DEVELOPMENT OF A CLIMATIC SOYBEAN RUST MODEL AND FORECASTING FRAMEWORK

LAUREN MICHELLE VAN NIEKERK

Submitted in partial fulfilment of the requirements
for the degree Masters of Science in Bioresource Systems

Supervisor: Prof. C. N. Bezuidenhout
Co-supervisor: Dr P. M. Caldwell

School of Bioresources Engineering and Environmental Hydrology
University of KwaZulu-Natal
Pietermaritzburg
November 2009

ABSTRACT

Soybean rust (SBR), caused by the fungus *Phakopsora pachyrhizi* Syd., is a real threat to soybean crops in South Africa. Its ability to spread rapidly and its potential to severely reduce yields have earned it the reputation as the most destructive foliar disease of soybeans. SBR has been reported in South Africa every year since its arrival in 2001. While extensive research had been done on the epidemiology and fungicide application requirements in South Africa, no work into the long term climatic vulnerability of soybean production areas to SBR had been done. This meant soybean producers do not know whether SBR is a threat in their areas. Through this research a SBR algorithm was developed using readily available climate data, *viz.* temperature and rainfall, to create a daily index specifying the climatic vulnerability of SBR infection. The algorithm was applied to a 50 year historical climate database, and a series of maps was created illustrating the long term vulnerability of different areas to SBR infection. These maps allow soybean producers to understand the climatic vulnerability of their area to SBR infection. Time series graphs were created for selected key soybean production areas to allow soybean producers to distinguish periods of high and low climatic risk during the season. This may help with decisions regarding the planting times, the maturation rate of different cultivars as well as the timing and application of fungicides. The framework for a near real time forecasting system was created outlining how the system could amalgamate recently recorded and forecasted weather data, run it through the SBR algorithm and provide a near real time, as well as forecasted vulnerability, based on the climatic conductivity for SBR infection. Anticipated limitations and difficulties on developing the forecasting system are also outlined.

PREFACE

The work described in this dissertation was carried out in the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, from January 2008 to November 2009, under the supervision of Professor C. N. Bezuidenhout and co-supervision of Dr P. M. Caldwell (Plant Pathology).

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

....	....
Signature (Student) Lauren van Niekerk	Date
....	....
Signature (Supervisor) Prof. C. N. Bezuidenhout	Date
....	....
Signature (Co-supervisor) Dr. P. M. Caldwell	Date

ACKNOWLEDGEMENTS

The author would like to thank the following organisations and people for their assistance and contribution to this research.

Professor Carel N. Bezuidenhout for supervising this research as well as providing constant support and encouragement,

Dr. Pat M. Caldwell for co-supervising this research as well as providing constant support and encouragement,

The Protein Research Foundation for financial support as well as the members of the PRF Soybean Rust Task Team for their valuable insight and advice,

The School of Bioresources Engineering and Environmental Hydrology for financial and academic support,

Mr Richard Kunz for his help in programming the algorithms and mapping, as well as his valuable insight and advice,

Mr Neil van Rij for his expert advice on soybean rust in KwaZulu-Natal and assistance in the verification of the algorithm,

My family and Hartley Bulcock for their unfailing moral support.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 Background

Soybean (*Glycine max* L.) is an important crop worldwide as it provides a relatively low-cost and nutritionally balanced source of protein (Sinclair, 1982). South Africa (SA) produced an estimated 506 595 tons of soybeans on approximately 237 750 hectares in the 2008/2009 growing season (National Crop Estimates Committee, 2009). However, soybean rust (SBR), caused by the fungus *Phakopsora pachyrhizi* Syd., is considered to be the most destructive foliar disease of soybeans because of its ability to spread rapidly and its potential to severely reduce yields (Miles *et al.*, 2003). The pathogen reduces yield by promoting premature defoliation of leaves, which decreases the number of filled pods and reduces the weight of seeds per plant. In February 2001, SBR was identified for the first time in South Africa in the Vryheid area of KwaZulu-Natal (KZN). The pathogen was positively identified as *P. pachyrhizi* by Pretorius *et al.*, (2001). Since then SBR has been positively identified in commercial soybean crops every year (Jarvie, 2009).

Soybean rust requires a temperature range between 15˚C to 28˚C for successful germination (Bromfield, 1980; Wang and Hartman, 1992). Optimum temperatures for infection in South Africa are between 20˚C and 25˚C (Nunkumar, 2006). Leaf wetness either from rainfall, high humidity or dew is also necessary for infection. A minimum of six hours of suitable temperatures and leaf wetness is required for successful infection (Nunkumar, 2006). Soybean plants are most susceptible to infection by *P. pachyrhizi* during flowering. Therefore, three factors are needed to promote uredospore germination. Those are (1) the presence of uredospores, (2) conducive climatic conditions and (3) a plant that is currently within its flowering phenological phase (Duxbury *et al.*, 1990). Currently, the application of fungicides is considered the only effective control method in commercial soybeans.

To date extensive research has been undetaken on the epidemiology of SBR in South Africa (Nunkumar, 2006). A network of sentinel soybean plots has been established to provide an early warning system for the presence of SBR in soybean production areas (Craven, 2008) and reports of SBR infection have been recorded (Jarvie, 2009). However, no attempt has been made to map the long term climatic vulnerability of South Africa to SBR infection. This implies that soybean producers do not know the climatic vulnerability, nor the period of most risk for their area, and thus may not be managing the risk of infection appropriately. Soybean producers may be applying fungicides when conditions are not suitable for infection, resulting in unnecessary production costs, increasing the potential of the pathogen to develop resistance to fungicides and increasing the environmental impact of soybean production.

1.2 Aim and Objectives

The aim of this research was to develop a model to help soybean producers to better understand the climatic risk associated with SBR infection in their area. This may help producers to make better informed decisions regarding the application and timing of fungicides.

The objectives of this research were

1. To conduct a comprehensive literature review concerning the relationship between SBR and climatic conditions. This has been done in Chapter 2.
2. To develop a algorithm based on first principles that would give an indication of the daily climatic risk to SBR infection in SA. This algorithm was to be based on the most available climate data, *viz.* daily temperature and rainfall. This has been done in Chapter 3.
3. To evaluate the accuracy of the algorithm based on independent weather and SBR outbreak data. This has been done in Chapter 3.
4. To create spatial maps which illustrate the long term climatic vulnerability of different soybean production regions in South Africa, Swaziland and Lesotho to SBR infection. This has been done in Chapter 4.
5. To create time series graphs for selected key soybean production areas, which will allow producers to identify periods of high and low risk throughout the soybean production season. This has been done in Chapter 4.
6. To create a framework for the development of a near real time forecasting system which would eventually warn producers when climatic conditions were conducive for SBR infection, and thereby assisting them in the timing and application of fungicides. This is done in Chapter 5.

This research made use of data gathered through a literature review and SBR experiments conducted by other researchers, and no new SBR experiments were carried out. A forecasting system was not created as it was however, outside the scope of this study. The framework for the development of such a system was created to advise future research in the development of an early warning system for SBR.

2. A LITERATURE REVIEW OF SOYBEAN RUST AND DISEASE MODELLING

2.1 Soybean Rust Background

2.1.1 Economic importance

Soybean (*Glycine max* L.) is an important crop worldwide as it provides a relatively low-cost and nutritionally balanced source of protein (Sinclair, 1982). Soybeans are grown in temperate to tropical regions of the world, with production being highest in Brazil, China and the United States of America (USA) (Hartman *et al.,* 1999). South Africa produced an estimated 506 595 tons of soybeans on approximately 237 750 hectares in the 2008/2009 growing season (National Crop Estimates Committee, 2009). An additional 60 000 tons of soybean were imported in that season (National Crop Estimates Committee, 2009). Soybean is often rotated with maize or wheat as it has been shown to increase subsequent maize or wheat yields. Reductions in disease incidence, improved soil moisture content as opposed to leaving the fields open and nitrogen fixing are all considered beneficial properties of intercropping with soybeans (Duxbury *et al.,* 1990). If grown in suitable areas with good management, soybeans have the potential to be the most profitable field crop in KZN (Duxbury *et al.,* 1990).

However *Phakopsora pachyrhizi* Syd., the causal agent of SBR, is considered to be the most destructive foliar disease of soybeans because of its ability to spread rapidly and its potential to severely reduce yields (Miles *et al.,* 2003). In 1973, the Animal and Plant Health Inspection Services (APHIS) of the United States Department of Agriculture (USDA) declared SBR as one of the top 100 most dangerous exotic pests and diseases and the foremost threat to soybean (Anon., 2002). The pathogen reduces yield by causing premature defoliation of leaves, which decreases the number of filled pods and reduces the weight of seeds per plant. The severity of the disease depends on the time of onset and the intensity of the disease at particular stages of growth. When early infections and favourable climatic conditions occur, yield losses of 50% to 60% can occur (Kloppers, 2002). The USA estimates that losses from SBR of up to $7.1 billion a year could be incurred in that country alone (Miles *et al.,* 2003). In 2006, Brazil estimated losses of $2 billion for the 2005/2006 harvest. Although spraying of fungicides reduces seed loss, the cost of spraying reduces profit margins

(Tempra, 2006). With losses between 10% - 80% being reported and in some cases complete crop failure when mono-cropping was practised, it can be argued that SBR is a significant threat to soybean production in SA. If significant losses occur, then more soybean products need to be imported, resulting in an increase in the country's export deficit (Caldwell *et al.*, 2002).

2.1.2 History

Phakopsora pachyrhizi (*cf.* Figure 2.1), the causal organism of soybean rust, has been recognised in the orient for many decades. According to Bromfield (1984) it was first recorded by Bresadola, in the west, in 1881 under the name *Uredo vignae*. In 1903, Henning identified the fungus as *Uredo sojeo* and in 1914, Sydow and Sydow gave the name *P. pachyrhizi* to a fungus that was found on *Pachyrhizus erosus* L. (yam bean) (Bromfield, 1984). *Phakopsora pachyrhizi* is now the generally accepted name for the pathogen that causes SBR (Bromfield, 1984). Scientific research into *P. pachyrhizi* began in the 1940s. In the 1970s research increased as production and yield of soybean increased, and cultivation in areas previously not cultivated, commenced (Bromfield, 1984).

Figure 2.1 Electron micrograph of an echinulated *Phakopsora pachyrhizi* uredospore with a germ tube and appresorium (du Preez, 2005).

2.1.3 Geographic distribution

Soybean rust is considered a global epidemic (*cf.* Figure 2.2) (Miles *et al.*, 2003). Soybean rust has been recognised in Japan since 1902. In 1934 it was identified in several Asian countries and in Australia (Bromfield and Hartwig, 1980). In 1951 it was reported in India (Sharma and Mehta, 1996). By 1994 it was found in several fields in Hawaii. The first confirmed reports of SBR in Africa were recorded in Kenya, Rwanda and Uganda in 1996 (Levy, 2003). Soybean rust arrived in Zambia and Zimbabwe in 1998, in Nigeria in 1999 and in Mozambique in 2000 (Akinsanmi *et al.*, 2001; Levy *et al.*, 2002). In February 2001, SBR was identified in KZN in SA (Pretorius *et al.*, 2001). In March of the same year it appeared in Paraguay and Brazil (Morel *et al.*, 2004; Yorinori, 2004). By 2002 it was found throughout Paraguay and in limited areas in the north of Argentina (Rossi, 2003). In August 2004 there was a confirmed report of SBR in Colombia. On the 10 November 2004 SBR was found in the southern states of the USA, however it was too late in the season to have an effect on yields (Rogers and Redding, 2004). In 2007, SBR was found in Iowa and Illinois, the two major soybean growing states in the USA and in Canada, although it was again too late in the season to cause major yield losses (Anon, 2007; Negus, 2007).

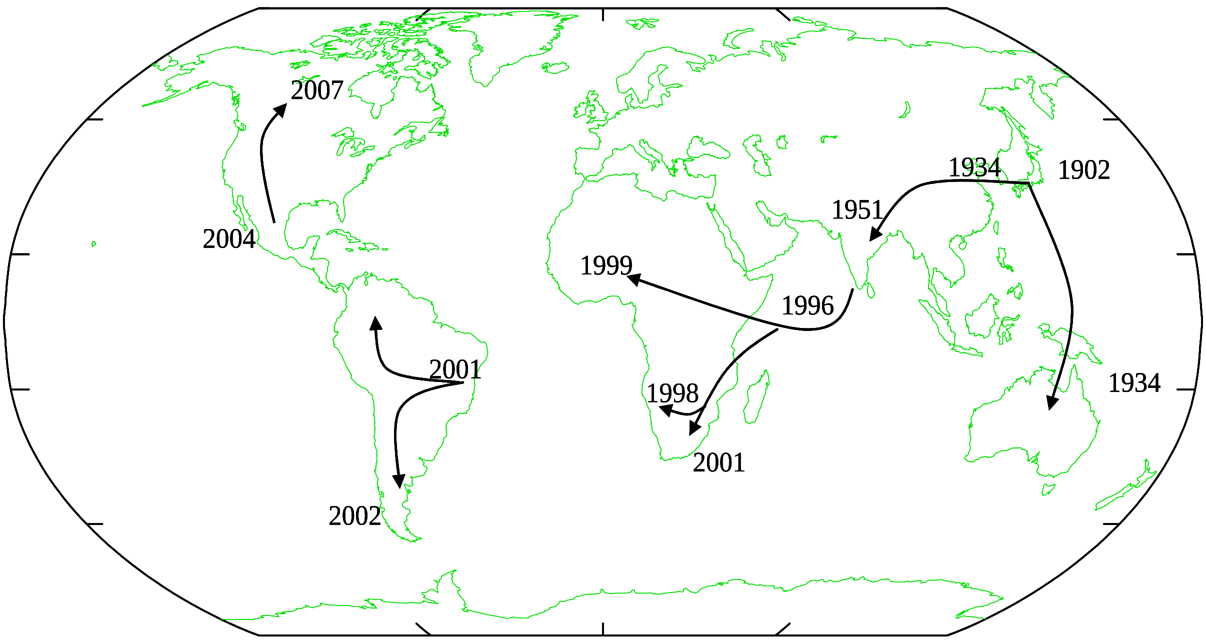

Figure 2.2 World map showing the spread of soybean rust from 1902 - 2007.

2.1.4 Soybean rust in South Africa

To date there has been no official effort to document the distribution of SBR in South Africa. The Soybean Rust Task Team, of the Protein Research Foundation, was established at a conference in Potchefstroom in 1998 after the arrival of SBR in Zimbabwe. This group supports a SMS network that alerts members when SBR has been positively identified in an area. These alerts have been collected from 2001 to 2009, with SBR being positively identified on commercial soybean crops every year. Figure 2.3 shows the distribution of SBR reports, with most being recorded in KZN and the eastern Highveld (Jarvie, 2009).

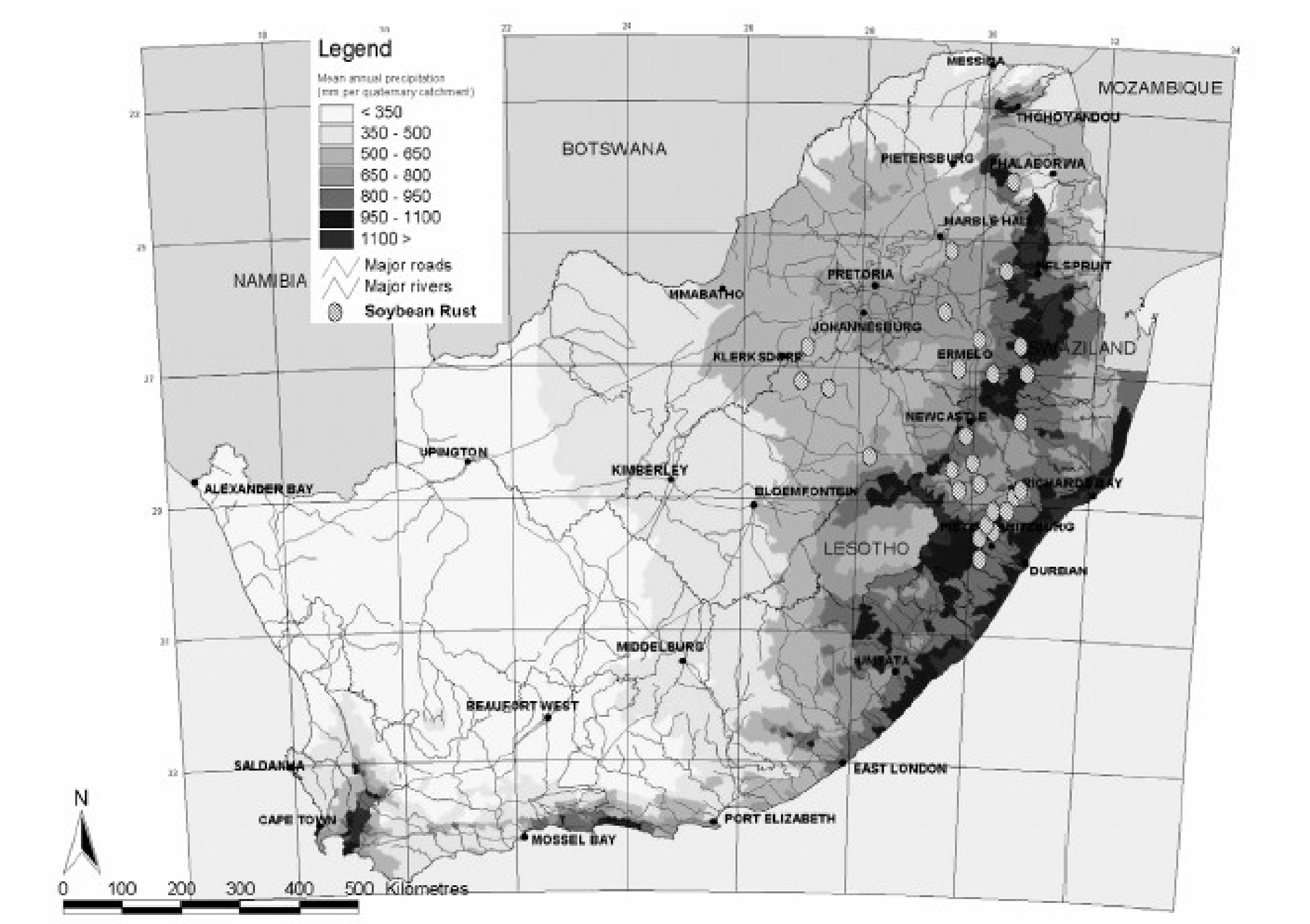

Figure 2.3 Distribution of locations of soybean rust reports in South Africa, from 2001 – 2008, superimposed over a map of mean annual rainfall (Jarvie, 2009).

2.2 Biophysical Processes of *Phakopsora pachyrhizi*

2.2.1 Symptoms

Early symptoms are small, water soaked lesions, mainly on the under surface (abaxial) of the leaf. Soybean rust usually infects older leaves at the base of the plant first and progresses upwards as the severity of the disease increases (Tichagwa, 2004). Lesions and pustules, restricted by the leaf veins, gradually increase in size and turn from grey to tan-brown in colour (Figure 2.4). Infected leaves turn bronze or yellow and eventually abscise. In severe cases of infection, lesions may also be found on pods, stems and petioles (Caldwell *et al.*, 2002). Clumps of brownish spores, called urediospores, are released from the pustules and can cause a visible cloud of rust spores when walking through an infected field. Patches of infected plants are highly visible in the field and are known as "hotspots". Once hotspots appear, it is usually too late to apply fungicides and little can be done to avoid major yield losses. Severity of the infection may be influenced by the soybean cultivar, the pathogen strain as well as environmental conditions (Sweets, 2002).

Figure 2.4 Soybean leaves showing chlorosis due to soybean rust (Frederick, 2008).

2.2.2 Host range

Phakopsora pachyrhizi is an obligate parasite and cannot live independently of a living host. In unfavourable conditions it must find an alternative host to survive (Agrios, 1997). The pathogen has an unusually wide range of hosts, compared to most other rust fungi that are normally host specific. Soybean rust is reported to naturally infect 95 plant species in 42 genera of legumes and 60 species of plants in additional genera when manually inoculated. Included in this is a common weed species in SA, *viz.* Kudzu vine (*Pueraria lobata* M&S) as well as a major crop species, the dry bean (*Phaseolus vulgaris* L.) (Hartman *et al.*, 2005). It is possible for the pathogen to directly penetrate its host, without finding an already existing opening, *e.g.*, a stoma or damaged area caused by insects or herbicides. This may be the reason why it has such a wide range of hosts (Koch *et al.*, 1983; Miles *et al.*, 2003). The high number of alternative hosts allows the possibility of a "green bridge" for inoculum reservation, where the disease can survive over winter, in a frost free area. This provides a source of spores for inoculum in the new planting season for areas with favourable summer conditions for infection (Pretorius *et al.*, 2007; Jarvies, 2009).

2.2.3 Life cycle and infection process

For *P. pachyrhizi* to successfully infect a host, a sequence of five events has to occur (Figure 2.5). These are (1) spore germination, (2) germ tube growth, (3) appressorium formation, (4) penetration and (5) colonisation after which new uredospores will develop. Each phase of development is influenced by biotic factors of the pathogen and the host, as well as abiotic factors such as environmental conditions (Nunkumar, 2006).

