the occurrence of current climates, the procedure was repeated to identify the frequency with which the current climate at a grid cell was found to be similar to other grid cells across the country. In this case, using the SCT data set as an example, climates were much more evenly distributed across South Africa, with a large number of grid cells only having four other cells with similar climates from across the region (Figure C.5). This is in contrast to the comparison with future climates where over thirty grid cells had ten of more grid cells with similar climates. This means that the current climates are relatively heterogeneous across the landscape but that future climates are likely to have a broader distribution (higher frequency).

The changes in climate can also be visualised by comparing maps of the bioclimate variable values as calculated for the current climate data with those calculated for the future climate scenario (See Appendix B, Figure B.1–Figure B.12).

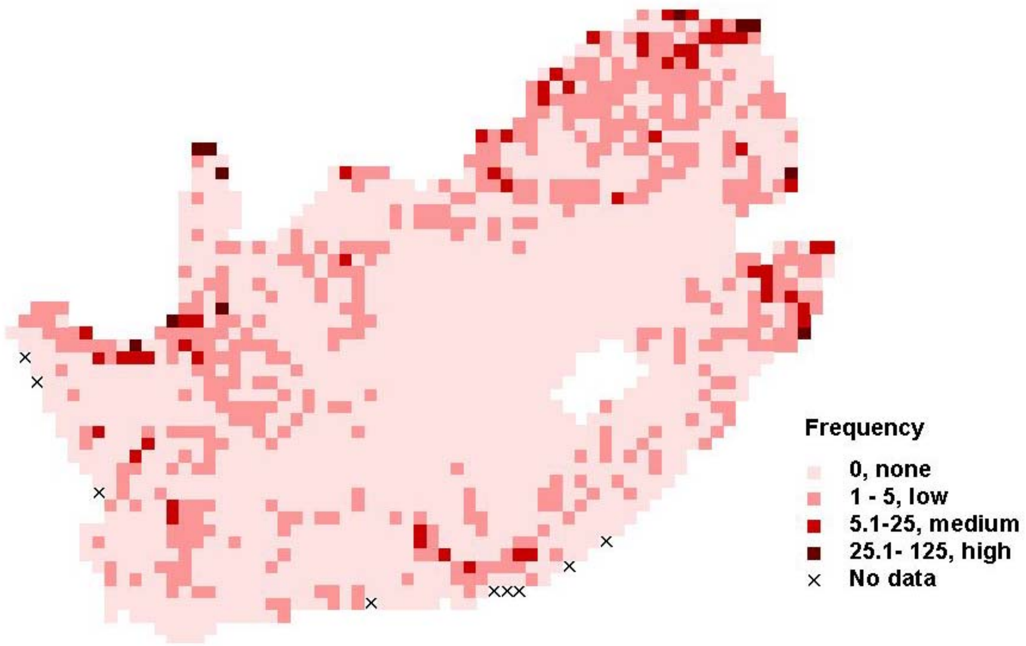


Figure C.3 — A grid map of South Africa indicating those grid cells that were most frequently similar to a future grid cell, SCT data. The different categories refer to the number of grid cells from the future climates with similar climates.