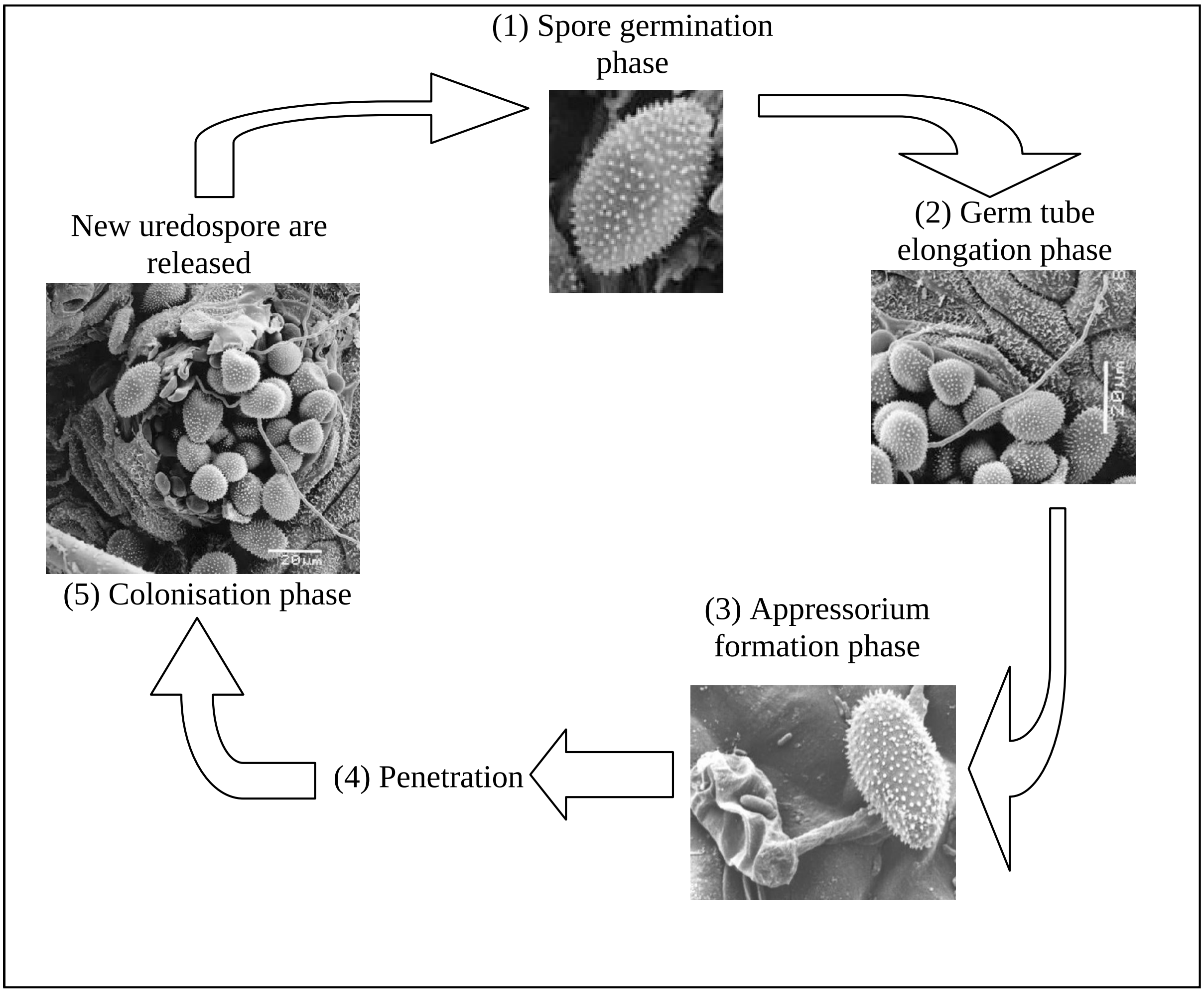

Figure 2.5 Life cycle of *Phakopsora pachyrhizi.*

2.2.4 Epidemiology

Conditions that support good growth and canopy development of soybeans also promote the development of SBR (Miles *et al.*, 2003). Soybean plants are most susceptible to infection by *P. pachyrhizi* during flowering. The onset of flowering is photosensitive and depends on the air temperature and the reduction in day length (Parsons and Birch, 1990). Flowering can last 3 to 5 weeks (Duxbury *et al.*, 1990). Extended photoperiods delay the germination of uredospores and the intensity of rust development, therefore, rust develops mostly at night (Tschanz and Tsai, 1982; Caldwell *et al.*, 2002). Pustules form on the leaves approximately nine days after infection and uredospores mature and become clearly visible 2 to 3 days later (Shanmugasundaram, 1999).

The ability to cause an epidemic is highly dependent on temperature and leaf wetness duration (LWD). These two environmental factors determine suitable infection periods. The timing of the first rain on the crop and the amount of rain also influence infection periods and severity. Moisture on the surface of the leaves is essential for spore germination, therefore, leaf wetness caused by humidity, dew, mist, rain or irrigation provides suitable conditions for spore germination. Uniform rainfall, throughout the season, promotes germination more compared to sporadic rainfall patterns (Wang and Hartman, 1992). A LWD of between 6 and 16 hours provides enough moisture for SBR to germinate (Nunkumar, 2006). The longer the LDW, the higher the chances of infection. Overhead irrigation can increase the chances of infection by extending the leaf wetness period (Killgore, 1995). Dry conditions can retard the development of SBR (Wang and Hartman, 1992). Relative humidity of between 75% and 95% provides adequate moisture for the germination of SBR (Nunkumar, 2006).

Temperature plays an important role in rust development. A temperature range between 19˚C to 28˚C has been identified as suitable for SBR germination (Bromfield, 1980). Optimum temperatures exist between 20˚C and 25˚C and a LDW of 6 hours or more (Nunkumar, 2006). Marchetti *et al*. (1976) states that after 6 hour, lesions began to develop on soybeans incubated at 18, 20, 23 and 28.5˚C. Temperatures outside of optimum presented greater lesion intensity after 8 hours of leaf wetness than after 6 hours. However, when temperatures are less than 15˚C or greater than 27˚C for extended periods, rust development is retarded, even if LWD is adequate (Wang and Hartman, 1992).

2.2.5 Disease triangle

For successful infection of *P. pachyrhizi* on a soybean plant, three basic conditions have to be met. These are firstly, suitable weather conditions, as discussed in Section 2.2.4 above. Secondly, the plant has to be in a suitable growth phase for infection. Thirdly, a source of inoculum needs to be present. This source of inoculum often comes from alternate hosts as *P. pachyrhizi* is an obligate parasite, so requires a live host to over-winter (Agrios, 1997). Figure 2.6 shows the interdependency of these three conditions. Infection will not occur if all three conditions are not adequately and simultaneously met.

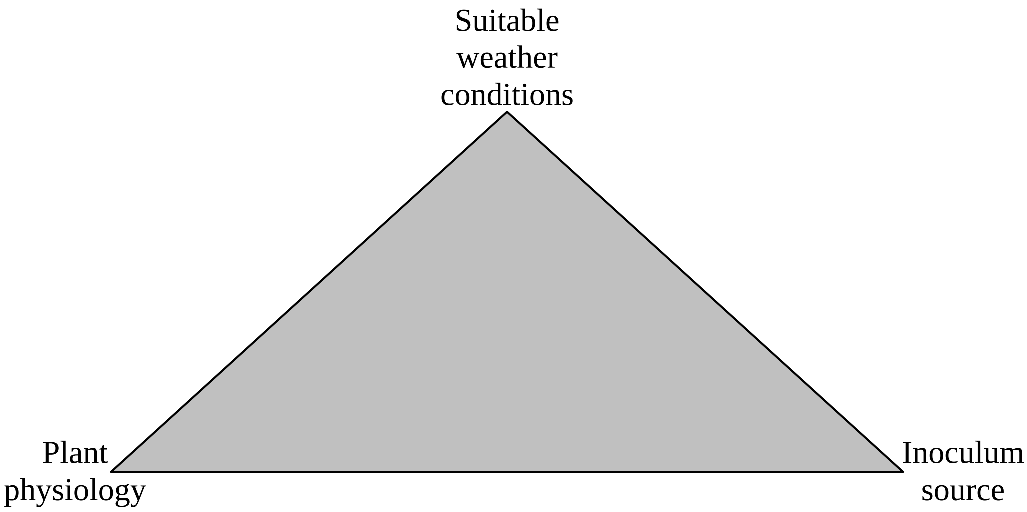

Figure 2.6 Disease triangle showing the three conditions necessary for soybean rust infection.

2.3 Disease Control

Soybeans have a narrow genetic base, therefore the possibility of finding and breeding durable resistance to SBR is presently limited (Singh *et al.*, 1995). Host resistance was first reported in the 1960s in field evaluations in Taiwan (Lin, 1966). Four genes that are resistant to *P. pachyrhizi* have been identified, however no commercially resistant cultivars are available (Miles *et al.*, 2003). Partial resistance or rate reducing resistance is also known in soybeans. In the field it provides moderate resistance as fewer lesions are found on plants throughout the season. Identification and utilisation of partial resistance, which may reduce yield losses caused by SBR, in breeding programmes is limited at present. Evaluation methods are time consuming and difficult to incorporate into current breeding programmes (Wang and Hartman, 1992; Hartman, 1995). Resistance is hoped to be the long term control of SBR, but at present there are no fully resistant commercial cultivars of soybean available, and moderate resistant cultivars are not always productive, having traits such as small seed size and viral disease susceptibility (Poonpolgul, 2004). The soybean genome was recently sequenced by the US Department of Energy in collaboration with several academic laboratories. This sequence is available to the public and it is now up to individual plant breeder to utilise the sequence to try develop SBR resistant cultivars suited to local conditions (USDE, 2009). Until resistance is developed, three agronomic methods are currently used to control SBR, *viz.* cultural, chemical and biological control.

2.3.1 Cultural control

Cultural control involves modifying current agronomic practices or adopting new practices to help prevent new incidences or progress of the disease (Bromfield, 1984). Such practices include:

- watering plants at noon to ensure that leaves have a chance to dry and hence do not extend the LWD,
- planting early maturing cultivars, thereby reducing the time available for the pathogen to infect,
- using soybean cultivars with short pod-filling stages,
- controlling weed hosts, and
- careful selection of planting sites, such as growing soybeans far away as possible from alternate hosts of SBR.

These practices may help reduce the chances of SBR infection (Bromfield, 1984; Anon., 2002).

2.3.2 Chemical control

Chemical control in the form of spraying fungicides is currently considered the most effective method of controlling SBR (*cf.* Figure 2.7). There are a number of registered fungicides in SA. Triadimenol, Flusilazole and Difenoconazole are some of the fungicides registered for SBR control in South Africa (Pretorius and McLaren, 2006). Spraying fungicides is most effective as a preventative control rather then a curative treatment (Bromfield, 1984; Hartman *et al.,* 1999). There is a window of approximately one week during which rescue spraying will be effective once rust has infected a field (Block, 2003). Most fungicides used in SA are sterol biosynthesis inhibitors (SBI) that may cause fungicide resistance in SBR (Caldwell *et al.,* 2002). Over or under dosage of fungicides may also cause resistance, which can also be passed onto other fungi (Caldwell *et al.,* 2002).

2.3.3 Biological control

Not much research has been undertaken on biological control of SBR. Thirty genera of fungi have been found inhabiting pustules of SBR infected plants, although it is not known how many are actually parasitic on the rust fungus (Littlefield, 1981). In addition, *Darluca filum* (Biv.) Castagne in the Far East does attack *P. pachyrhizi*, although it does not appear to mitigate yield losses. The probability of effective biological control in the near future is not high (Anon., 2002).

Figure 2.7 Manual preventative spraying of soybean rust (Miles *et al.*, 2003).

2.4 Modelling Soybean Rust

Models are simplified conceptual representations of reality. They represent complex features or systems in the environment in a simplified fashion. Modelling does not replace observation; rather it is a tool that can be used to help explain, aid understanding or give insight and meaning to observation (Hardisty *et al.*, 1993; Wainwright and Mulligan, 2004). Through modelling, distributions and patterns can be revealed across sets of data (Aspinall, 1991). Models can also be used to support the development and testing of hypotheses, as well as predictive estimates of the future. Modelling is a useful tool because observation is not always possible, feasible or ethical in the environment. For example, it would not be ethical to observe the spread of disease through an area by infecting that area and then observing the results (Wainwright and Mulligan, 2004). Modelling also provides a powerful way of managing resources, including crops (Hardisty *et al.*, 1993).

There are five basic steps in modelling, *viz.* (1) problem identification, (2) gestation (where background information is collected and an understanding of how the system works is gained), (3) model building (which is a cycle of development, testing and verification), (4) simulation and then (5) evaluation of results. Models can be built graphically, using boxes, links and flows. This way of modelling helps the user to easily conceptualise the problem and is often easier to use, especially for users without computer programming experience. Users with programming experience often construct models in computer code and tend to solve problems using mathematical equations (Wainwright and Mulligan, 2004). A good model explains a system as accurately as possible, while still remaining as simple as possible. The model developer determines which inputs are relevant to the proposed model. The greater the number of inputs, the more complicated the model and therefore care should be taken to only include those inputs which are relevant to the understanding of the system. An indication of the errors associated with the creation of the model, as well as the output is also important since it helps to give validity to the modelled data (Aspinall, 1991).

Some work on modelling of SBR has been undertaken, particularly in South America and in the USA, which mainly focused on modelling the potential severity of rust infections in anticipation of the arrival of the disease. Linear regression models, mechanistic simulation, neural networks and population dynamics have all been applied, using different input variables to develop accurate disease development and severity models. These models have identified three main correlated variables, *viz.* (1) the day the disease was observed, (2) the cumulative degree days for rust development and (3) the cumulative degree days for soybean development. This means that the plant's physiological development stage, temperatures above critical thresholds and spore availability were determining factors in SBR development in the Americas. Moisture which causes leaf wetness did not seem to be a limiting factor in these areas, although it was also closely correlated to the above three factors (Batchelor *et al.*, 1997; Kim *et al.,* 2005; Del Ponte *et al.*, 2006b). Whether models predict the severity of SBR using site specific models or calendar models, all models aim to predict and reduce the impact and risk associated with SBR.

Lalancette and Hickey (1986) suggested altering a plant growth model to simulate the development of the disease because the infection process of the pathogen is closely linked to the development of the host. Yang *et al.* (1991a) and Pivonia and Yang (2004) developed stimulation models, fuzzy logic models and empirical models to simulate soybean growth and more intensively, predict the potential severity of SBR in the USA in anticipation of its arrival. A soybean growth simulation model (SOYGRO) had been used to predict growth and yield of soybeans. This model was adapted into the SOYRUST model which was used to predict the daily increase in severity of an existing SBR infection based on environmental and pathogen related conditions. The SOYRUST model was linked to the SOYGRO model to simulate yield loss effects of SBR (Yang *et al.*, 1991a; Yang *et al.*, 1991b; Jun, 1999; Del Ponte *et al.*, 2006b).

Yang *et al.* (1990) used population dynamics to provide quantitative data about the relationship between disease outbreaks and climate data. This method requires few parameters as inputs. However, care must be taken when this is the case, as even small errors in the parameters will be amplified when predicting the variables which will be even further amplified when analysing these variables. Population dynamics was carried out in the USA to try to predict the potential impact of the disease, using minimum, maximum and average temperatures at 2 hour intervals.

Sutherst and Maywald (1985) developed a computer program, called CLIMEX, which was originally designed to predict the distribution and abundance of animals, based on biological data and geographical observations. CLIMEX provided a quick assessment of the climatic vulnerability of an area for a biological process. However, this was only at a gross scale of distribution and abundance (Sutherst and Maywald, 1985). This program was later used together with procedures developed by Pivonia and Yang (2004) to predict the likelihood of *P. pachyrhizi* surviving in different geographical areas in the USA. Using long term climate data, Pivonia and Yang (2004) determined the effect of accumulated stress on the ability of *P. pachyrhizi* to over winter on alternate hosts.

The NOAA ARL HYSPLIT_4 (National Oceanic and Atmospheric Administration, Atmospheric Research Laboratory, Hybrid Single-Particle Lagrangian Integrated Trajectory) model was developed to hind cast the likely source of spores that were responsible for introducing the pathogen to South America. This model proposed that the source of spores was from Africa (Pan *et al.*, 2004). The model was revised to forecast the dispersal of spores from central South America to areas in the north. The model was used on a weekly basis in 2005 to predict and map the likelihood of spores spreading into the USA (Pan *et al.*, 2005). The SRAPS (Soybean Rust Aerobiology Prediction System) model also simulates the movement and establishment potential of SBR spores in the Americas (Isard *et al.*, 2004).

In Brazil, Del Ponte *et al.* (2006b) developed a linear regression model to assess the correlation between disease severity and daily weather variables after the disease was detected. Daily maximum and minimum temperatures, cumulative rainfall over a period of 30 days and the number of rainfall events above 5 mm within that same period, were used. Analysis revealed that the number of rainfall events (used to predict leaf wetness) gave a better prediction of disease severity compared to the mean rainfall and temperature. This model also determined that rainfall was not a limiting factor for SBR development in Brazil. The model was practically applied to assess the spatial epidemic potential for specific sites in Brazil. Results showed that the main soybean production areas had a low to moderate infection potential based on climatic conditions. Conditions were also not conducive every year as spores did not over winter in these areas and had to migrate from further south every year (Del Ponte *et al.*, 2006b).

Pivonia and Yang (2006) incorporated the effects of temperature on the infection cycle of the pathogen into a model. Night time temperatures were used, which is important because SBR only infects at night. The model predicts the time frame of infection from disease onset. It assumes that spores are present in the air, early in the growing season, and hence available for infection. This is important when trying to model outbreak occurrences, as well as severity (Pivonia and Yang, 2006).

2.5 Conclusion

Soybean rust poses a substantial threat to soybean production in SA and other parts of the world, owing to its ability to severely reduce yields. Research had been undertaken on the biological and epidemiological characteristics of SBR, both in SA and in other countries around the world. This has resulted in an understanding of the symptoms, host range and infection processes of SBR. Research into different methods of control of the disease has also been undertaken. So far, no durable resistance to SBR in soybeans has been identified. Therefore, spraying of fungicides is currently considered the most efficient method of control.

Modelling is a powerful tool for identifying relationships between datasets as well as revealing patterns in data. Soybean rust models developed overseas include linear regression models, mechanistic simulation, neural networks and population dynamics to understand the relationship between weather variables, disease occurrence, severity as well as the impact on yields. These models have revealed that minimum and maximum temperature, the physiological stage of the plant as well as the spore availability was cumulatively necessary for infection. Moisture was also found to be an important, however not a limiting, factor in South America. The accuracy and reliability of the model depends on the accuracy of the input data and, therefore, it is vital to ensure that the input variables are correct and accurate. To date no model has been developed in SA which predicts the climatic vulnerability of different areas to SBR infection.

3. METHODOLOGY

The aim of the research was to develop an index to estimate the likelihood of soybean rust infection at a daily time scale based on daily minimum temperature (T_{min}), daily maximum temperature (T_{max}) and daily rainfall. Maps were to be generated, thereby allowing an assessment of the climatic vulnerability to SBR infection based on the availability of these variables. This section explains the steps taken to develop the algorithm. An overview of the databases used to derive the algorithm are given, followed by a brief explanation of the data preparation process. The extrapolation of hourly temperature data from daily temperature records is explained followed by the process undertaken to derive the index algorithms. Finally, the model verification and output processing are discussed.

3.1 Soybean Rust Database, Climate Databases and Disease Modelling

The accuracy and reliability of a model depends mostly on (1) the accuracy of the input data used and (2) on the reliability of the modelling techniques used. Temperature and leaf wetness are the two most important factors that determine suitable infection periods for the SBR pathogen (*cf.* Chapter 2). To develop and verify the index, two databases were used. (1) A temperature and rainfall database, from an automatic weather station operated by the Department of Agriculture and Environmental Affairs at Cedara, KZN. (2) A SBR outbreak database, collected through fungicide trials conducted at Cedara. An overview of these datasets is provided. The 50 year temperature database used to extrapolate hourly temperature data, used together with the 50 year rainfall database, to create the maps showing historical climatic vulnerability to SBR infection, will be overviewed.

3.1.1 Soybean rust outbreak database

When SBR arrived in SA, little research had been undertaken into the effectiveness of fungicides to control this pathogen in SA. Therefore, SA was unprepared to deal with the management of SBR (du Preez, 2005). Soybean populations are inbred and attempts to breed resistance have been unsuccessful. Spraying of fungicides is presently the only viable method of control (Hartman *et al.*, 1999).

Research was undertaken at Cedara (29˚ 32'S, 30˚ 17'E) to evaluate the efficiency of different fungicides used for SBR control. This area is well suited for fungicide research as it is located in a mist-belt, receives adequate rainfall and experiences night time temperatures conducive for *P. pachyrhizi* infection. The purpose of the research was to develop a database detailing the efficiency of a group of fungicides which underwent emergency registration for use when SBR was first identified in SA. The research aimed to determine the optimum dosage, optimum timing of dosages, as well as optimum number of fungicide applications for the control of SBR. This research was carried out from the 2001/2002 to the 2003/2004 growing seasons. Several plots were sprayed with different fungicides, in addition to there being a control plot in which no fungicide was sprayed (du Preez, 2005). Control plot data for the growing periods 2001/2002 and 2002/2003 were used in this study. The 2003/2004 growing season data were not used as these trials were conducted on different land and using different planting techniques (du Preez, 2005). Care was taken to ensure the same processes were used in preparing the plots for planting, planting techniques, weed control, disease assessment and harvesting (du Preez, 2005). Disease severity was determined by visually inspecting the plants twice weekly from the time of flowering to maturation. A rating scale developed at Cedara based on the position and density of pustules, as well as the level of defoliation of the plants, was used to assign infection ratings (du Preez, 2005).

3.1.2 Cedara weather station database

Climate data collected by an automatic weather station based at Cedara were used. These data include temperature, rainfall, relative humidity and leaf wetness at 15 minute intervals from 14/01/1998 to present time. The 15 minute interval values were analysed for each day to determine T_{min} and T_{max} values. Daily rainfall was also totalled for each day, from 08:00 to 08:00 the following day. These data, together with the SBR outbreak database, were used to derive the disease index algorithm.

3.1.3 Temperature database

Temperature is important for the development of SBR as daily temperatures less than 15˚C or greater than 27˚C are unsuitable for uredospore infection (Wang and Hartman, 1992). Schulze and Maharaj (2004) produced a 50 year period database, spanning from 1950 to

1999, of daily T_{min} and T_{max} for southern Africa. The spatial resolution of this dataset is one arc minute, thereby giving a grid of approximately 1.6 × 1.6 km covering SA, Lesotho and Swaziland. Below is a summary of the development of the temperature database that was used to map climatic susceptibility of SBR at different locations in SA.

First, raw data were obtained from

- the South African Weather Service (SAWS),
- the Institute for Soil, Climate and Water (ISCW), which is part of the Agricultural Research Council, and
- the South African Sugarcane Research Institute (SASRI) (Schulze and Maharaj, 2004).

A series of checks to ensure the data were reliable and as accurate as possible was undertaken. Errors were identified and marked for later correction and missing data were filled in. Some of the errors associated with the data included records where T_{max} values were less than T_{min} values and temperatures that had been recorded in degree Fahrenheit instead of degree Celsius. Checks were also done on suspect data, such as diurnal temperature ranges that were less than 1˚C, T_{min} and T_{max} both above or below 20˚C and temperatures that were the same (to the nearest 0.1˚C) for more than three consecutive days. These were marked for checking against values from surrounding stations and corrected if necessary. Temperatures greater than 45˚C were compared to temperature records from surrounding stations and if found to be vastly different, were marked for later correction. Physical data regarding the stations, such as latitude, longitude and altitude, were also verified (Schulze and Maharaj, 2004).

Using a lapse rate correction, daily temperature values were estimated for areas where no data were available. The lapse rate is the rate of change in temperature with respect to altitude (South African Weather Bureau, 1965). The environmental lapse rate is accepted as -6.5˚C per 1000 m increase in altitude. However, this is affected by local factors, such as location, season, time of day, topography, relative humidity and cloudiness (South African Weather Bureau, 1965). Therefore, based on research by Clemence (1986), Schulze and Maharaj (2004) delineated 11 different lapse rate regions for SA, each with a monthly lapse rate for maximum and minimum temperature.

Once these lapse rates had been established, steps were taken to determine temperature values for areas where there were no measurements (target stations). A total of 973 stations were selected that had temperature records greater than 1500 days, *i.e.*, roughly 50 months or 4 years (Schulze and Maharaj, 2004). The records were extended to the period of 1950 to 1999. Using target and control stations a method, developed by Schulze and Maharaj (2004) called Difference in Standard Deviation Method (DSDM), was used to fill in areas with no data or replace data marked as erroneous. The target stations were ranked according to the difference in the 12 month standard deviation of daily temperature compared to the control station, and the station with the lowest difference in a specific month used to fill in missing data. Estimated temperatures were then checked according to criteria specified by Schulze and Maharaj (2004). These data could then be used to determine hourly temperature values.

3.1.4 Rainfall database

Rainfall, often represented as mean annual precipitation (MAP in mm.a^{-1}) is important as it gives an indication of the overall moisture condition within an area. It also influences the overall type and condition of vegetation in an area. However, MAP is a gross figure and limited in its ability to simulate daily events dependent on rainfall. Lynch (2004) developed a standardised daily rainfall dataset for input into hydrological simulation models, using varies techniques, including Geographic Information Systems (GIS). This dataset has three categories of data, *viz.*,

1. temporal point data that were recorded at a specific site,
2. infilled temporal point data that is estimated for a site where no gauge is present, and
3. spatial rainfall values, represented as a raster.

1. Temporal point data

The four sources of rainfall data used in the development of the rainfall database were

- the South Africa Weather Services (SAWS),
- the Agricultural Research Council (ARC),
- the South African Sugar Research Institute (SASRI), and
- various municipalities, private companies and individuals (Lynch, 2004).

Records from a total of 12 153 stations were used which, when combined into a single database, had in excess of 100 million observed values. Errors in the data were identified and corrected (Lynch, 2004). Missing data were filled in using the preferred methods of expectation maximisation algorithm (EMA) and median ratios. The EMA method repeatedly calculates the linear regression between target and control stations until a best fit is found. The median ratio method uses a ratio of the mean monthly median of control and target station. The daily rainfall is adjusted using this ratio. When these methods were not suitable, the inverse distance weighted algorithm (IDW) and monthly infilling techniques were used. The IDW method is based on the generally accepted geographic principle that features closer together are more similar than those that are further apart (Tobler, 1970). Therefore IDW assumes that stations closer together are more likely to have similar data than stations further apart (Johnston *et al.*, 2001). Therefore the missing values are filled in according to the geographically closest station (Lynch, 2004). The monthly infill technique uses a regression equation from surrounding stations to calculate the missing daily data. If the rainfall is less than 2 mm, then it is assigned to the first day and the rest of the month records no rainfall. Refer to Lynch (2004) for a more detailed account of these methods. After filling in missing data, the number of rainfall records increased to over 341 million values (Lynch, 2004).

ii. Filled in temporal point data

In order to create a continuous data set that could be incorporated into a spatial dataset, rainfall figures needed to be calculated for areas where no stations were present. Rainfall figures for areas without rainfall records can be estimated using interpolation and regression techniques (Lynch, 2004). In areas of relatively uniform topography and high density of rainfall stations, the IDW technique was used, as described in Section 3.1.4i (Johnston *et al.*, 2001). However, in areas with a more complex topography and fewer rain gauges, a regression technique was used. The regression technique builds relationships between variables, based on explanatory principles defined by Lynch (2004).

iii. Spatial rainfall values

Temporal rainfall values were converted into a raster which represented the spatial distribution of rainfall over southern Africa. A geographic weighted regression (GWR) approach was used, based on an algorithm which included a series of explanatory principles to represent the distribution of MAP. The result was a one arc minute raster which represented the spatial distribution of MAP in southern Africa (Lynch, 2004).

3.1.5 Integrating the temperature and rainfall databases into a Southern African quinary catchments database

The South African Quinary Catchment Database was developed by the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal, (Schulze *et al*., 2009). This database outlines a hierarchical system of catchments where each of the 1946 quaternary catchments (4th level sub-basin) was subdivided into three quinary catchments (5th level sub-basin) using Jenk's optimisation (Schulze and Horan, 2009).

The daily rainfall database developed by Lynch (2004) and described in Section 3.1.4 was integrated with the quinary catchment (QC) database to provide a single rainfall record for each QC (Schulze *et al.,* 2009). The most suitable rainfall station was selected for each QC by identifying the centroid within each QC and then identifying the closest 10 rainfall stations to that centroid. The 10 stations were then ranked according to the following multi-criteria selection approach (Kunz, 2004; Schulze *et al.,* 2005; Wartburton and Schulze, 2005; Schulze *et al.,* 2009):

- Distance of station to centroid,
- Length of station's rainfall record (number of years),
- The time period of the record (which years),
- Similarity between the station's mean annual precipitation (MAP) and the corresponding raster based estimate derived by Lynch (2004),
- Proportion of observed values to infilled values,
- Topography of the catchment (difference between station altitude and average altitude of the QC), and
- Prevailing direction of known weather systems

The highest ranked station was used to represent the entire quinary (Schulze *et al.,* 2009).

The temperature database developed by Schulze and Maharaj (2004) and discussed in Section 3.1.3, was integrated with the quinary catchments in order to provide a daily temperature value for each quinary for the 50 year period from 1950 to 1999. A grid point close to the centroid of each quinary was selected. The altitude of this point was taken, and assumed to be representative of the entire quinary (Schulze *et al.,* 2009). Then, 50 years of daily temperature values from the Schulze and Maharaj (2004) database were assigned to the quinary at the selected point.

3.2 Trial Data Preparation

In order to develop the SBR index, two separate groups of data were needed *viz.*(1) one for the development of the index and (2) a second independent set for to verify the index. Soybean rust outbreak data, which were collected by du Preez (2005) during SBR fungicide trials at Cedara during the 2001/2002 and 2002/2003 growing season were used. A graph of the data was created in order to compare the two data sets. Figure 3.1 and Table 3.1 reveal that the two datasets are similar in structure, with similar means, maximums and standard deviations. Data were collected during two different soybean growing seasons each with a new season of crops and are therefore independent in time (du Preez, 2005), but not in space. The data were divided into two groups, according to the soybean growing seasons. The 2001/2002 growing season was used for developing the algorithm while the 2002/2003 growing season was reserved to verify the algorithm.

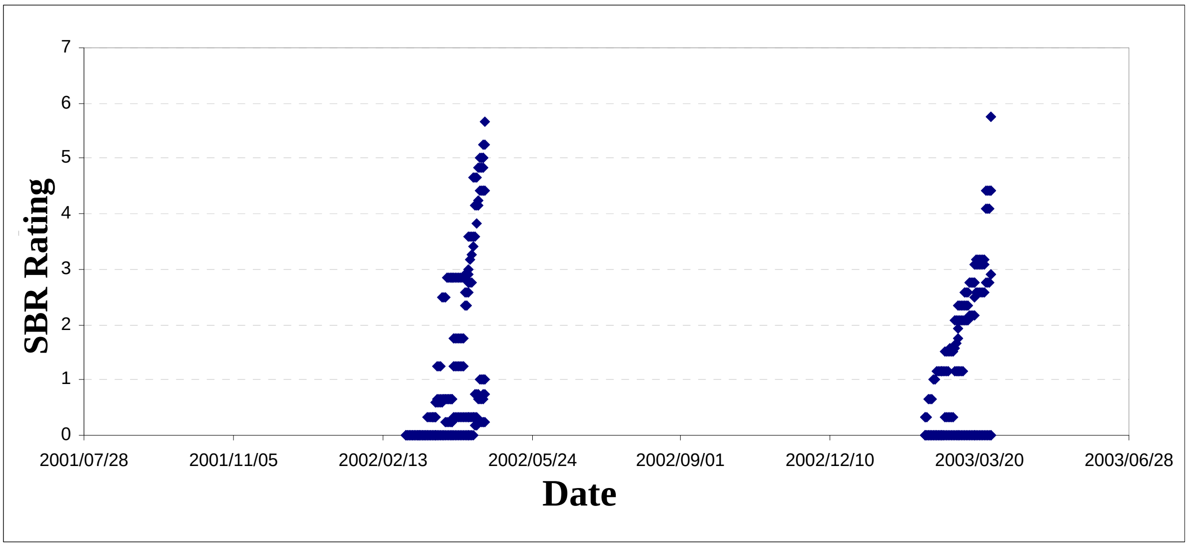

Figure 3.1 Trends in soybean rust outbreak ratings over the two soybean growing seasons.

Table 3.1 Statistical information from the 2001 - 2002 and 2002 - 2003 soybean growing seasons

	2001 – 2002 Growing Season	**2002 – 2003 Growing Season**
Maximum	5.67	5.75
Mean	0.86	1.05
Standard deviation	1.42	1.35

3.3 Algorithm Development

An algorithm based on first principles gathered from the literature (*c.f* Chapter 2) was developed. The algorithm is sensitive to temperature, with conducive temperatures between 15˚C and 28˚C and optimum temperatures between 20˚C and 25˚C (Bromfield, 1980; Wang and Hartman, 1992, Nunkumar, 2006). Leaf wetness, of at least 6 hours, is essential for uredospore germination (Wang and Hartman, 1992). Since leaf wetness data are not readily available, it was decided to use rainfall as an indication of leaf wetness because rainfall would either land directly on the leaves or would indirectly result in evaporation and high humidity, causing leaf wetness. This approach is limited and it is recommended that further research be undertaken to account for other forms of moisture, such as mist, humidity and dew.

Soybean rust uredospores are photosensitive and therefore SBR only develops at night (Tschanz and Tsai, 1982; Caldwell *et al.*, 2002). It was necessary to disaggregate daily T_{min} and daily T_{max} into hourly values in order to isolate the vulnerability of the night time hours only. Each day's data stretched from 07:01, through the day and ended at 07:00 the next morning. This was done to keep all the night time hours together.

The daily temperatures from Cedara were disaggregated into hourly temperatures using the sine-log equations developed by Linsley-Noakes *et al.* (1995). This equation is based on the principle that the daytime solar cycle follows a sine-curve from sunrise to sunset (*cf.* Eq. 3.1).

$$T_t = (T_{max} - T_{min}) \times \sin\left[\frac{(\pi\ t)}{L + 4}\right] + T_{min} \qquad (3.1)$$

where: T_t = Temperature at time (t) after sunrise (˚C)
T_{max} = Daily maximum temperature (˚C)
T_{min} = Daily minimum temperature (˚C)
t = Time after sunrise (hours)
L = Day length (hours).

A second equation (Eq. 3.2) was used to determine night time temperature (Lindsey-Noakes *et al.*, 1995).

$$T_t = T_s - \frac{(T_s - T_{min})}{\ln(24 - L)} \times \ln(t) \qquad (3.2)$$

where: T_t = Temperature at time > 1 hour after sunset (˚C)
T_s = Temperate at sunset (˚C) (derived from Eq. 3.1)
T_{min} = Daily minimum temperature (˚C)
t = Number of hour after sunset (hours)
L = Day length (hours).

Sunrise and sunset were calculated using the FAO 56 method (*cf*. Eq. 3.3 - Eq. 3.8) (Allen *et al.*, 2006).

Day light hours *(N)* is calculated by

$$N = \frac{24}{\pi}\omega_s \qquad (3.3)$$

where: ω_s = sunset hour angle in radian.

The sunset angle *(* ω_s *)* is calculated by

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)] \qquad (3.4)$$

where: φ = latitude in radian

δ = solar declination in radian.

Radian latitude *(* φ *)* is calculated by

$$\varphi = \frac{\pi}{180}[\text{decimal degrees}] \qquad (3.5)$$

Solar declination (δ) is calculated by

$$\delta = 0.409\sin\left(\frac{2\pi}{365}\right)J - 1.39 \qquad (3.6)$$

where: J = Julian days (the number of the day of the year).

Sunrise and sunset are estimated from day length (L). Solar noon (12:00) is assumed to be the middle of the day, therefore sunrise is calculated as

$$Sunrise = Solarnoon - \left(\frac{L}{2}\right) \qquad (3.7)$$

Sunset is calculated as

$$Sunset = Solarnoon + \left(\frac{L}{2}\right) \qquad (3.8)$$

As an indication of darkness, it was assumed that if the sun rises within the first 30 minutes of an hour period, then that period was considered light. If the sun rises after the first 30 minutes of the hour, that period was considered dark. If the sun sets within the first 30 minutes of the hour period, that period was considered dark. If the sun sets after the first 30 minutes of the hour, that period was considered light. A darkness indicator (D) assumes the value one when the hour is considered dark and zero when the hour is considered light.

3.4 Index Calculations

An hourly temperature index was designed to combine the influences of the hourly temperature and darkness. Equation 3.9 depicts how this index (I_h) was calculated. This index gives an indication of the vulnerability to SBR infection, based on temperature and darkness, for SBR germination, for each hour.

$$I_h \begin{cases} 0 & if \quad T \leq 15 \\ D \times (T - 15) \times 0.2 & if \quad 15 < T \leq 22 \\ D \times 1 & if \quad 22 < T \leq 25 \\ D \times (T - 25) \times 0.333 & if \quad 25 < T \leq 28 \\ 0 & if \quad T > 28 \end{cases} \tag{3.9}$$

where: I_h = Temperature index for hour h
T = Hourly temperature (˚C)
D = Darkness indicator.

If it was light, an index value of zero was assigned regardless of the temperature, as SBR uredospores cannot germinate and therefore infect under light conditions. If it was dark and temperature was within the optimum range (between 20 ˚C and 25 ˚C), then an index value of 1 was assigned, representing optimum germination conditions. If it was dark and temperatures were in the suitable range (*i.e.* between 15˚C and 20˚C; or 25˚C and 28˚C) then an index value between 0 and 1 was assigned depending on the closeness of the temperature to optimum (Figure 3.2). Therefore, the index value gives a representation of how suitable an hour was for infection, with 1 being most suitable and 0 being most unsuitable.

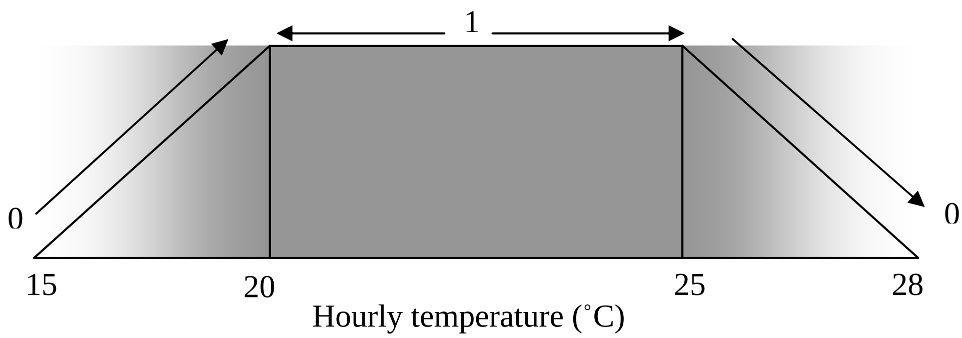

Figure 3.2 A graphic depiction of the hourly temperature index for soybean rust during dark conditions (*cf*. Eq 3.9).

Hourly temperature indexes from hour 1 (representing 7:01 – 08:00) to hour 24 (representing up to 06:01 - 07:00 the following morning) were totalled for each day to derive a daily temperature index (I_T, *cf*. Eq. 3.10).

$$I_T = \sum_{1}^{24} I_h \qquad (3.10)$$

where: I_T = Daily temperature index

It was also important to include the influence of rainfall, as an indicator of leaf wetness, since leaf wetness is essential for uredospore germination (Wang and Hartman, 1992). Equation 3.11 was used to incorporate the influence of rainfall into the algorithm.

$$I_R \begin{cases} I_T \times 2 & if \quad R > 0 \\ I_T & if \quad R = 0 \end{cases} \qquad (3.11)$$

where: I_R = Rainfall index

R = Rainfall ($mm.d^{-1}$)

I_T = Daily temperature index (Eq. 3.10)

If any rainfall occurs the equation multiplies the daily temperature index by two, indicating that all basic conditions for SBR have occurred, namely darkness, suitable temperature as well as leaf wetness. On the other hand, if only darkness and temperature conditions were met the index is smaller. If none of the conditions were met, or it was light, a value of zero is assigned. The multiplication of two was based on expert knowledge of SBR, and assumed that any rain would either wet the leaves directly or cause evaporation which would facilitate leaf wetness. More research is needed to verify this assumption. This includes new trials and falls outside the scope of this study. The results of the index were compared graphically to the results of the SBR rating trials conducted at Cedara (*cf*. Graph 4.1 in Section 4.1).

A threshold of I_R = 12 was selected as a conservative value from which conditions are suitable for SBR infection. The reasoning for this is that there is a maximum of 10 hours of darkness during spring and summer, and the maximum hourly temperature index is 1, without rainfall. Thus, even if all the hours in a night have an optimum temperature for SBR infection, the maximum for a night can only be 10. However, with rainfall, the maximum hourly index can be 2 (*cf*. Eq. 3.11). Therefore, a minimum of six hours of conducive temperatures and rainfall (6 hours × 2) is required to reach a minimum threshold of 12. Six hours of conducive temperatures and leaf wetness is the minimum requirement for SBR infection (Marchetti *et al.*, 1976; Nunkumar, 2006).

3.5 Verification of the Algorithm

Data from the SBR trials during the 2002/2003 growing season at Cedara were used to verify the model. Temperatures were disaggregated using the Linsley-Noakes *et al.* (1995) method and a darkness indicator was calculated using the FAO 56 method (Allen *et al.*, 2006) as described in Section 3.3. Model algorithms were then applied to the 2002/2003 data using the same methods as described in Section 3.4. The results of the index were compared to the results of the SBR rating trials conducted at Cedara in a graph (*cf*. Graph 4.2 in Section 4.2.1).

The algorithm and associated maps (*cf.* Section 4.3) were shown to members of the Protein Research Foundation SBR task team who agreed that the algorithm seemed to be accurately representing the actual conditions for SBR germination (van Rij, pers. Comm.). Verification of the index was limited because of a lack of data, as SBR outbreak data of only two growing seasons were available for the same area. Further research is needed to further verify this algorithm; however that is beyond the scope of this project.