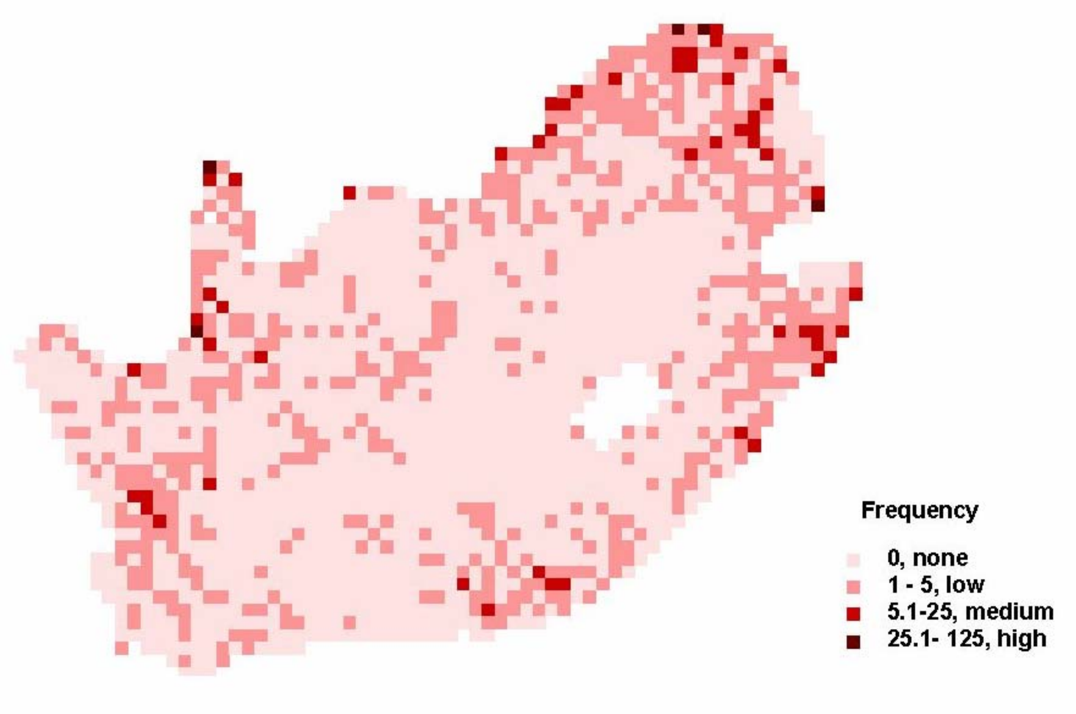


Figure C.4 — A grid map of South Africa indicating those grid cells that were most similar to future grid cells, Cramer data. The different categories refer to the number of grid cells from future climate with similar climates.

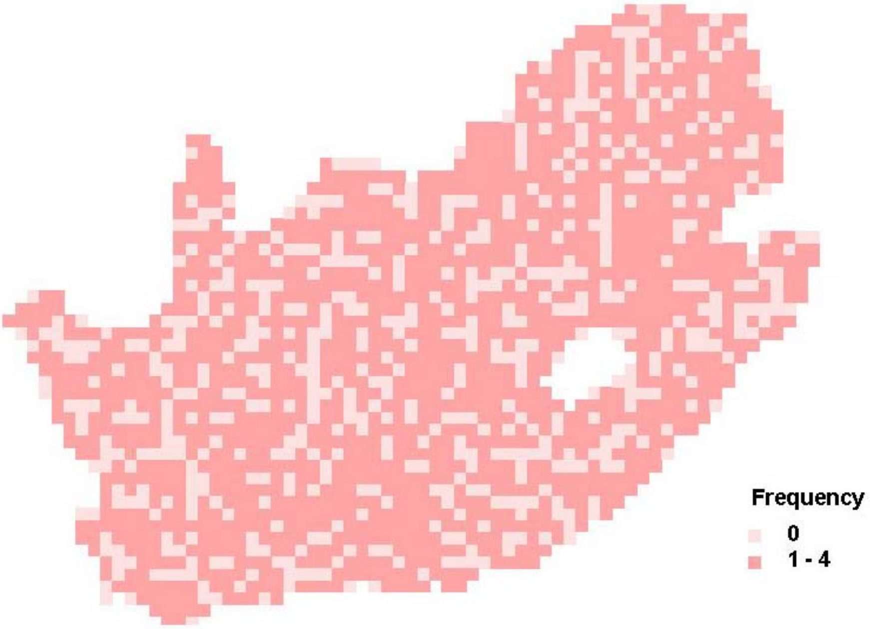
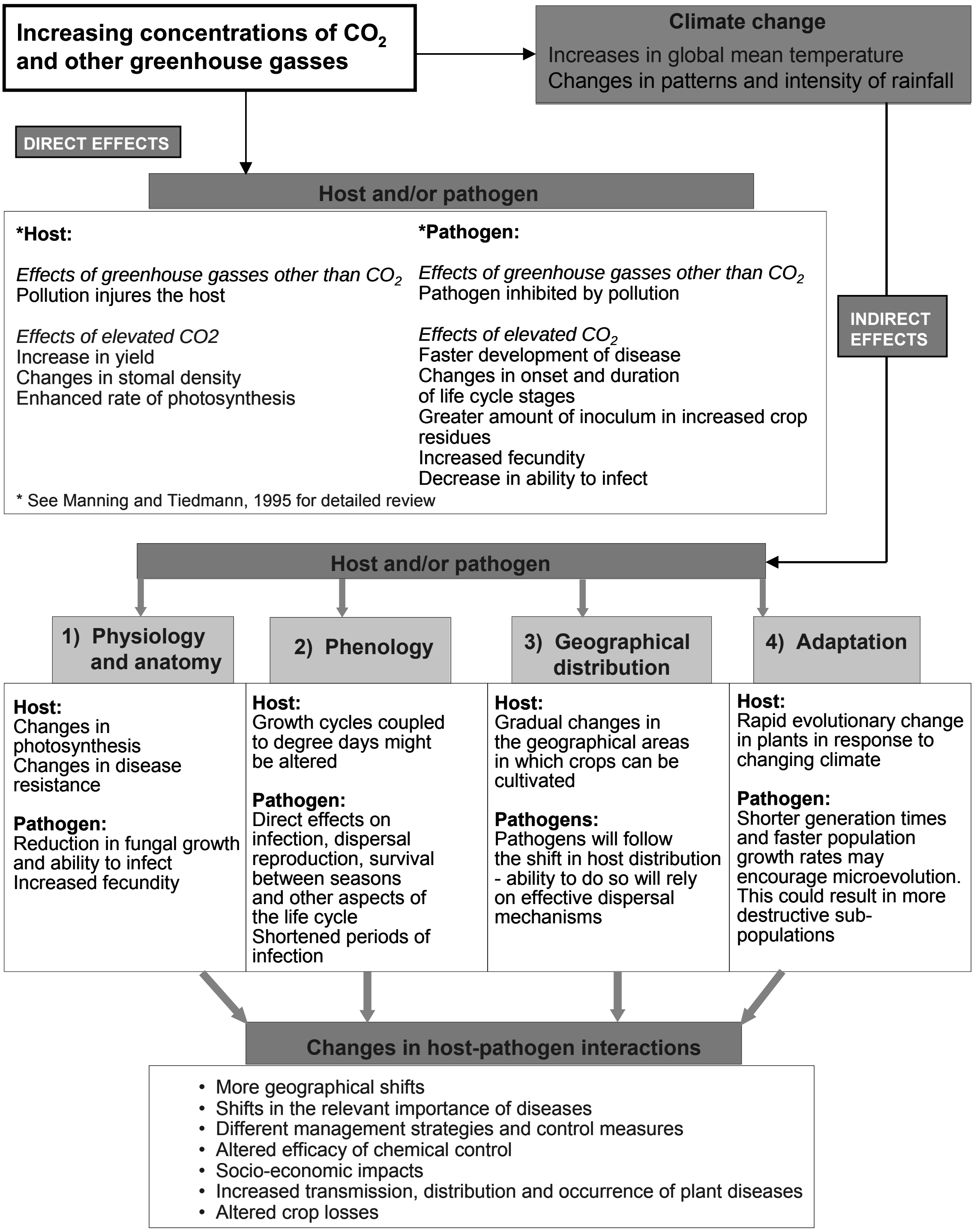