3.6 Accuracy Assessment

An accuracy assessment was carried out in order to determine the reliability of the SBR forecast. The hit score method was decided upon based on the nature of the SBR forecast. The SBR forecast is a discrete-deterministic forecast, stating whether or not an event will occur (Mason, 2002), *i.e.* there will be rust within 14 days. Verifying this forecast involves asking the question, "Did SBR occur within 14 days of suitable index values being recorded?" Table 3.2 shows the possible answers to this question.

Table 3.2 Possible hit score outcome

	Forecast	
Observed	Rust	No Rust
Rust	Hit	Miss
No Rust	False alarm	Correct Rejection

Weather data were collected from an automatic weather station situated at Pannar Seed (Pty) Ltd, in Greytown from 1 October 2000 until 31 March 2009. Owing to weather station malfunctions, data were not collect for the period 17 October 2005 to 31 January 2006. As a result, the 2005/2006 soybean growing season was excluded from this verification. Soybean rust infection data were collected from the soybean sentinel plots also situated at Pannar. These trials were monitored weekly and any signs of disease were recorded and reported to the Protein Research Foundation SBR Task Team. Unfortunately, because the plants were only inspected once a week, there could have been a one week lag period from when infection actually occurred to when it is reflected in the data. The weather data were run through the SBR algorithm (as described in Section 3.3) and daily index values were obtained. This was overlaid with the recorded SBR infection data.

Unfortunately, it was not possible to determine the flowering date of the soybean trials as this had not been recorded by Pannar. Therefore, the 1st of January was assumed to be the date from which soybean plants were susceptible to infection. This date was assumed because the plants will only start to flowering once day length begins to decrease. The 21st of December is the longest day of summer, after which day length begins to decrease. Flowering will initiate a few days after the day length begins to decrease and is largely dependent on the soybean cultivars, planting date and a combination of environmental factors including air temperature. The 1st of January is a conservative date and may lead to more “False alarms” than are actually true. A hit score table was drawn up. The table was totalled and the hit score results calculated using Equation 3.12 and Equation 3.13.

$$\text{HIT} = \frac{\text{Number of correct forecasts}}{\text{Total number of forecasts}} \times 100 \quad 3.12$$

$$\text{FALSE ALARM} = \frac{\text{Number of false forecasts}}{\text{Total number of forecasts}} \times 100 \quad 3.13$$

3.7 Model Application

The algorithm was programmed in Fortran and automated to use the Schulze and Maharaj (2004) temperature database and the Lynch (2004) rainfall database as input for climate data. It was decided to map the period from the beginning of October to the end of April since this overlapped with the soybean production season. Twenty four intervals were selected, at two week intervals from the beginning of October until the end of December, when the risk of SBR was believed to be moderate, and at one week intervals from the beginning of January until the end of April, when the risk of SBR is high. Table 3.3 summarises these dates.

Table 3.3 Date intervals used to calculate a soybean rust index for South Africa, Lesotho and Swaziland.

Interval	Date	Interval	Date
1	25 September – 9 October	13	5 February – 11 February
2	10 October – 23 October	14	12 February – 18 February
3	24 October – 6 November	15	19 February – 25 February
4	7 November – 20 November	16	26 February – 4 March*
5	21 November – 4 December	17	5 March – 11 March
6	5 December – 18 December	18	12 March – 18 March
7	19 December – 31 December	19	19 March – 25 March
8	1 January – 7 January	20	26 March – 01 April
9	8 January – 14 January	21	02 April – 08 April
10	15 January – 21 January	22	09 April – 15 April
11	22 January – 28 January	23	16 April – 22 April
12	29 January – 4 February	24	23 April – 29 April

* The 29th of February (leap years) were included in this interval

The model output showed the number of years out of 50 years (for the period 1950 to 1999) during which every quinary in SA reached a threshold of I_R = 12 for a period of two days. This was repeated for each interval in Table 3.3. The results were mapped using Arcview 3.3 and represented as a percentage of years where the minimum threshold was met. Three different regions were mapped separately *viz.* KwaZulu-Natal, the northern soybean producing regions and the central soybean producing regions. This allows users to view their areas of interest in more detail. Although areas currently not under soybean production were excluded, the data are available for these areas and can be mapped. Various researchers working on SBR were asked to comment on the accuracy of the maps and for suggestions on the best way to present the maps to various target groups, e.g. Soybean producers (van Rij, pers. Comm.).

3.8 Time Series Graphs at Key Soybean Production Areas

Key soybean production areas were selected in each region. A central quinary catchment for each area was located and the data from that quinary were extracted for each of the 24 intervals in Table 3.3. The data were represented on a time series graph, to show the development of the rating over the soybean growing season (from October to April) for each area. This gave a risk profile for the area over time, allowing soybean producers to identify periods of high risk ratings in their areas, where climatic conditions are conducive for SBR infection.

3.9 Conclusion

This chapter has described the methodology that was undertaken to derive the results of this study. Overviews of the databases used to develop, verify and map the algorithm have undertaken. A detailed account has been given of how data was handled within the model and how values such as sunrise and sunset calculated. The algorithm development and verification process has been described and an accuracy assessment carried out. The graphs resulting from the development of verification process are given in the results chapter which follows. The results of the accuracy assessment are also given in the following results chapter. The mapping process has also been described allowing readers to better understand the content and format of the maps. All the results as well as an interpretation are presented in the following chapter.

4. RESULTS AND DISCUSSION

4.1 Algorithm Development

Figure 4.1 shows the SBR Index (I_R) and actual recorded SBR outbreaks during the 2001/2002 season. Soybean rust requires a reasonable short, but sustained period of suitable conditions for infection. At least 6 hours of leaf wetness and suitable temperatures are required (Nunkumar, 2006). A minimum index value (I_R) for the development of SBR of I_R = 12, represents a minimum of 6 hours of suitable temperature and darkness, (*cf.* Section 3.6). Point j in Figure 4.1 shows where the SBR infection became visible 14 days after thresholds of I_R = 12 were sustained for at least 2 days (Point i).

Point a and c in Figure 4.1 shows that conditions for SBR germination were not suitable throughout October and November, with only a few days exceeding an index value of 10 (Point b). Point d shows how index values in December start to increase, with a greater number of days exceeding a value of 10 and a few days exceeding 14 (Point e). However, these index values are not sustained, the index soon drops to values of below 8 again (Point f). January experiences the first day that exceeded an index value of 15 and limited consecutive days where values above 12 are sustained (Point g). However, SBR uredospores may have not start germinating as the soybean plants were not yet at the susceptible flowering period. February shows mostly low index values, with a one day peak of 15 and another one day peak of 16 (Point h). The index starts to rise above 10 from 26/02/2002. The first sustained period of high values, with all days above 12, occurs from the 01/03/2002 to 03/03/2002 (Point i) followed by another three day period of high index values on 21/03/2002 (Point k). The first of the SBR ratings (Point j) occurs approximately 12 days after the first sustained peak of high ratings (Point i). Therefore it appears that Point i represents the climatic conditions which were suitable and triggered infection, which became evident 12 days later represented by Point j. This trigger can be substantiated by Shanmugasundaram (1999) as well as Caldwell and Laing (2002), who observed uredospores on soybean leaves approximately nine days after infection and these uredospores matured and became clearly visible two to three days later. It therefore appears that a period of at least 2 days with consistent high index values (above 12) initiates the SBR outbreak, if the plants are susceptible to infection.

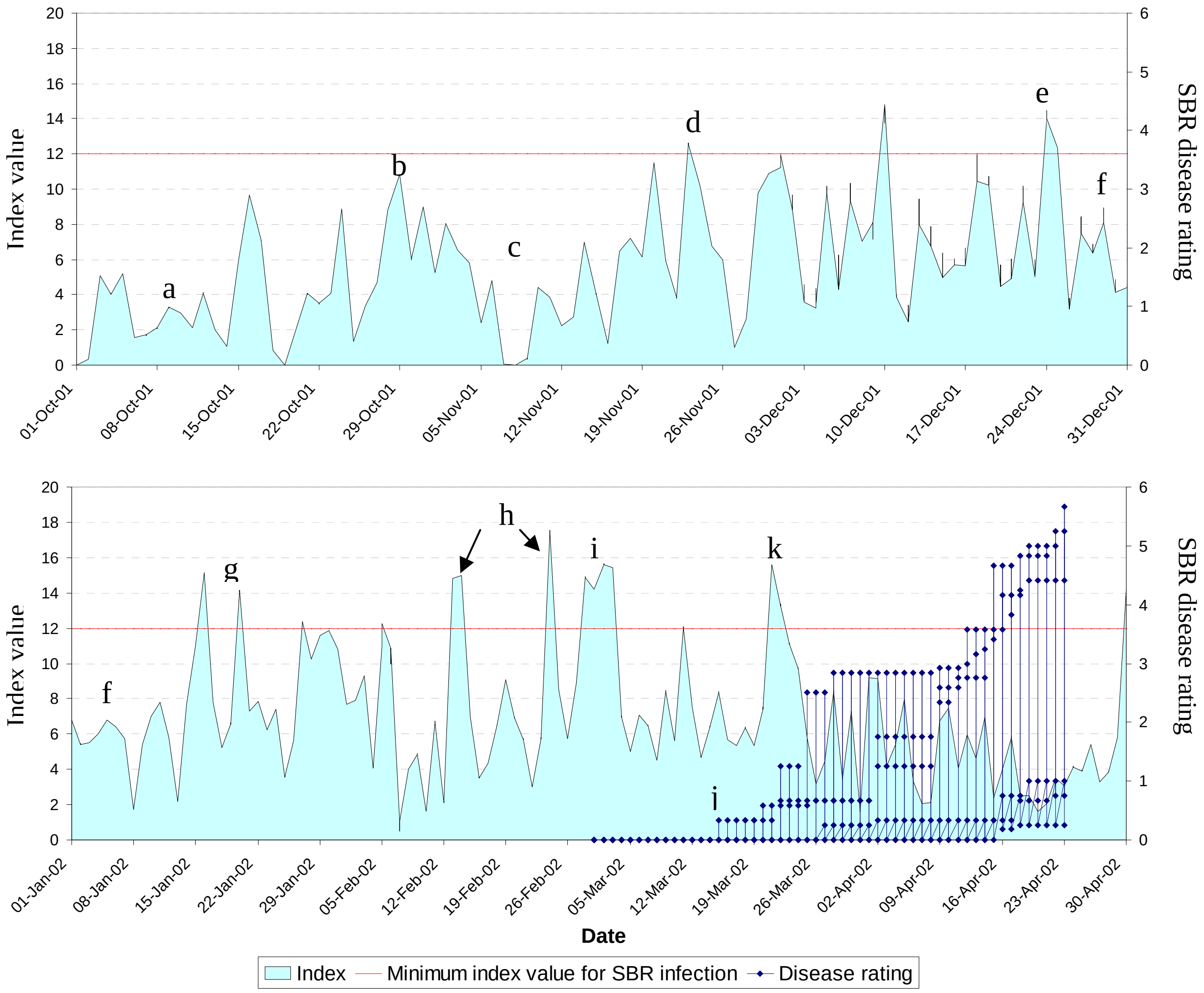

Figure 4.1 Comparison of index values and soybean rust ratings for the Cedara growing season 2001/2002, split into the first and second half of the season with letters a to k explained in the text.

4.2 Algorithm Verification

4.2.1 Independent season at Cedara

Figure 4.2 shows the SBR Index (I_R) and actual recorded SBR outbreaks during the 2002/2003 season. Figure 4.2 shows similar trends to Figure 4.1. Point a, of Figure 4.2, shows low index values during October and November with no days exceeding a value of 10. During the latter part of December, the values start to exceed 12 (Point b) and there is a four-day period from 30/12/2002 to 02/01/2003 (Point c) where values between 15 and 17.5 are experienced. However, SBR uredospores could not start germinating as the soybean plants were not yet at the susceptible flowering period. January also experienced two single day peaks, *i.e.* on 08/01/2003 (Point d) and 19/01/2003 (Point f), exceeding values of 14 although a majority of the index values range between 6 and 11. The gap in the index at Point e was checked and is attributed to unseasonably low minimum and maximum temperatures (11 ˚C and 15 ˚C, respectively). Point g shows index values start to exceed 12 from 31/01/03 and from 02/02/2003 to 04/02/2003 with a period of three days of values exceeding 15. This is followed by a period of four days (05/02/2003 to 08/02/2008) where index values exceeded 12. Point h shows that approximately thirteen days after the start of the sustained peak, SBR was observed. This, again, can be substantiated by Shanmugasundaram (1999), who observed uredospores on soybean leaves approximately nine days after infection. These uredospores matured and became clearly visible two to three days later. During the independent season (2002/2003) the algorithm shows similar forecasting capabilities compared to the 2001/2002 season. The algorithm managed to generate a number of index values above 12 approximately 14 days prior to an observed outbreak. This was achieved even though the SBR outbreaks in the two seasons were approximately one calendar month apart.

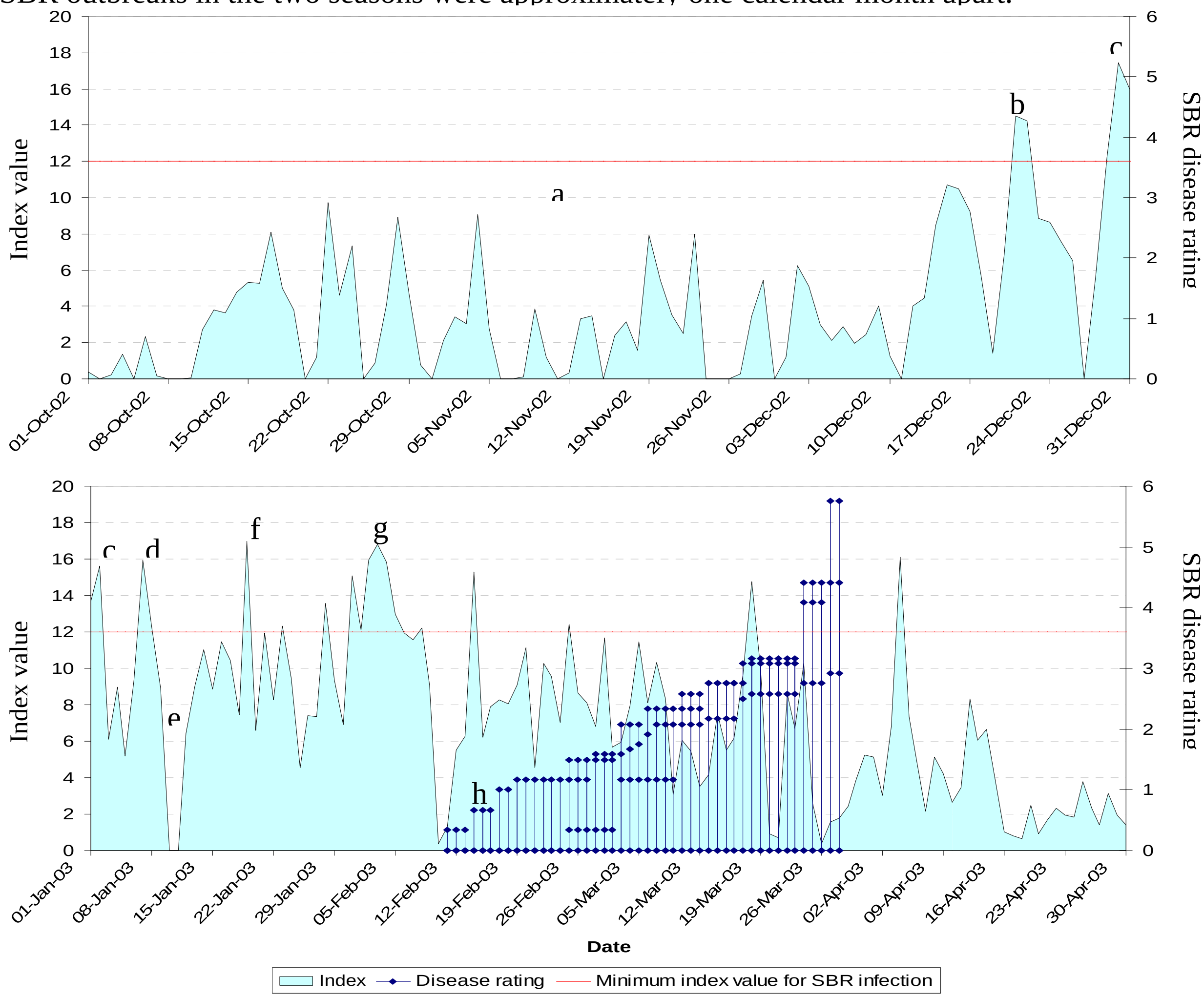

Figure 4.2 Comparison of index values and soybean rust ratings for the Cedara growing season 2002/2003, split into the first and second half of the season with letters a to h explained in the text.

4.2.2 Results of accuracy assessment

Table 4.1 illustrates the results of the hit score count conducted on soybean rust sentinel trials at Pannar Seed Company (Pty) Ltd, in Greytown for the period 2000 to 2009 (excluding the 2005/2006 season) (*cf.* Section 3.6).

Table 4.1 Soybean rust hit score table

	Forecast		
Observed	Rust	No Rust	Total
Rust	25	0	25
No Rust	59	0	59
Total	84	0	84

The percentage of correctly forecast rust outbreaks at Greytown was 29.8%, while false alarms were 70.2%. The algorithm predicted a SBR outbreak every year at Greytown. Every year the index value indicated values above 12 and within 12 days SBR was found in the sentinel plots. However, there were also many false alarms, which may imply that the model is too sensitive to the relationship between temperature and rainfall on SBR infection and over estimating the likelihood of an infection. Although there appear to be a greater number of false alarms than accurate predictions, it must be emphasised that this accuracy assessment is conservative since flower initiation was unknown. Another uncertainty is the SBR outbreak date. The reported date of infection may be up to a week late (*cf.* Section 3.6), which may have caused valid estimates to be discarded as false alarms. When the 14 day lead time is increased to 21 days, the hit rate increased from 29.8% to 44%, while the false alarms drop from 70.2% to 56%.

Although the algorithm seems to be over sensitive, this is preferred to an under responsive model. The consequences of an under responsive algorithm is that conditions suitable for SBR infection will go undetected, and soybean producers may not be able to protect their crops against SBR, resulting in yield losses. An over sensitive algorithm may result in soybean producers spraying their crops for SBR when the pathogen or environmental conditions are not conducive for infection. This may result in unnecessary production costs, but will most likely have less economic impact than a disease outbreak. Further research is recommended using more accurate data regarding the dates of flowering initiation and the exact date that rust appears. It is also recommended that verification be carried out in a location where the climatic vulnerability of SBR infection is lower than at Greytown. This would produce a more precise assessment by which to judge the accuracy of the model. Further research into the inoculums pressure is also important. Even when all other conditions are ideal for infection, the absence of sufficient inoculum will prevent infection. The lack of inoculums may be another reason for the large number of false alarms. The three way interaction between environment, host susceptibility and inoculums pressure is important for further research into infection likelihood.

4.3 Algorithm Application: Spatial and Temporal Distribution of Climatic Vulnerability to Soybean Rust in South Africa, Lesotho and Swaziland

Figures 4.3, 4.5 and 4.7 illustrate the spatial distribution of climatic vulnerability to soybean rust risk in the main soybean production areas of southern Africa. The maps indicate the individual index values for relatively small homogenous climate zones (quinery catchments) in the region during the most SBR risk prone interval for the area. This allows soybean producers to assess whether there is a climatic risk of SBR infection in their specific area. It should be noted that infection is dependent on host susceptibility (most susceptible during flowering), favourable climatic conditions for infection as well as inoculums pressure. The presence and dispersal of inoculums is outside the scope of this study, therefore when suitable climatic conditions are referred to, it is an assessment of the climatic conditions. It indicates the climatic risk of infection assuming the plant is susceptible and there are inoculums present for infection. Similar maps depicting the risk during other intervals are available in Appendixes A, B and C. The time series graphs (Figures 4.4, 4.6 and 4.8) show the level of risk, over time, within the soybean production season at certain key soybean production locations. These time series graphs illustrate the times of low, high and variable climatic vulnerability to SBR, allowing for more efficient planning regarding spray applications and risk assessment.

4.3.1 Soybean rust susceptibility map for KwaZulu-Natal

Figure 4.3 illustrates the index values at the time of maximum risk, across the province of KZN. KwaZulu-Natal is the third largest soybean producing province in SA and produced

72900 tons of soybeans on 27000 hectares in the 2008/2009 growing season (National Crop Estimate Committee, 2009). The main commercial soybean production areas are Vryheid (Point b), Bergville/Winterton and Greytown (Point d). Soybean production is expanding in the Karkloof area, just east of Howick (Point c). Soybean rust research trials were undertaken at the KwaZulu-Natal Department of Agriculture at Cedara (Point c). Maps for the rest of the soybean production season in KZN are illustrated in Appendix A.

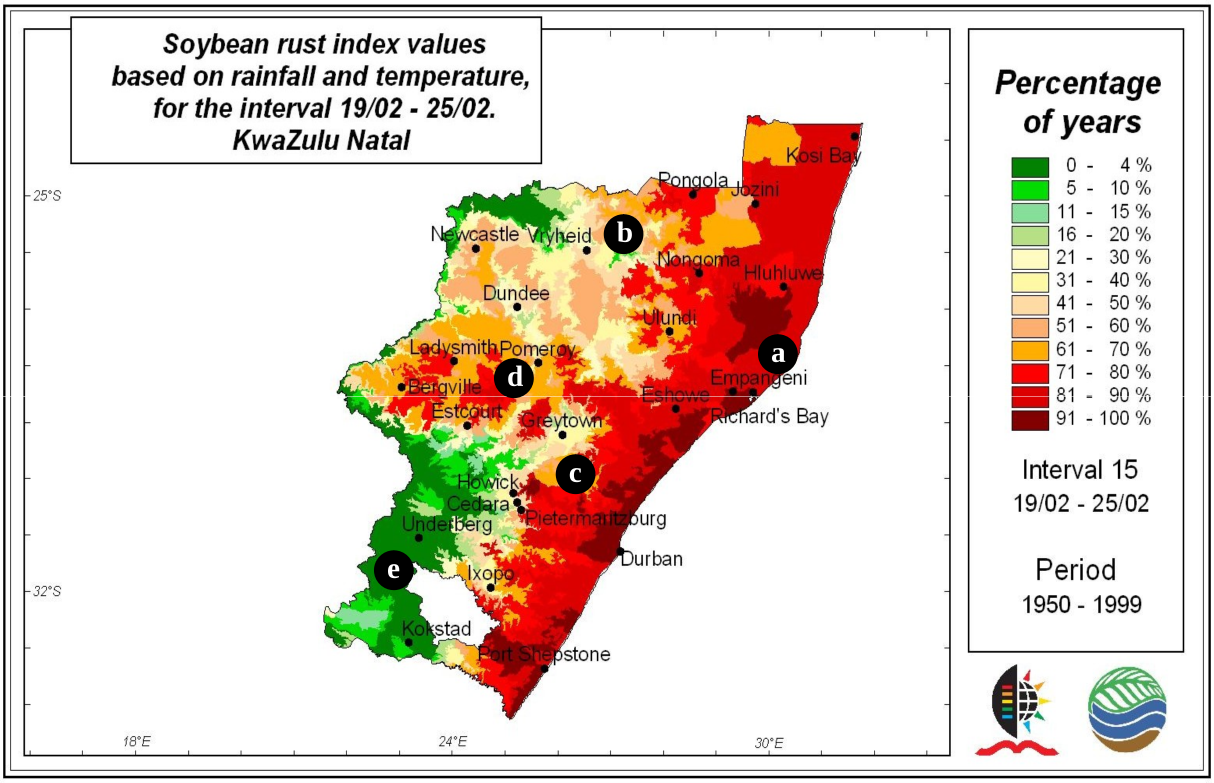

Figure 4.3 Soybean rust climatic susceptibility map, based on index values, for the time interval of most risk in KwaZulu-Natal, South Africa, with points a to e described in the text.

Figure 4.3 (Point a) shows a thick red band along the coast where climatic conditions are conducive to SBR infection. Here the climatic susceptibility of SBR infection is high, with index values of between 71% and 100%. Currently soybeans are not grown extensively along the coast due to a greater demand for sugarcane production in these areas. However, research in SA and Zimbabwe encourages sugarcane producers to intercrop with soybeans (Schumann *et al.*, 2000). This will allow them to gain from the nitrogen fixing properties of soybeans, reduce fertilizer costs, improvinge weed control as well as providing income from soybean yields. It is felt that the economic gains from intercropping with soybeans are preferred to

leaving fields fallow or applying nitrogen fertilizers (Schumann *et al.*, 2000; Shoko and Tagwira, 2005; Smit and Rhodes, 2009a). Soybean cultivar trials planted at Empangeni in 2008 did show signs of SBR infection (Smit and Rhodes, 2009b). Farmers considering growing soybeans along the coast must be cautious due to the potential high risk of infection in these areas. The risk of SBR infection on alternate hosts, such as Kudzu vine (*Pueraria lobata* M&S), is high. This would provide an inoculum source of SBR spores that may spread to soybean production areas nearby, such as Vryheid (Point b) (Hartman *et al.,* 2005).
Point b illustrates the index values surrounding Vryheid and Newcastle. These index values indicate moderate to high values between 41% and 50%, and 51% and 60%, respectively. Vryheid is close to areas that have a higher index, such as the 71% to 80% index values found at Pongola and Nongoma in the east. These areas may provide an inoculum source from alternative hosts, even if soybeans are not produced commercially here. Therefore, suitable climatic conditions, together with a source of uredospores from alternate hosts in highly suitable conditions in the east, may result in a higher chance of infection in Vryheid, where soybeans are produced commercially. Soybean producers in this area may be advised to carry out preventative spraying for SBR. Currently, the model does not account for uredospore availability and movement, and this should be further researched.

Point c illustrates the index values around Cedara and Karkloof, east of Howick. The Karkloof valley has high index ratings of between 91% and 100%. The main farming activities in this area are dairy, maize, timber, vegetables as well as soybeans (Burger, 2009). Therefore SBR is a substantial threat to commercial soybean farms in this area. Soybean producers know that there is high climatic risk of SBR infection and, therefore, should carefully monitor conditions to ensure timely preventative spraying annually.

Point d illustrates the index values for the Bergville area and the area from Ladysmith to Greytown. The index values illustrate a large area of high susceptibility with values ranging between 61% and 80%. This is one of the main soybean production areas in KZN, with maize farmers often intercropping with soybeans in order to exploit the nitrogen fixing properties of soybean crops. Soybean rust outbreaks have been reported regularly in the Bergville area since 2001, confirming that all conditions are conducive for SBR in this area. Therefore, soybean producers in these areas may be advised to spray as a preventative measure.

The area surrounding Underberg and Kokstad show little risk of SBR infection, remaining within 0% to 10% index values throughout the entire area. The average daily temperatures for these areas are 17˚C and 15˚C, respectively. Temperatures in this area are rarely conducive for SBR infection. In comparison, the average daily temperature at Bergville is 21˚C and well within the optimum range. In addition, no SBR outbreak has been reported in the Kokstad/Underberg area to date.

4.3.2 Time series graph at specific locations in KwaZulu-Natal

Figure 4.4 shows the temporal distribution of the long term climatic vulnerability of SBR at three key soybean production areas in KZN. It shows the percentage of years, from the period of 1950 to 1999, where the disease index of 12 was reached for a period of at least two days, during the periods defined in Section 3.7 (Table 3.3).

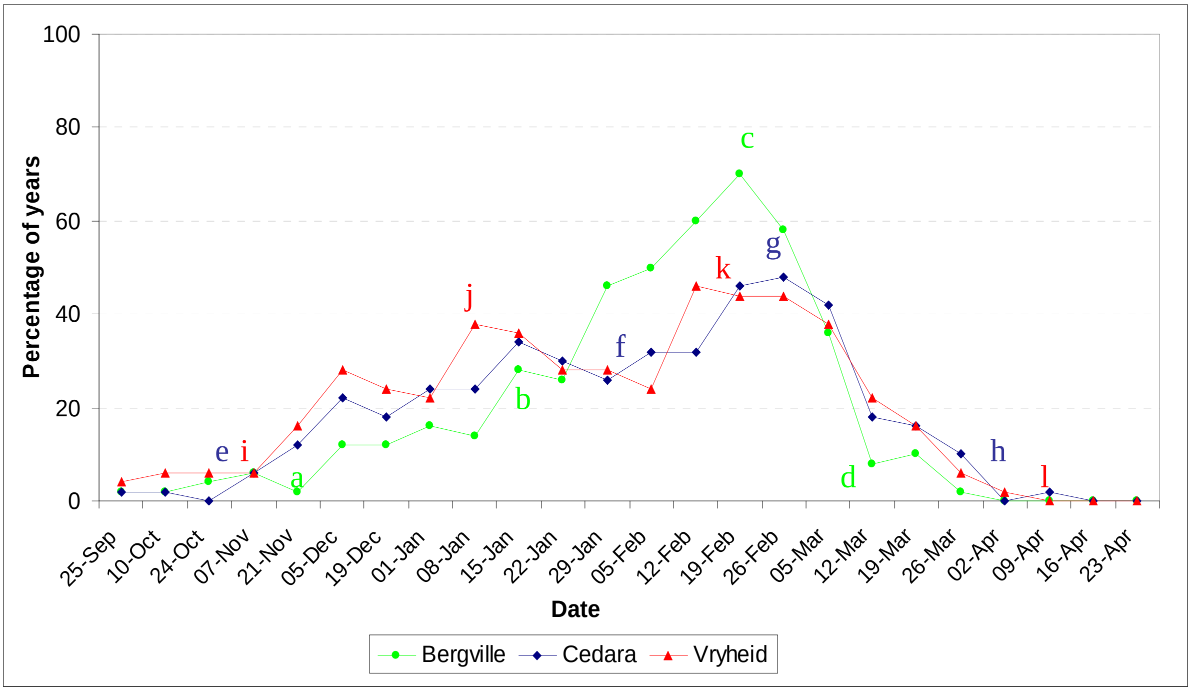

Figure 4.4 Time series showing the percentage of years in which climatic conditions were conducive for soybean rust, for three main soybean production areas in KwaZulu-Natal, South Africa.

In each of these disease curves three periods of risk can be identified, namely low risk, variable risk and high risk. In a period of low vulnerability, climatic conditions for SBR infection are seldom met at that time of year, often in less than 10% of the years. High risk occurs where climatic conditions for SBR infection are almost always met at that time of the year. If soybean producers' crops are at a susceptible stage to infection, the producers may be advised to always spray during these high risk periods. A period of variable risk is where conditions for infection are met to varying degrees, and the percentage may fluctuate from week to week. It is during these periods of variable risk that a near real time SBR forecasting system would be of most value.

Figure 4.4 (Point a) shows a period of low risk in the Bergville area until the middle of December. From the middle of December the risk increases steadily and there is a period of slight variability (Point b) where risk decreases slightly, but overall there is an upward trend in risk. A period of high risk starts from the middle of January and peaks at 70% in the middle of February (Point c). After the risk has reached this peak, it begins to steadily decrease reaching a low level (Point d) by the middle of March. The period of most risk to infection is from the middle of January until the middle of March. If soybean producers can plant early maturing cultivars that flower and mature before the middle of January or late maturing cultivars that flower and mature after the middle of March, the plant will enter the most susceptible stage of growth before or after the period of most risk. This will decrease the chances of SBR infection.

Point e shows a period of low risk for the Cedara area until the middle of November, after which the risk begins to steadily increase. The risk becomes slightly variable as it increases (Point f) but overall remains in the region of 30%. Risk in the Cedara region peaks at about 50% at the beginning of March (Point g) and remains high for a few weeks. The risk begins to rapidly decrease and reaches low levels by the end of March (Point h). Point i shows a period of low risk for the Vryheid area until the middle of November. The risk rapidly increases to 40% (Point j), after which it decreases again. Vryheid starts to experience high risk from the beginning of February and peaks at about 40% in the middle of February (Point k). The high risk is sustained throughout February and begins to drop off at the beginning of March. Vryheid enters a period of low risk from the beginning of April (Point l). Cedara and Vryheid display similar trends in climatic vulnerability to SBR infection. Both areas experience an increase in risk towards the end of November. This means that risk may increase too early for even early maturing cultivars to mature before climatic vulnerability increases. Both areas also experience a decrease in climatic vulnerability towards the end of March. If soybean producers plant late maturing cultivars which flower and mature towards the end of March, they will most likely miss the period of greatest climatic vulnerability for infection. There were still suitable conditions for infection, up to 20% of the 50 years under review after the end of March. However, this may be too late in the season for infection to significantly influence yield losses.

All soybean production areas in KZN display a similar time trend to the climatic susceptibility of SBR infection. Risk in all areas reaches high levels, and therefore soybean producers may be advised to take precautionary spraying measures against SBR during high susceptibility periods if their crop is in a susceptible phase. The risk remains variable to high throughout most of the season. However, if soybean producers are able to plant late maturing crops which only come into the susceptible flowering stage from the middle of March, their chances of SBR infection are greatly reduced. This would mean that soybean producers would not need to incur the expense of spraying against SBR and would not be likely to experience yield losses due to SBR. Alternately, soybean producers may wish to grow early maturing soybean cultivars that come into flowering before the period of high risk. If plants flower and mature before the middle of January, the effects of SBR infection will have little effect on yield even if infection occurs. However, this may also coincide with the mid-summer drought, which may adversely affect yields. However, early or late planted soybean may not receive adequate rainfall and heat to produce optimum yields. Therefore, producers need to weigh up the benefits of reducing the likelihood of infection compared to potentially lower yields. Soybean producers in KZN, particularly in areas where risk is real but not ever present, would likely benefit from a near real time early warning system that warned them when climatic conditions were suitable for infection. This would allow soybean producers to only spray when conditions were suitable for SBR infection, thereby reducing production costs, preventing the development of resistance to fungicides by the pathogen and reducing the environmental impact of fungicide application. Planting early or late maturing cultivars together with a near real time forecasting may be able to mitigate most of the SBR threat in the province.

4.3.3 Soybean rust susceptibility map for the northern soybean production regions

Figure 4.5 illustrates the index values at the interval of maximum risk, for the northern soybean production areas. This includes the Limpopo, North-West and Gauteng provinces. The Limpopo province is the fourth largest soybean producing province in SA, producing 44 000 tons of soybeans on 16 000 hectares in the 2008/2009 growing season (National Crop

Estimate Committee, 2009). Some of the main soybean production areas in the Limpopo province are situated between Marken and Mookgophang (Point a and b). The North-West Province is the fifth largest soybean producing province in SA. The North-West produced 18 200 tons of soybeans on 6 500 hectares in the 2008/2009 growing season (National Crop Estimate Committee, 2009). The main soybean production areas are in the east of the province around Potchefstroom (Point d), Rustenburg, Koster and Brits (Point c). Gauteng is the smallest of the soybean producing province in SA and produced 12 395 tons of soybeans on 6700 hectares in the 2008/2009 growing season (National Crop Estimate Committee, 2009). The main soybean production areas are in the east of the province, around the Nigel and Springs areas (Point e). Maps for the rest of the soybean production season in the northern regions are illustrated in Appendix B.

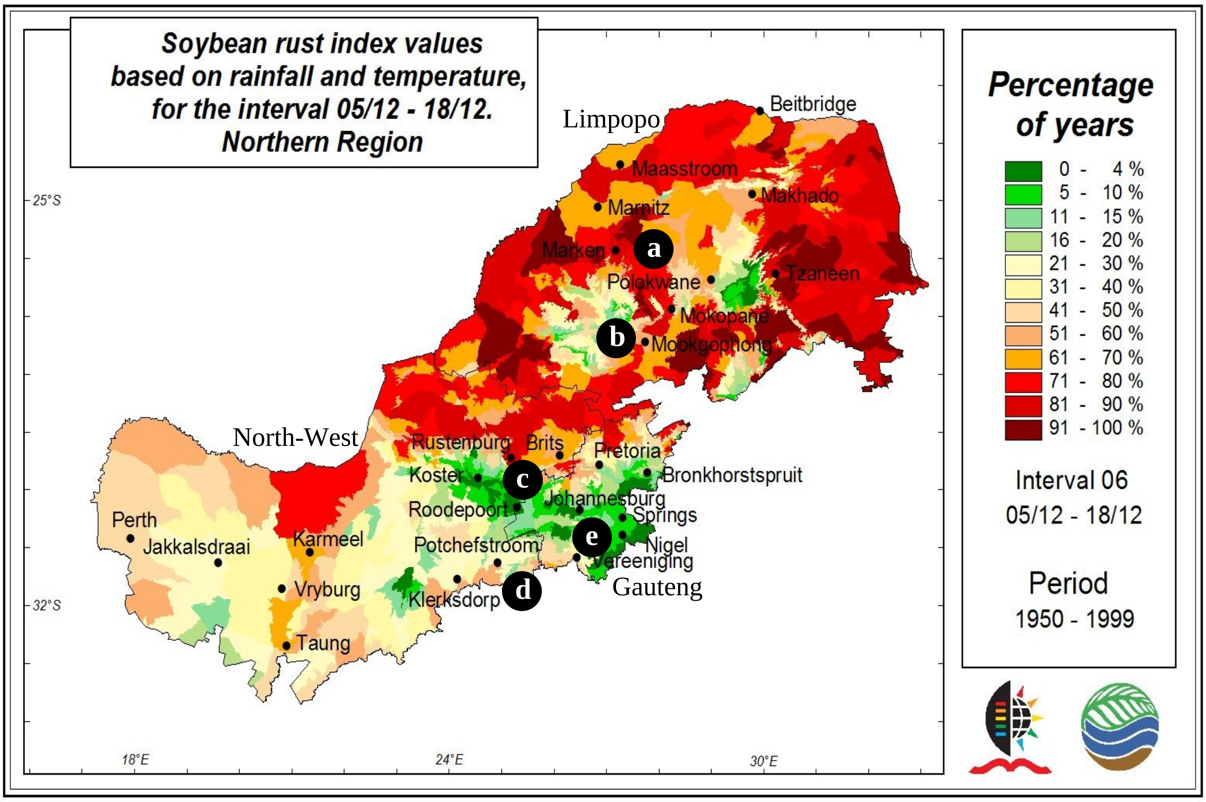

Figure 4.5 Soybean rust climatic susceptibility map, based on index values, for the interval of most risk in the northern soybean production regions of South Africa, with points a to e explained in the text.

Most of the Limpopo province has high index values (above 61%). The eastern portion of the province has a high climatic vulnerability to SBR (above 81%). Currently this area is not a main soybean production area, and there have been few reports of SBR in this area. This may be because of a lack of suitable inoculums to cause infection. However there is high enough climatic vulnerability for SBR could infect alternate hosts and provide an inoculum source for soybean production areas further west near Marken and Mookgophang. Index values remain higher in the east of Limpopo, across the entire map series (see Appendix B), meaning that this could be a possible over wintering area for SBR, providing an inoculum source for re-infection once conditions become suitable again further west.

Point a in Figure 4.5 shows the index values in one of the main soybean production areas in Limpopo, *viz*. the area surrounding Marken. The index values here are above 71%, with the area just north of Marken having values that exceed 90%. This soybean production area has a high climatically vulnerability to SBR infection and the risk of SBR infection to commercial soybean farms is high. South of Marken (Point b) is the soybean production area of Mookgophang. Mookgophang has slightly lower index values than Marken (between 61% and 70%). However, the areas surrounding Mookgophang have values of 71% to 80% and the area to the east has values that exceed 91%. Overall, the climatic risk of SBR infection to commercial soybean farms is high in the Limpopo province. Soybean producers need to be cautious and may be advised to annually apply preventative fungicides.

The North-West province overall has lower index values than the Limpopo province. Most of the North-West province has values between 21% and 60%. Point c illustrates the climatic vulnerability around the main soybean producing areas in the North-West province, *viz.* Rustenburg and Koster. Index values in this area are between 61% and 80% and commercial soybean farms in this area are at risk to SBR as this area has a high climatic vulnerability. Soybean producers may be advised to annually carry out preventative SBR spraying in these areas, if inoculums are present to cause infection. East of this area with high index values, is another soybean production area, Koster. The index values in Koster are comparatively lower (below 10%) with values rising to only 20% throughout the map series (see Appendix B). Therefore, the climatic vulnerability for SBR is much lower in this area compared to other soybean production areas in the northern regions. High risk areas to the west (Point c) may provide an inoculum source to this lower risk area, but because conditions are less suitable, and only become suitable later in the soybean season, the potential impact of the disease may be limited.

Point d illustrates the index values at the soybean producing area of Potchefstroom. The index values in this area of the province are much lower than in the north east. The index values around Potchefstroom are between 21% and 60%. These index values are quite varied and this makes the management of SBR difficult for soybean producers. In areas where risk is consistently high, soybean producers can be advised to spray for SBR every year. However, in areas such as Potchefstroom, this advice may mean that soybean producers often spray when climatic conditions are not suitable for infection. It is in areas such as Potchefstroom, where there is a substantial but not ever present risk to SBR infection, that a near real time, early warning system would be of most use. This warning system would warn soybean producers when conditions are suitable, advising them to spray, and allowing them to save money by not spraying when conditions are unsuitable.

Point e illustrates the index values in the soybean production areas in the east of Gauteng. The index values in this area are between 0% and 20%. This is considerably lower than many other soybean production areas, where values are often above 60% (see Point c). The climatic susceptibility to SBR is very low in this area and the economic costs of preventative spraying may not be worth the yield losses prevented. Soybean producers may also benefit from a near real time early warning system, however, the risk to their commercial crops would likely not be worth the cost of preventing SBR through spraying.

4.3.4 Time series graph at specific locations in the northern soybean production regions

Figure 4.6 illustrates the temporal distribution of the long term climatic vulnerability of SBR at four key soybean production areas in the northern soybean production areas of SA. It shows the percentage of years, from the period of 1950 to 1999 when the disease index of I_R=12 was reached for a period of at least two days, in the periods defined in Section 3.5.