Figure C.5 — A grid of South Africa showing the frequency with which a single grid cell was used to explain the climate of other grid cells, when measuring the similarity of current climate to itself.

Appendix D — Flow diagram of the potential direct and indirect impacts of climate change on crops and pathogens



Increasing concentrations of CO_2 and other greenhouse gasses

Climate change
Increases in global mean temperature
Changes in patterns and intensity of rainfall

DIRECT EFFECTS

Host and/or pathogen

***Host:**

Effects of greenhouse gasses other than CO_2
Pollution injures the host

Effects of elevated CO2
Increase in yield
Changes in stomal density
Enhanced rate of photosynthesis

***Pathogen:**

Effects of greenhouse gasses other than CO_2
Pathogen inhibited by pollution

Effects of elevated CO_2
Faster development of disease
Changes in onset and duration of life cycle stages
Greater amount of inoculum in increased crop residues
Increased fecundity
Decrease in ability to infect

* See Manning and Tiedmann, 1995 for detailed review

INDIRECT EFFECTS

Host and/or pathogen

1) Physiology and anatomy

Host:
Changes in photosynthesis
Changes in disease resistance

Pathogen:
Reduction in fungal growth and ability to infect
Increased fecundity

2) Phenology

Host:
Growth cycles coupled to degree days might be altered

Pathogen:
Direct effects on infection, dispersal reproduction, survival between seasons and other aspects of the life cycle
Shortened periods of infection

3) Geographical distribution

Host:
Gradual changes in the geographical areas in which crops can be cultivated

Pathogens:
Pathogens will follow the shift in host distribution - ability to do so will rely on effective dispersal mechanisms

4) Adaptation

Host:
Rapid evolutionary change in plants in response to changing climate

Pathogen:
Shorter generation times and faster population growth rates may encourage microevolution. This could result in more destructive sub-populations

Changes in host-pathogen interactions

- More geographical shifts
- Shifts in the relevant importance of diseases
- Different management strategies and control measures
- Altered efficacy of chemical control
- Socio-economic impacts
- Increased transmission, distribution and occurrence of plant diseases
- Altered crop losses

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