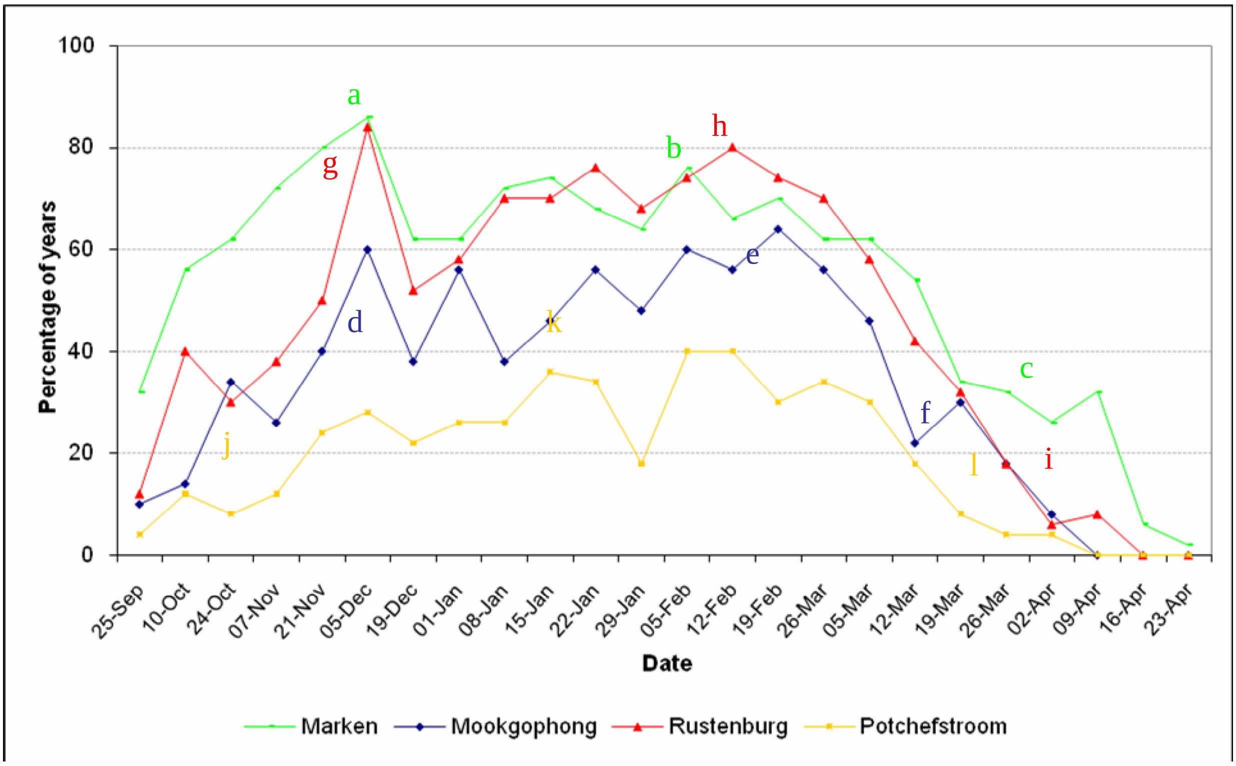

Figure 4.6 Time series showing the percentage of years where climatic conditions were conducive for soybean rust, for four main soybean production areas in the northern soybean production areas of South Africa.

Point a illustrates that Marken often experiences conditions suitable to SBR infection early in the soybean production season. However, at this period plants are more than likely not at a susceptible stage of growth, so the actual risk of infection is not high. Risk decreases slightly but remains high throughout the soybean season and reaches another peak at Point b. The risk of infection based on climatic vulnerability continues to remain high until the beginning of March, when it begins to decline, however this decline is slow and remains in the 30% range (Point c) until the beginning of April. Risk has reached a low level by the end of April. The implication for soybean producers in the Marken area is that SBR is a risk throughout the soybean production season. Marken experiences high index values between 60% and 80% throughout the soybean production season. It is likely that all soybean cultivars, both early and late maturing, are going to come into the susceptible flowering stage during a high risk period. Commercial soybean producers in the Marken area may be advised to spray their crops annually with fungicides as the risk of yield losses due to SBR infection is high.

Point d shows variable risk during the beginning of the season in Mookgophang. Although the risk is variable, it remains high, with between 40% and 60% of the years having vulnerable climatic conditions for infection throughout the majority of the soybean production season. A peak is reached in the middle of February (Point e). The risk quickly decreases and reaches a level of just above 20% by the middle of March (Point f). Most cultivars will flower and mature during a high risk period. However, if soybean producers can plant cultivars that mature after the middle of March, the risk of infection will decrease. However, early or late planted soybean may not receive adequate rainfall and heat to produce optimum yields. Therefore, producers need to weigh up the benefits of reducing the likelihood of infection compared to potentially lower yields. Soybean rust is a real threat to commercial soybeans in the Mookgophang area. This risk fluctuates significantly during the soybean season making the management of SBR necessary but difficult. Soybean producers cannot be advised to spray for SBR every year as this may result in the application of fungicides even when local conditions are unsuitable for infection. This results in greater production costs, possible fungicide resistance development and negative environmental impacts. Soybean producers in this area would most likely benefit from an early warning system, which would warn them when conditions were suitable for infection. This would allow them to make better decisions regarding the necessity and timing of fungicide applications.

Point g illustrates that Rustenburg, like Marken and Mookgophang, often experiences conditions suitable for SBR infection early in the soybean production season. Point g shows the peak, where 80% of the years experienced conditions suitable SBR infection in the middle of November. There is a sharp decrease in risk following this, but risk remains high, between 60% and 80% throughout the season, and reaches another peak of 80% at the beginning of March (Point h). Risk rapidly decreases from the beginning of March and reaches low levels by the beginning of April (Point i). Commercial farms in the Rustenburg area experience a great risk to SBR infection. Index values of between 60% and 80% are experienced throughout the soybean production season which indicates that the risk of SBR infection on commercial soybean farms is great throughout the entire soybean production season. All soybean cultivars, whether early or late maturing, are likely to come into the susceptible flowering stage during a high risk period in this area. Soybean producers in this area may be advised to always spray their crops against SBR, as there is a real threat of the disease in this area.

Point j illustrates the number of years where conditions were suitable for SBR infection early in the season in the Potchefstroom area. Vulnerability remains low (below 20%) early in the season. However, as the season progresses the level of risk increases. By the middle of January the risk increase, with Point i showing that 40% of the last 50 years have had suitable conditions for SBR infection by the middle of January. Although this level is comparatively lower to other soybean production areas in the northern production region, such as Marken and Rustenburg, it still implies that almost every second year experiences suitable conditions for SBR infection. The risk in Potchefstroom decreases earlier than other areas, from the beginning of March and decreases below 10% by the middle of March (Point l). If soybean producers can plant late maturing cultivars that flower and mature after the beginning of March, the chances of infection will be reduced. The intermediate index values present in this area makes the management of SBR difficult for soybean producers. It would be unwise to advise soybean producers to spray every year as this will mean up to every second year they would be incurring the unnecessary expense of spraying when conditions are unsuitable for infection. This may lead to fungicide resistance in the pathogen and may have a negative environmental impact as well as increase farmer's production costs. Soybean producers in the Potchefstroom area would most likely greatly benefit from a near real time warning system which would warn them when local climatic conditions are suitable for infection and allow them to make appropriate management decisions regarding the application and timing of fungicide treatments.

Overall, the soybean production areas in the northern regions display similar trends to SBR risk. All the soybean production areas experience high risk throughout most of the soybean production season. This means that either early or late maturing soybean cultivars are likely to come into the disease susceptible flowering stage at a period of high SBR risk. Soybean producers in Potchefstroom and Mookgophang may be able to prevent yield losses by planting cultivars that flower and mature in March as the risk in these areas decreases from the beginning of March. Soybean producers in the Limpopo province and north east of the North-West Province always experience high risk to SBR infection and may be advised to spray annually when their crops reach the vulnerable flowering stage. However, soybean producers in Gauteng and the rest of the North-West province may only experience suitable conditions for SBR every fourth to fifth year. It is the soybean producers in these areas that would most likely benefit the most for a near real time SBR warning system, which would warn them when conditions were suitable for infection. This would assist them in making management decisions regarding timing and application of fungicides.

4.3.5 Soybean rust susceptibility map for the central soybean production regions

Figure 4.7 illustrates the index values at the interval of maximum risk, for the central soybean production areas. This includes Mpumalanga, Free State, Swaziland as well as Lesotho. Mpumalanga is the greatest soybean producing province in SA, producing 256 250 tons of soybean on 120 000 hectares in the 2008/2009 growing season (National Crop Estimate Committee, 2009). This accounts for almost half of SA's soybean production. The main soybean production areas are Groblersdal, Marble Hall (Point a), Mashishing (Point b), Piet Retief, Ermelo (Point c) and Delmas (Point d). The Free State is the second largest soybean producing province in SA, producing 44 000 tons of soybeans on 16 000 hectares in the 2008/2009 growing season (National Crop Estimate Committee, 2009). The main soybean producing areas are in the eastern part of the Free State and include Parys (Point e), Bethlehem, Reitz (Point f) and Koppies. Swaziland (Point g) is becoming a substantial producer of soybean, for their local market, producing approximately 38000 tons of soybeans in the 2008/2009 growing season (United States Department of Agriculture, 2009). Cold and harsh alpine conditions in Lesotho do not only inhibit SBR development, but also make cropping in general a difficult practice. Maps for the rest of the soybean production season in the central regions are illustrated in Appendix C.

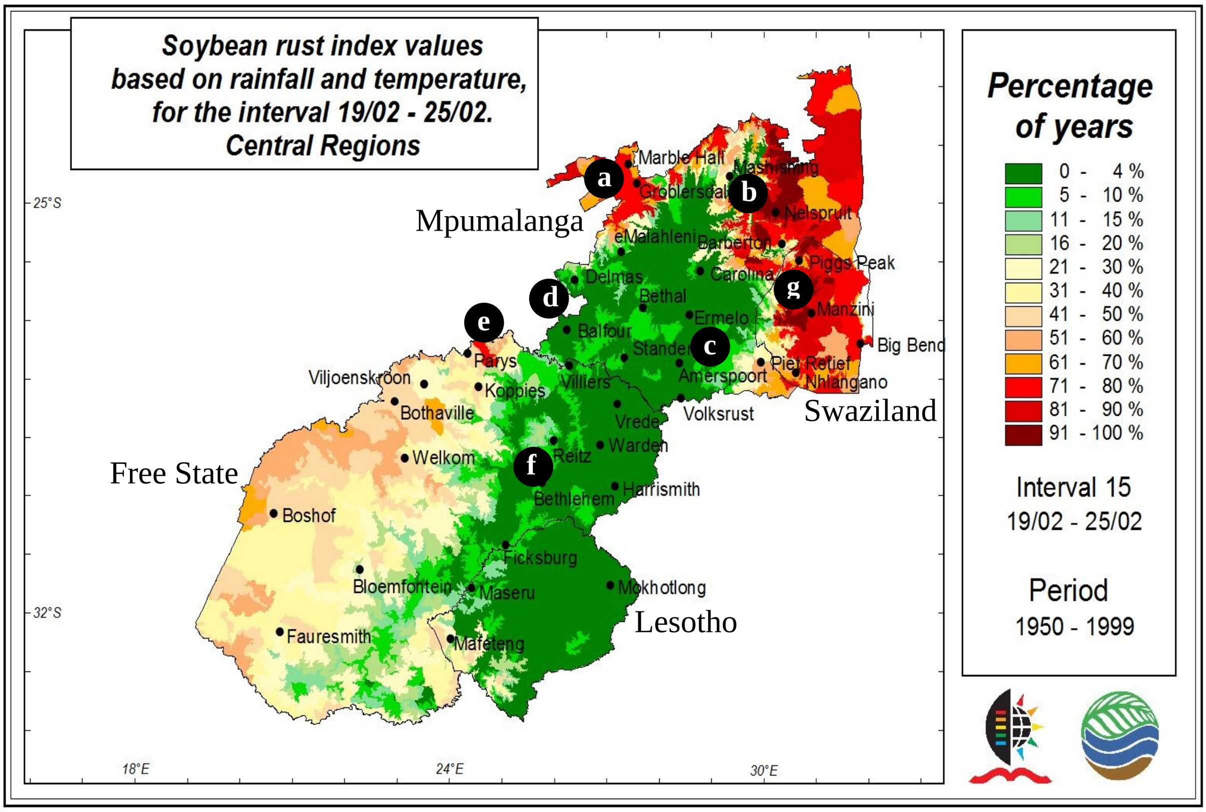

Figure 4.7 Soybean rust climatic susceptibility map, based on index values, for the interval of most risk in the central soybean production regions of South Africa, Swaziland and Lesotho.

Point a of Figure 4.7 illustrates the index values for the area surrounding two main soybean producing areas in Mpumalanga, Marble Hall and Groblersdal. Index values in this area show that climatic conditions are suitable for SBR infection over 71% of the last 50 years. Point b illustrates the index values for the area surrounding Mashishing. The index values here show that climatic conditions often result in vulnerable conditions for SBR infection, (above 71% with large area east of Mashishing having index values above 91%). Commercial soybean farms in the north of Mpumalanga are at great climatic risk to SBR infection and soybean producers may be advised to annually spray for SBR. The index values in central, south and eastern Mpumalanga are lower than in the north. Point c illustrates the index values for the areas surrounding Ermelo and Piet Retief. Point d illustrates the index values around Delmas. Index values reach 51% to 60% around Piet Retief and only 0% to 4% around Ermelo and Delmas. Commercial farms in the Piet Retief area still experience a substantial risk to SBR, with a possible 1 out of every 2 years having suitable climatic conditions for SBR infection. In addition, areas surrounding Piet Retief experience index values of up to 100%. This may increase the risk of infection as the inoculums may infect alternate hosts in surrounding areas and then spread more easily to Piet Retief. Soybean producers in areas like Piet Retief, where the threat of SBR is real but not guaranteed would likely benefit the most from a near real time early warning system, which would warn soybean producers when conditions are suitable for infection, allowing them to plan optimum application and timing of fungicide application. Soybean producers in Ermelo and Delmas (Point d) have little climatic risk to SBR. Although they may experience conditions suitable for SBR infection occasionally (possibly once every ten years), the cost of spraying fungicides to prevent yield losses due to SBR would most likely not outweigh the actual yield losses due to SBR. Soybean producers may also benefit from a near real time early warning system, to warn them when conditions are suitable. However, overall the climatic risk of SBR infection to commercial soybean farms in this area is low.

Most of the eastern Free State illustrates low index values, below 20%, while most of the central and western Free State illustrates slightly higher index values of between 21% and 60%, with a few isolated areas in the west having between 61% and 70%. Overall, the Free State displays lower index values than Mpumalanga, with very few areas going above 60%. This means the climatic vulnerability for SBR infection in the Free State is lower than Mpumalanga. However, Point e illustrates the index values for the area surrounding Parys in the Free State. This area has values of 71% to 80%, much higher than the rest of the province. Commercial soybean farms in this area have a greater climatic risk to SBR infection. Soybean producers in this area may be advised to spray for SBR every year as the risk of infection is high. Just south of Parys is the area of Koppies. Koppies has a lower risk than Parys, *viz.* between 41% and 50%. Although the risk of SBR is not as ever present as it is in Parys, it is still a real threat in this area. Soybean producers in this area would greatly benefit from a near real time warning system which warned them when conditions were suitable for SBR infection. Soybean producers in this area would incur unnecessary productions expenses if they sprayed annually against SBR as conditions are not always suitable for infection.

Point f illustrates the index values of between 0% and 10% for the soybean producing areas of Bethlehem and Reitz. The risk of SBR in these areas is low and the expense of spraying for SBR would most likely not substantiate the reduction in yield losses due to SBR infection if it occurs. Soybean producers in this may also benefit from a near real time warning system. However, overall the risk to SBR infection in these areas is low.

Point g illustrates the index values for the Kingdom of Swaziland. The whole of Swaziland experiences high values of above 61% save for a narrow band along the western border of the country where index values are between 5% and 40%. Soybean production is expanding in Swaziland, meaning that the risk of SBR to the expanding commercial soybean industry is great due to the highly suitable climatic conditions found throughout most of the country. Soybean producers in Swaziland need to be prepared to take precautionary measures against SBR infection. Soybean producers in the whole of Swaziland, except in the narrow corridor in the west, could be advised to spray fungicides annually against SBR.

4.3.6 Time series graph at specific locations in the central soybean production regions

Figure 4.8 illustrates the temporal distribution of the long term climatic vulnerability of SBR at three key soybean production areas in the central soybean production areas of SA. It shows the percentage of years, from the period 1950 to 1999, where the disease index of I_R = 12 was reached for a period of at least two days, in the periods defined in Section 3.5.

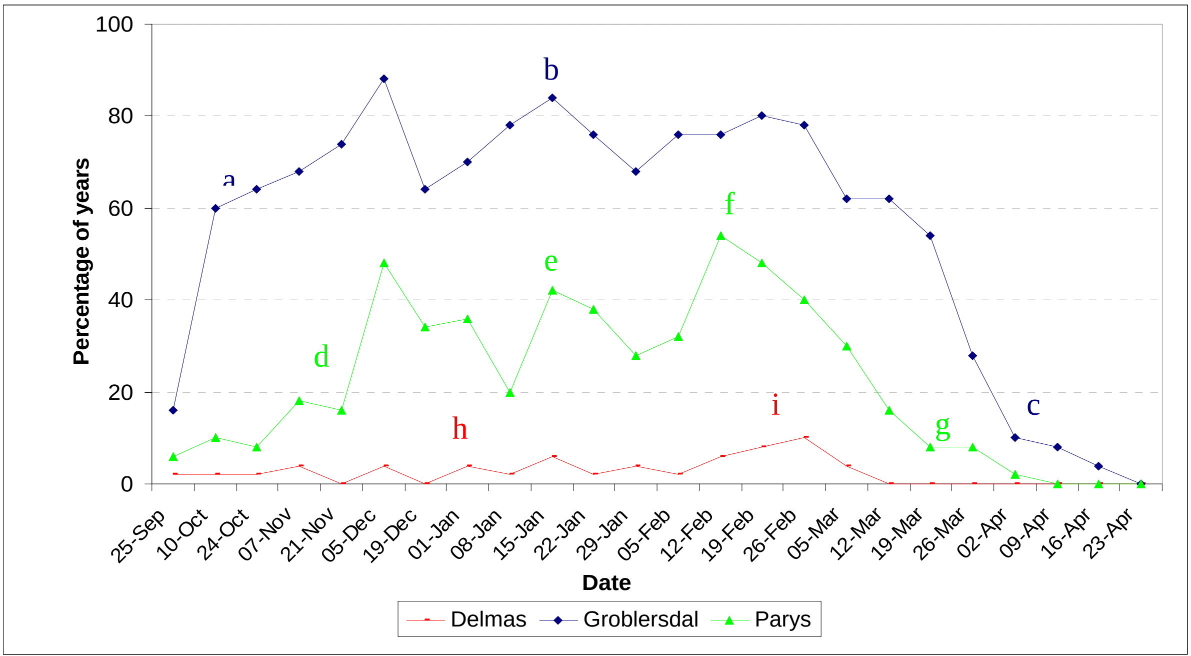

Figure 4.8 Time series showing the percentage of years where climatic conditions were conducive for soybean rust, for three main soybean production areas in the central soybean production areas of South Africa.

Point a illustrates the percentage of years where conditions were suitable for SBR infection in the Groblersdal area from 1950 - 1999. The level of risk increases rapidly to 60% in the beginning of the soybean production season and continues to increase to above 80% by the middle of December. The risk fluctuates slightly throughout January (Point b) but overall remains high, between 60% and 80%. Towards the middle of March the risk begins to decrease and by the beginning of April the risk decreases to about 10% (Point c). Soybean producers in the Groblersdal area are at very high climatic risk to SBR infection, with high index values being experienced throughout the soybean production season. This means that all soybean cultivars, whether early or late maturing, are likely to be at a growth stage susceptible to infection during a time of high risk. Soybean producers in the Groblersdal area may be advised to spray their crops annually against SBR as the climatic vulnerability in their area is very high.

Point d illustrates that conditions for SBR infection in Parys remain lower than Groblersdal and only begin to increase towards the end of November. From the end of November the risk begins to increase rapidly and remains in the range of 20% to 50% throughout the rest of the soybean production season (Point e). At the beginning of February the risk increases and peaks at about 55% (Point f) in the middle of February. This is the period of most risk for soybean producers in the Parys area. From the peak in the middle of February the risk begins to decrease rapidly, dropping below 40% by the beginning of March and below 20% by the middle of March. Although the threat of SBR is real in the Parys area, the period of most risk starts later and finishes earlier than in areas such as Groblersdal. Climatic conditions of SBR only become suitable towards the end of November. However, this is still too early in the season for even the early maturing soybean cultivars to mature, so plants will still come into risk during the higher risk periods at the beginning of February. However, risk starts to decrease from the beginning of March and decreases to less than 20% by the middle of March. If it is possible to plant soybeans cultivars that come into the susceptible flowering stage after the middle of March, the chances of SBR will be greatly reduced as climatic conditions will not be suitable for SBR infection. Soybean producers in the Parys area would most likely benefit greatly from a near real time warning system. As only between 20% and 40% of the last 50 years experienced suitable climatic conditions for SBR, soybean producers may incur unnecessary expenses by spraying when conditions are not suitable for infection. The warning system would warn soybean producers when climatic conditions are suitable for

SBR infection, allowing them to plan application and timing of fungicide treatments more accurately.

Point h illustrates that climatic conditions for SBR in Delmas remain very low, especially when compared to areas like Groblersdal, throughout the soybean production season. Risk remains below the 10% level throughout most of the season and peaks at about 15% at the beginning of March (Point i). Commercial soybean producers in the Delmas area have little concern of SBR infection as climatic conditions are seldom suitable for infection and indicator values remain below 4% (Point d). Soybean producers in Delmas would most likely not have to spray against SBR as the cost of spraying would far outweigh the prevention of yield loss, when considering the chances of infection.

4.4 Discussion and Conclusion

The SBR index appears to be a suitable tool for calculating the risk of SBR over large areas. The verification in Cedara and Greytown showed that the algorithm can accurately predict SBR within 14 days of suitable climatic conditions for infection being experienced. Similar predictions were produced even though SBR occurred one calendar month earlier in the 2002/2003 season than it did in the 2001/2002 at Cedara. The date that SBR infection occurred at Greytown was also progressively earlier each year, however the algorithm accurately predicted the outbreak each year. Verification at Greytown indicated that the algorithm may be over sensitive, however, further verification at a site less suited to SBR infection is needed to more accurately verify the model. Index values are high in most of the soybean productions areas in KZN, Limpopo, North-West province and northern Mpumalanga. Vulnerability is lower, but still conductive in the northern Free State and in the south of the North-West province. The areas in western Mpumalanga and eastern Free State have very low risk of SBR infection. Table 4.2 summarises the risk for the main soybean production areas in South Africa, along with area specific recommendations for preventing SBR infection.

Table 4.2 Summary of recommended methods for the control of soybean rust in some of the most important soybean production areas in South Africa.

Area	Early Cultivars	Late Cultivars	Preventative Spraying	Early warning system	Risk rating	Most vulnerable time	Highest rating (%)
Bergville	Yes	Yes	Yes	Yes	Variable to high	February	70
Cedara	No	Yes	Yes	Yes	Variable	Mid-February to Mid-March	50
Delmas	Yes	Yes	No	No	Low	End February	10
Groblersdal	No	No	Yes	No	High	October to end March	90
Marken	No	No	Yes	No	High	November to end March	85
Mookgophang	No	Yes	Yes	Yes	Variable to high	January to March	60
Parys	Yes	Yes	Yes	Yes	Variable	February	50
Potchefstroom	No	Yes	Yes	Yes	Variable	February	40
Rustenburg	No	No	Yes	No	High	November to Mid-March	80
Vryheid	No	Yes	Yes	Yes	Variable	February to Mid-March	50

In areas where the climatic vulnerability to SBR occurs later in the season, the use of early cultivars may help producers reap high yield before climatic conditions promote SBR infection. In areas where climatic vulnerability to SBR decreases earlier in the season, planting cultivars that come into the vulnerable flowering stage later may produce high yields while avoiding the period of high climatic vulnerability. Preventative spraying is recommended to all producers whose crops will mature during a high risk period or who experience high climatic vulnerability throughout the season. Areas where climatic vulnerability fluctuates throughout the season (where the risk of SBR infection is real but not ever present) would benefit from an early warning system which would warn soybean producers when climatic conditions are suitable for SBR infections, so that they only apply fungicides during these periods. This would help reduce production costs while still ensuring high yields. Using this information will allow producers to decide whether the application of fungicides is financially viable (if yield losses prevented will outweigh the cost of fungicide application) based on the level of climatic risk for infection when their crops are at a susceptible stage. It will also allow for better planning regarding the timing of fungicide applications, so that soybean producers only spray during high risk periods and do not spray when conditions are not suitable for infection. This will avoid the expense of unnecessary fungicide applications, reducing productions costs, reducing the chances of the pathogen developing resistance to fungicides and reduce the environmental impacts of fungicide use in soybean production.

This chapter has presented the results of the algorithm development and verification process as well as the results of the accuracy assessment. The algorithm was applied to a 50 year historical climate database and the results mapped. These maps as well as time series graphs using the 50 years data for selected key soybean production sites were presented in the chapter. It has become apparent from these maps and graphs that some areas do have a climatic risk of SBR infection, however this risk is not throughout the entire season or every year. It is for farmers in these areas that the management of SBR is most difficult. They may not wish to spray fungicides to prevent infection every year, as in many years the climatic conditions are not suitable for infection. This means that they are incurring unnecessary cost of applying fungicides. However, the favourability of the climate for infection is high enough that farmers cannot be advised not to apply fungicides. Therefore, the development of an early warning system which warns farmers when conditions are suitable for infection would be most beneficial to these farmers. The warning system would provide farmers with knowledge of real time climate conditions and would aid them in the decisions whether to apply fungicides or not. The framework for the development of such a warning system is provided in the following chapter.

5. FORECASTING FRAMEWORK

In Chapter 4 it became clear that many soybean production areas in South Africa would benefit form a near real time early warning system that would warn them when conditions were suitable for soybean rust infection. This chapter aims to develop a framework of a weather based forecasting system for SBR, based on available and forecast weather data. Currently, no weather based SBR forecast early warning system (EWS) exists in SA or anywhere else in the world. This chapter does not describe the development of a EWS, but produces a framework or recommendations for such a system should it be developed in the future.

5.1 Forecasting Overview

A forecasting system is a system that forecasts the likelihood of a future event occurrence based on the data currently available. Forecasting systems are decision support tools, which provide users with an assessment of present and forecast conditions, based upon which, users can make management decisions (Skelsey *et al.*, 2008). Early warning systems allow for the identification of risk periods before they occur, allowing enough time for appropriate action to be taken (de Groot *et al.*, 2006).

Currently forecasting systems in SA, include weather forecasting, fire forecasting, crop yield forecasting as well as limited crop disease forecasting. The fire forecasting system, for example, uses 42 delineated regions based on fuel load (type of land cover) together with daily weather forecasts including temperature, relative humidity, wind speed and time since the last rain event. Daily forecasts of Fire Danger Index values are created based on these parameters (DWAF, 2004). This information can be used to determine response team readiness or to plan preventative fire break burning.

A SBR forecasting system would allow the identification of periods of likely infection based on local weather conditions. Forecasting the time period where SBR could infect based on weather conditions, could help forecast the severity of the infection and its potential impact on crop yields (Pivonia and Yang, 2006). Currently, spraying of fungicides is the most efficient means of SBR control in South Africa (Caldwell *et al.*, 2002). An early warning system may help in the timing of these fungicide applications. Further research into the interaction between host physiological stage, favourable weather conditions for infection and inoculums availability are needed for the development of a forecast system that provides accurate and reliable predictions of the likelihood of infection.

There are three management decisions which soybean producers may decide to use, i.e. preventative spraying, curative spraying and no spraying. The management decision taken will depend on the level of perceived threat, the vulnerability of the crop and the cost of spraying versus the estimated loss due to infection (Roberts *et al.,* 2005). The warning system may also help to reduce the cost of production by avoiding unnecessary and unsustainable spray treatments in times when weather conditions are unsuitable for SBR infection (Roberts *et al.,* 2005; Skelsey *et al.,* 2008). Avoiding unnecessary spray treatments helps to prevent resistance build up of the pathogen to fungicides and reduces the environmental impact of soybean production, while still ensuring plant health and high yields (Skelsey *et al.,* 2008).

5.2 An overview of Current Disease Forecasting Systems

There are many crop disease forecasting systems in use in worldwide and in South Africa. The United States of America (USA) is at the forefront of SBR forecasting, however, most systems rely on a number of inputs as described below.

5.2.1 International soybean rust forecasting

Soybean rust modeling in Asia focuses on examining changes in the epidemic with trials carried out under controlled conditions (Tan, 1996; Del Ponte *et al.,* 2006a). However, in Brazil and the USA, two of the major soybean producing countries in the world, extensive work has been done on modeling the risk of infections and spread over the last few years. There are many models used to forecast different aspects of SBR in the USA. Much work was done on the modelling of SBR spore dispersal potential, likelihood of infection, areas of infection and effects on yield in the USA, in the anticipation of the arrival of SBR (Pan *et al*., 2005; Pivonia and Yang, 2006a; Del Ponte *et al.,* 2006b). However, most of these forecasting models are site specific as the pathogen relies and adapts to local conditions. An empirical model based on crop scouting, where crops are physically inspected for signs of disease, and current weather vulnerability have resulted in an online mapping service that advises soybean producers of the current likelihood of infection in the USA (Roberts *et al,* 2005; Roberson, 2006; Pivonia and Yang, 2006; Schonyers *et al.*, 2006). Reis *et al.* (2004) created a model in Brazil that predicted the daily vulnerability for infection based on literature. This model may be able to provide near real time assessment of risk if connected to an automated weather station in the field. This will only allow for a site specific risk assessment for the climatic vulnerability of SBR. Disease forecasting in Brazil is currently limited to site-specific warning systems using temperature and rainfall as inputs as well as a national scouting network which alerts users of the first appearance of SBR in an area (Del Ponte and Esker, 2008). Brazil is currently trying to develop a large scale weather based SBR forecasting system (Del Ponte, pers. comm.)

5.2.2 Forecasting disease in South Africa

One example of a crop disease forecasting system in SA, based on weather data, is the Metos Downy Mildew Early Warning (DMEW) model currently in use in vineyards in the Western Cape. This model was adapted from the Netherlands to local conditions. Initially the model had accuracy and reliability problems, but has since been revised and improved for accuracy and user friendliness. The revised DMEW model calculates infection periods and intensity of infection based on favorability of climatic conditions. A weighting system allocates greater values to weather variables that were closer to optimum compared to those that were non-optimum, and a sum of risk is given for each individual day. The risk is categorized as low, moderate or high risk, and represented on a graph. The model is limited because it relies on point weather data, and the accuracy of the predictions decreases the further away they are from the weather station. Farmers currently feel that the model does not accurately forecast risk of infection based on forecasted weather patterns because of the propagation of errors. Hence, the current model does not give producers enough time to take action (Haasbroek and Vermeulen, 2000).

Currently, there are no weather based forecasting systems in SA that predict the likelihood of SBR infection. The only early warning system in use is the planting of sentinel crops in soybean producing areas, such as Greytown, Kestell, Piet Retief, Potchefstroom and Winterton. Sentinel soybean plots are planted at an earlier date than the commercial soybean crop. It is intended that the sentinel crops mature earlier than the commercial crops and therefore reach the vulnerable stage of flowering earlier in the season. If the earlier maturing sentinel crops become infected, then this gives an early indication that commercial crops are likely to also be infected. Soybean producers are warned of the presence of SBR via SMS (cell phone message) or an alert on the farm radio network (Craven, 2008).

5.3 Forecasting models in South Africa

The South African Weather Service (SAWS) currently provides a short-term (1 to 2 days) and medium-term weather forecast (3 to 7 days) and a long term weather forecast. The short term weather forecast is based on current observed temperatures and rainfall. Two temperature forecasts are done per day, one in the morning, which is valid for that day and one in the evening, which is valid for the following day. Rainfall is forecast in the evening for the following day (Banitz, 2001). This information is available to the public through the SAWS website. The long term weather forecast is based an objective multi-model Prediction System. This allows for the forecasting of future weather based on different models and a forecast expressed as a difference from normal conditions for 1, 2 and 3 month periods. Other weather forecasting systems are being developed and run in SA. The University of Stellenbosch, in a project funded by the Water Research Commission (WRC), adapted an Australian developed model, called the Conformal Cubic Atmospheric Model (C-CAM), to local conditions and so far have had highly accurate forecasts, especially in the eastern parts of the country (Holtzhausen, 2005).

The Climate System Analysis Group (CSAG) is based at the University of Cape Town, South Africa. This group is involved with climatic modeling at a regional and global scale, with practical applications as well as scenarios response to global climate change. One application which is a core focus of the group is the application of seasonal forecasts for agricultural and water use. Data, information and support material are available through the CSAG data portal (CSAG, 2009).

Ghile and Schulze (2008) developed a GIS based forecasting framework which transformed immediate (today), near real time (up to 7 days) as well as distant future (up to one season) weather and climate forecasts into agrohydrological forecasts at quaternary catchment scale. This framework describes how weather and climate forecasts, which may have little immediate practical application to decision making can be converted into useful inputs into models, such as ACRU, which allows for practical and applied forecasts with greater informative value to users. An in-depth overview of this forecasts framework would be of great value in the development and application of a SBR forecasting system.

The development of a SBR early warning system could be based on the principles used in the weather and fire forecasting systems in SA. By examining the shortcomings and successes of the DMEW model, an understanding of the complications of applying a crop disease model to South African conditions can be better understood and accounted for during the development process. An understanding of the collection, analysis and development of risk indictors can also be understood by studying the DMEW model. DMEW tends to lean towards a user based package, where individual users input data and calculate the risk levels for their specific farms. This allows for site specific risk calculations. However, it may also allow for misunderstanding in the interpretation of risk levels as well as misuse of the model (Haasbroek and Vermeulen, 2000). The fire warning system also provides a good understanding of the analysis and conveying of near real time risk data to the parties concerned. It is a central based model, where data are input and analysed by a central management team. Data are categorised into risk levels and conveyed to the parties concerned (DWAF, 2004). An analysis of the two types of models (user based and central based) will provide useful information into the type of model that should be considered for the SBR early warning system.

An understanding of the weather forecasting model and availability of recent data are essential as this is the likely source of forecast weather data to be used in the SBR forecasting system. An analysis into the accuracy of the 2 day weather forecast was done by Banitz (2001) and it is important to account for these inaccuracies as they will be amplified by the disease forecast and decrease the reliability and accuracy of the early warning.

5.4 Forecasting Framework

5.4.1 Temporal scale of forecasting

The temporal scale of the forecast is important. Forecasts on the likelihood of conditions for infection being met need to be delivered to users (mainly farmers) with sufficient time to make an informed decision about the action they wish to take. The reaction time of the forecast is largely determined by the time it takes for a farmer to implement a spray from the time the warning is received (Skelsey *et al.*, 2008). Near real time forecasts, based on current weather conditions (Figure 5.1, Point a) will provide an accurate assessment of the likelihood of infections at the present moment. However, this requires the collecting of near real time data on a continuous basis and speedy processing from the model. In SA, upkeep and maintenance of weather stations is often neglected, or data are manually recoded. This makes the automation of a warning system difficult. Automated weather stations which are maintained regularly are necessary if an up-to-date and accurate near real time forecast system is to be maintained.

Future forecasts of the likelihood of future conditions being suitable for SBR infection are also possible. The lead time of the disease forecast depends on the duration of the weather forecast available (Figure 5.1, Point b). Currently SA provides a reasonably accurate forecast of up to 4 days. Using there values, a predication of climatic vulnerability for SBR infection of up to 4 days may be given, allowing sufficient response time for soybean producers to prepare and apply fungicides, if needed. The forecast can be rerun daily, allowing for an up-to-date risk analysis of current conditions suitable for SBR and an up-to-date analysis of forecast risk of SBR using the latest revised forecast weather data.

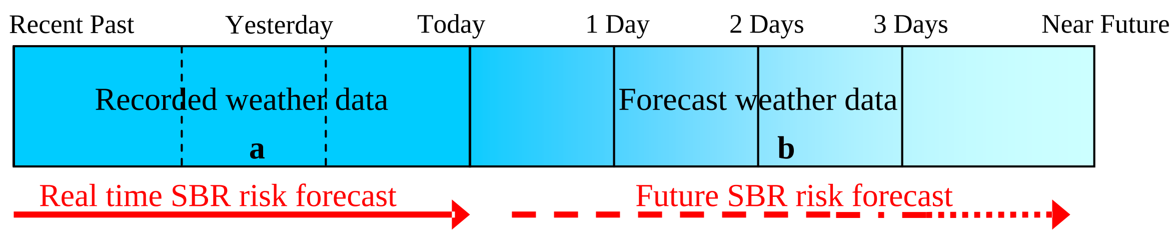

Figure 5.1 Graphic depiction of the time scale of the soybean rust forecast based on available and forecast weather data.

5.4.2 Spatial scale of forecast system

The spatial scale of the forecast is important as it needs to be of a high enough resolution to allow soybean producers to access accurate data of their specific location. However, the finer the scale, the more data the forecasting systems needs to handle, and the more difficult and expensive the system becomes to develop and to maintain. The spatial scale of the system will ultimately depend on the availability of weather stations or the accuracy of recent weather forecasts. The accuracy of the SBR forecast will also depend on the proximity of the soybean field to the weather station. Weather station data are for a point location and the accuracy of the forecast will decrease the further away the site is from the weather station. One way of overcoming this would be to integrate point weather data with a spatial database, such as the Quinary Catchment database. This allowed for the application of the model to any area needed, not restricting it to areas where data were available. However, research is needed to establish the accuracy of such interpolations.

Interpolation has been used for many weather and other databases in SA, including the database used to map historical risk to SBR in SA in this research (*c.f.* Appendix A, B and C) (Lynch, 2004 ; Schulze and Maharaj, 2004; Schulze *et al*., 2009. However, one of the limitations of interpolation arises from the complex and non-uniform landscape found in SA. Interpolation assumes a uniform landscape and in many areas of SA, and in particular the soybean producing areas, this is not the case. Various interpolation methods would need to be tested and the most suitable method for the SA context selected.

5.4.3 Error assessment

There are many points in a forecasting system where an error may be introduced. These errors need to be identified and understood in order to minimize and mitigate the impact they have on the forecast. Errors that may arise from the data include:

- Incorrectly recorded data,
- Spatial errors due to point data being applied over a large area, and
- Spatial errors due to interpolation.

Errors may also arise from the algorithm which may under- or over-estimate the likelihood of infection. Total errors would be the combination of data errors and algorithm errors. Further research is necessary to understand the extent and implications of these errors on the forecast and to possibly correct them.

5.5 Farmer Spraying Practices

The value of an early warning system to producers can be determined by the extent to which it improves decision making and help with the implementation of timely responses to warnings. An early warning system will help reduce losses of yield by warning soybean producers when to apply fungicides or reduce economic production costs by preventing unnecessary fungicide applications when conditions are unsuitable for infection (Roberts *et al.,* 2005; Skelsey *et al.,* 2008).

In order for the warning system to operate at a level that is useful for soybean producers, an understanding of farmers' current spraying practices is needed. It is recommended that interviews be carried out with soybean producers to gain better understanding of standard spraying practices to aid in the development of this warning system. Currently soybean producers in areas where the disease is considered epidemic, are spraying every year regardless of whether or not local conditions are suitable at the time or whether there have been any outbreaks reported. In areas of new outbreaks, soybean producers spray as soon as they receive a report of SBR in their area. Soybean producers tend to spray fungicides at least once, and often twice, depending on the severity of the disease reported. The first application will be applied during flower emergence and then followed by a spray 3 to 4 weeks later. In areas where local conditions make access to the fields difficult, soybean producers may spray earlier rather than later, and so additional applications may be applied.

The time it takes for farmers to prepare and apply fungicides depends on their level of preparation. If the soybean producers has the fungicides ready and their own means of application (tractor or self driven sprayer), it takes approximately 24 hours to prepare and apply the fungicide from the time the decision is made. However, if the farmers need to apply the fungicide aerially, it may take up to a week to book the aircraft and plan the spray. This preparation time has an effect on the value of a forecasting system. If a near real time warning is sent out, soybean producers need to be prepared to spray within 24 hours in order to mitigate the risk of infection. If they are unprepared when the warning goes out, the system will be of no value. Specialists felt that forecast warnings of up to a week will allow soybean producers enough time to prepare for spraying (Dunlop, pers. comm..; Hackland, pers. comm.; Jarvie, pers. comm.; Liebenberg, pers. comm.; van Wyk, pers. comm.).

5.6 System Development Process and Proposed Warning System Architecture

The proposed warning system architecture is illustrated in Figure 5.2. A record of weather data would be compiled. This would be collected from observed weather data, from the recent past up until the present day, and forecast data for as long as is available. Various forecasts are available in South Africa, varying in length from 1 day to three months upwards. Data would be run through the SBR algorithm to obtain an index rating for each day in the weather record. This may need to be converted into user friendly categories such as conducive, optimal and not conducive. The forecast categories would be passed onto users (soybean producers and other interested parties) through a warning system utilising either cell phone SMS, computer email or a risk map on the internet. It may be necessary to incorporate an accuracy assessment to give users an indication of the confidence level of the warning. Based on the current and forecast index values and the current stage of development in the individual producer's crops, they can then make an informed decision on whether or not to apply fungicides.

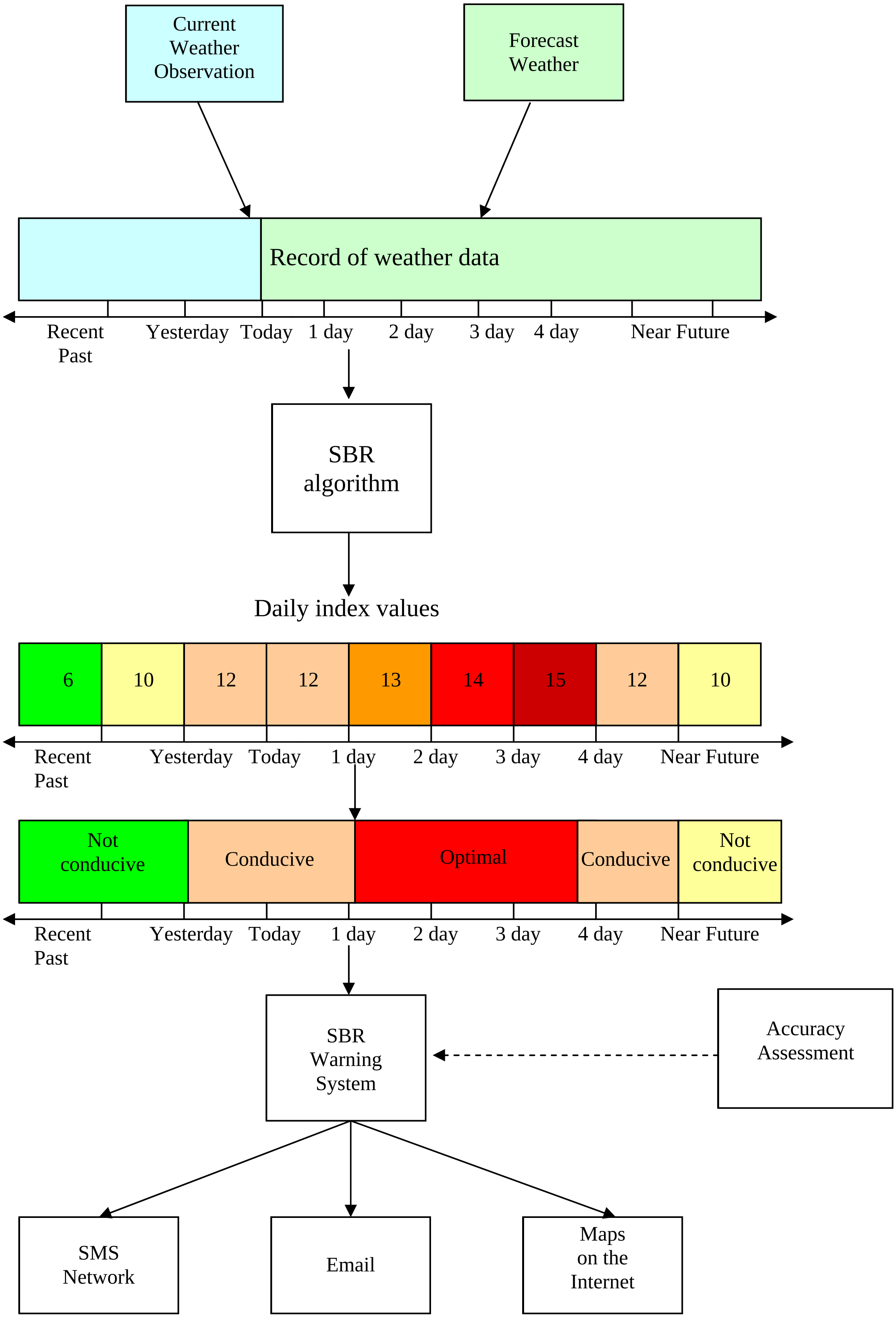

Figure 5.2 Diagram of soybean rust early warning system architechture.

More research into the functioning and the application of this system is needed. An assessment of the best suited (most accurate for application to the SBR index to southern Africa) weather forecast should be undertaken. A means of doing this would be to collect the records of forecast weather values, and run the model with the forecast data, resulting in a one week forecast for each day, indicating the likelihood of a SBR infection. This would need to be compared to the actual recorded weather data and the recorded SBR outbreaks, to determine the most suited forecast for predicting SBR infection. The length of the forecast best suited to producers' spraying practices needs to be investigated. This will determine the maximum length of forecast required, i.e. 1 week. The system can then be updated regularly with the best available forecast and the likelihood of a SBR infection represented on a map or as a index rating for specific areas.

6. CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Conclusion

Loses of soybean yield caused by the fungus *Phakopsora pachyrhizi* Syd. (Soybean rust) have a potentially devastating effecting on the soybean industry in South Africa. There have been reports of SBR on commercial soybeans every year since its arrival in 2001 (Jarvie, 2009). *P. pachyrhizi* has very specific epidemiological requirements for infection to take place. This means that it is possible to create a model, based on the epidemiological requirements which will represent the climatic vulnerability of infection at different periods of the soybean production season. This research has shown that overall the climatic potential of infection in all of the major soybean producing areas is great. However, the vulnerability of specific areas varies, allowing producers in specific areas to indentify the level and period of most risk for their area. The results of this research may aid producers to make better informed decision regarding the necessity and timing of fungicide applications.

In SA no work had been done on modelling the long term climatic vulnerability of different soybean producing areas to SBR infection. The algorithm developed in this research successfully predicted the historical climatic vulnerability to SBR infection in the soybean production regions of SA. The soybean production areas in KZN experience moderate to high climatic vulnerability throughout the season. Risk generally increase rapidly in the beginning of the season, therefore most areas would not benefit from planting early maturing cultivars. Risk typically peaks in February (at between 50% and 70%) and decrease rapidly after the beginning of March. Producers may be able to plant late maturing cultivars which mature after the risk begins to decrease, thereby reducing the climatic vulnerability to infection. If crops are going to mature during a high risk period, producers are advised to apply fungicides to prevent crop losses.

The northern soybean production regions experience varied degrees of climatic vulnerability. Producers in most of Limpopo and northern North-West province experience high climatic vulnerability to infection throughout the year and are advised to apply preventative fungicides to prevent yield losses. In the areas around Mookgophang in Limpopo risk is more variable.

Producers may wish to still apply preventative fungicides every year, however producers in this area would likely to benefit greatly from an early warning system which warned them when conditions were climatically suitable for infection. This would allow them to spray only when there was a climatic chance of infection, potentially reducing the cost of applying fungicides under uncertain conditions. Gauteng and central to southern North-West province experience lower climatic vulnerability to SBR infection. The use of late maturing cultivars and an early warning system will allow producers to only spray when conditions are suitable for SBR infection, reducing unnecessary fungicide applications, thereby reducing production costs while still ensuring high yields.

In the central soybean production regions experience varied climatic vulnerability. The areas in the north and east of Mpumalanga as well as Swaziland experience high climatic vulnerability to SBR infection and producers in these areas may be advised to carry out annual preventative spraying to prevent yield losses. In the central and southern parts of Mpumalanga, eastern Free State and Lesotho, the climatic vulnerability of SBR infection is low. Soybean producers in these areas have very low climatic vulnerability of SBR infection and may not need to carry out any preventative control methods. The areas in central and western Free State experience varied degrees of climatic vulnerability. Producers in these areas may benefit form an early warning system which would warn them when conditions were suitable for SBR infection. This would allow then to apply fungicides only when conditions were conducive for infection, preventing unnecessary production costs while still ensuring high yields.

The forecasting framework outlines how an early warning system for SBR might be developed. The framework proposes that recently recorded weather data be amalgamated with forecast weather data and run through the SBR algorithm. This would give an indication of the near real time and forecast climatic vulnerability of SBR infection. The framework outlines some important consideration to be undertaken when developing such a system as well as some recommendations for the running of the system.

Soybean rust is a considerable threat to soybean producers in SA. In some areas, the annual application of fungicides is the only viable control methods, until resistance is developed. However, in other areas the use of either early or late cultivars may allow farmers to producer good yields that mature before or after periods of high risk, allowing for high yields without the application of fungicides. This will reduced production costs, help prevent pathogen resistance to fungicides and reduce the environmental impact of soybean production. Other areas may benefit from an early warning system which will provide producers with an estimation of the current and forecast climatic vulnerability. Producers can then make an informed decision regarding the necessity to apply fungicides based on the phonological stage of their crop and the climatic vulnerability.

6.2 Recommendations for Future Research

This research has resulted in an algorithm to aid soybean producers' understanding of the long term climatic vulnerability of their area to SBR infection. This research has also highlighted many difficulties and shortcomings in the data and decision support tools available for understanding the potential impact of SBR on commercial soybean production. Outlined below are some recommendations for future research which may help improve the understanding and management of this destructive soybean disease.

The model developed through this research used rainfall as an indication of leaf wetness. It was assumed that rainfall would either directly wet the leaves or would result in evaporation which would create humidity resulting in leaf wetness. However, other forms of precipitation may also result in leaf wetness. Further research may be necessary to include the effects of mist, fog and relative humidity on leaf wetness, into the SBR model.

The development, verification and accuracy assessment of the model were based on limited data. Further research into verification and accuracy assessment of the model using independent and accurate data from soybean production areas around the country, and in other soybean producing countries, is recommended to improve the robustness of the model.

Soybean rust infection is dependent on three variables, *viz.* availability of spores, climatic vulnerability and host plant physiological vulnerability. This research focused on climatic vulnerability. However, closely linked to this is the physiological vulnerability of host plants. Soybean rust infects when the plant has reached the flowering stage. This stage depends on the cultivar used, either early or late maturing and environmental conditions, *viz.* the shortening of day length and air temperature. It has become apparent during this research that certain soybean production areas may be able to limit the chances of SBR infection by planting cultivars that mature before or after high risk periods. Therefore, further research into which cultivars are most suited to which areas should be undertaken. This will allow for the identification of cultivars best suited to certain areas to limit chances of infection based on maturation rate and reduce the need for the application of fungicides. Further research into spore availability is also necessary. Models incorporating spore availability and dispersal patterns (including wind dispersal) would strengthen the model.

The near real time forecasting system would provide valuable warnings to soybean producers when climatic conditions are suitable for SBR infection. This will allow soybean producers to only spray when conditions are suitable, preventing unnecessary fungicide applications, lowering production costs, help prevent the pathogen developing resistance to fungicides and reducing any negative environmental impacts from fungicide application. However there are several obstacles to be overcome before this system can be successfully developed. Firstly, a network of functioning weather stations which are serviced regularly needs to be in operation. Some areas lack weather data as there are no stations in these areas. If interpolation methods are used, then various interpolation methods would need to be tested and the most suitable method selected. It is possible that new weather stations may have to be built in soybean production areas in order to allow a good coverage of stations to provide accurate data. This would improve the spatial scale of the data and improve the output of interpolated data.

It is recommended that interviews be carried out with soybean producers to aid in the development of the warning system. This will provide more information on current producer's practices and help gain a better understanding of what producers would hope to gain from a warning system.

Forecast weather data may have errors and associated uncertainty. Data errors, together with model uncertainty, will result in an overall forecast error. An assessment of the accuracy of the forecast weather data needs to be undertaken. This will aid in the understanding of the uncertainty associated with the SBR forecast and will allow for a level of uncertainty to be issued with the forecast.

7. REFERENCES

Agrios, G. E. 1997. *Plant Pathology*. 5th edition. Academic Press, New York, USA. 573-574.

Akinsanmi, O. A., Ladipo, J. L. and Oyekan, P. O. 2001. First report of SBR *(Phakopsora pachyrhizi)* in Nigeria. *Plant Disease*: 85: 97.

Allen, R.G., Pereiera, L. S., Raes, D. and Smith, M. 2006. Crop Evapotranspiration. *FAO Irrigation and Drainage* 56: 41-49.

Anonymous. 2002. *NPAG Data: Phakopsora pachyrhizi Australasian Soybean Rust.* United States Department of Agriculture Animal and Plant Health Inspection Service. USA. http://www.aphis.usda.gov/plant_health/plant_pest_info/soybean_rust/downloads/UreMelPp502.pdf. Accessed 05/05/2008.

Anonymous. 2007. *Asian soybean rust in the USA - 2007 final report* http://www.sbrusa.net/cgi-bin/sbr/public.cgi. Accessed 13/02/2008.

Aspinall, R. 1991. Use of an inductive modelling procedure based on Bayes Theorem for analysis of patterns of spatial data. In: Farmer, D. G and Rycroft, M. J. (Eds.) *Computer modelling in the environmental sciences.* Clarendon Press, Oxford, UK: 325-339.

Banitz, E. 2001. Evaluation of short-term weather forecasts in South Africa. *Water South Africa* 27: 489-498.

Batchelor, W. D., Yang, X. B. and Tschanz, A. T. 1997. Development of a neural network for soybean rust epidemics. *Transactions of the ASAE* 40: 247-252.

Block, T. 2003. U.S. Soybean Growers Warily Eye Spreading Invasive Rust Disease. *American Farm Bureau*, USA.

Bromfield, K. R. 1980. SBR: some considerations relevant to threat analysis. *Protection Ecology* 2: 251-257.

Bromfield, K. R. 1984. *SBR, Monograph* (Americans Phytopathology Society). No. 11. American Phytopathological Society. St. Paul, USA.

Bromfield, K. R. and Hartwig, E. E. 1980. Resistance to SBR (*Phakopsora pachyrhizi*) and the mode of inheritance. *Crop Science* 20: 254-255.

Burger, L. 2009. No nonsense no-till (part 2). http://www.dairyconnect.co.za/dairyMail/issues/apr2009/no_till.djhtml. Accessed 27/05/2009.

Caldwell, P. M. and Laing, M.D. 2002. Soybean rust – A new disease on the move. Southern African Society for Plant Pathology Monthly Feature, March 2002. http://saspp.org/content/view/20/11/. Accessed February 2010.

Caldwell, P. M., Laing, M.D. and Ward, J. 2002. The threat to South African soya crops continues. *Farmer's Weekly*. Republican Press, Johannesburg, South Africa, February: 37-39.

Clemence, B. S. E. 1986. *Estimation of spatial distribution of pan evaporation over southern Africa*. Unpublished MSc dissertation, University of Natal. Pietermaritzburg, South Africa.

Climate System Analysis Group. 2009. *Information fact sheet.* Environmental and Geographical Sciences. University of Cape Town. http://www.csag.uct.ac.za. Accessed 27 October 2009.

Craven, M. 2008. Monitering help om sojaboonroes te bekamp. *SA Graan* 10: 46-47.

de Groot, W. J., Goldammer, J. G., Keenan, T., Brady, M. A., Lynham, T. J., Justice, C. O., Csiszar, I. A. and O'Loughlin, K. 2006. Developing a global early warning system for wildland fire. In: Sivakumar, M. V. K and Motha, R. P. (Eds.) *Managing Weather and Climate Risks in Agriculture.* Springer. Berlin, Heidelberg: 355-366.

Del Ponte, E. M. Departamento de Fitossanidade, Faculdade de Agronomia, Universidade Federal do Rio Grande do Sul. Porto Alegre. Brazil. Contact Details: emerson.delponte@ufrgs.br

Del Ponte, E. M. and Esker, P. D. 2008. Meteorological factors and Asian Soybean rust epidemics – A systems approach and implications for risk assessment. *Science and Agriculture: Special Edition* 65: 88 – 97.

Del Ponte, E. M., Godoy, C. V., Canteri, M. G., Reis, E. M. and Yang, X. B. 2006a. Models and applications for risk assessment and predication of Asian Soybean Rust epidemics. *Fitopatology Brasil* 31: 533-544.

Del Ponte, E. M., Godoy, C. V., Li, X. and Yang, X. B. 2006b. Predicting severity of Asian soybean epidemics with empirical rainfall models. *Phytopathology* 96: 797-803.

Dent, M. C., Lynch, S. D. and Schulze, R. E. 1989. *Mapping mean annual and other rainfall statistics over southern Africa.* WRC Report No. 109/1/89. Water Research Commission, Pretoria, South Africa.

Department of Water Affairs and Forestery. 2004. *South Africa leads with launch of fire warning system.* http://www.woodsa.co.za/WoodSA/article.asp. Accessed 14/08/2009.

Dunlop, Eve. Protein Research Foundation Soybean Rust Task Team. Greytown, South Africa. Contact details: eve.dunlop@pannar.co.za

du Preez, E. 2005. *Chemical control of soybean rust* (*Phakopsora pachyrhizi*) *of soybeans.* Unpublished MSc dissertation. University of KwaZulu-Natal. Pietermaritzburg, South Africa.

Duxbury, M. R., Birch, E. B., Parson, M. J. and Greenfield, P. L. 1990. Introduction and Environmental Requirements. *Soyabeans in Natal.* Pietermaritzburg, South Africa.

Frederick, R. 2008. *Soybean Rust.* Home and Garden Information Center. USA. www.hgic.umd.edu/content/soybeanrust.cfm. Accessed 30/05/2008.

Haasbroek, P. and Vermeulen, A. 2000. New and future warning systems for downy mildew. *Wynboer: A technical guide for wine producers.* http://www.wynboer.co.za/recentarticles/0410early.php3. Accessed 19/08/2009.

Hackland, Nigel. Protein Research Foundation Soybean Rust Task Team. Rivonia, South Africa. Contact details: Nigel.hackland@basf.com

Hardisty, J., Taylor, D. M. and Metcalfe, S. E. 1993. *Computerised Environmental Modelling: A practical introduction using Excel.* John Wiley and Sons, West Sussex, UK.

Hartman, G. L. 1995. Highlights of SBR research at the Asian Vegetable Research and Development Center. In: Sinclair, J. B. and Hartman, G. L. (Eds.) *Proceedings of the Soybean Rust Workshop,* 9-11 August 1995. College of Agriculture, Consumer and Environmental Science, National Soybean Research Laboratory Publication Number 1, Urbana, Illinois, USA: 19-28.

Hartman, G. L., Sinclair, J. B. and Rupe, J. C. 1999. *Compendium of soybean diseases.* 4th edition. Minnesota, USA.

Hartman, G. L., Miles, M. R. and Frederick, R. D. 2005. Historical viewpoint and soybean resistance to soybean rust. *Proceedings of the 2005 Illinois Crop Protection Conference*. Illinois, USA: 16-20.

Holtzhausen, L. 2005. Project provides new tools for weather man's toolbox. *Water Wheel July/August 2005.* http://www.worldwatercouncil.org/fileadmin/wwc/Sections_for/Journalists/Water_Media_Program/wmp_resources_Holtzhausen_23.08.05.pdf Accessed 14/08/2009.

Isard, S. A., Main, C. E., Keever, T., Magarney, R., Redlin, S. and Russo, J. M. 2004. *Weather based assessment of soybean rust threat to North America: First year report to Aphis.* United States Department of Agriculture, Animal and Plant Health Inspection Services. https://netfiles.uiuc.edu/ariatti/www/SBR/Rep_15Jul04.htm. Accessed on 30/05/2008.

Jarvie, Antony. Protein Research Foundation Soybean Rust Task Team. Greytown, South Africa. Contact details: antony.jarvie@pannar.co.za

Jarvie, J. A. 2009. A review of soybean rust from a South African perspective. *South African Journal of Science* 105: 103-108.

Johnston, K., Ver Hoef, J. M., Kirvoruchko, K. and Lucas, N. 2001. *Using ArcGIS Geostatistical Analyist.* Environmental Systems Research Institute, Redlands CA, USA.

Jun, Z. 1999. SOYGRO model used for simulation of soyabean yield. *Soybean Science* 18: 67-72.

Killgore, E. M. 1995. Field Notes on the Detection of Soybean Rust, Initial Surveys and the Current Status of the Disease in Hawaii. In: Sinclair, J. B. and Hartman, G. L. (Eds.) *Proceedings of the Soybean Rust Workshop,* 9-11 August 1995. College of Agriculture, Consumer and Environmental Science, National Soybean Research Laboratory Publication Number 1, Urbana, Illinois, USA: 38-45.

Kim, K. S., Wang, T. C. and Yang, X. B. 2005. Simulation of apparent infection rate to predict severity of soybean rust using a fuzzy logic system. *Phytopathology* 95: 1122-1131.

Kloppers, R. 2002. *New soybean disease in SA.* http://saspp.org/content/view/34/16/. Accessed 25/05/2008.

Koch, E., Ebrahim-Nesbat, F. and Hoppe, H. H. 1983. Light and electron microscopic studies on the development of Soybean Rust (*Phakopsora Pachyrhizi* Syd) in susceptible soybean leaves. *Phytopathology* 106: 302-320.

Kunz, R. P. 2004. *Daily rainfall data extraction utility: User manual v 1.0.* Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Lalancette, N. and Hickey, K. D. 1986. Disease progression as a function of plant growth. *Phytopathology* 76: 1171-1175.

Levy C. 2003. Measures to control soybean rust in southern Africa and initial investigation of the meteorological factors that favour its development. *Phytopathology* 93: 103.

Levy, C., Techagwa, J. S. and Tattersfield, J. R. 2002. The status of SBR in Zimbabwe and SA. In: Moscardi, F., Hoffmann-Campo, C. B., Saraiva, O. F., Galerani, P. R., Krzyzanowski, F. C., Carrão-Panizzi, M. C. (Eds.) *Proceedings VII World Soybean Research Conference.* 29 February – 5 March 2004, Foz de Iguassu, Brazil: 354-360.

Lin, S. Y. 1966. Studies on the physiological races of the SBR fungus, *Phakopsora pachyrhizi* Syd. *Journal of Taiwan Agricultural Research* 15: 24-28.

Liebenberg, Andries. Protein Research Foundation Soybean Rust Task Team. Potchefstroom, South Africa. Contact details: LiebenbergA@arc.agric.za

Linsley-Noakes, G. C., Louw, M. and Allan, P. 1995. Estimating daily positive Utah chill units using daily minimum and maximum temperatures. *Journal of South African Horticultural Science* 5: 19-23.

Littlefield, L. J. 1981. *Biology of the Plant Rusts.* Iowa State University Press, USA.

Lynch, S. D. 2004. *Development of a raster database of annual, monthly and daily rainfall for southern Africa*, WRC Report No. 1156/1/04. Water Research Commission, Pretoria, RSA.

Mason, S. 2002. *Analyzing and Communicating forecast quality and probability*. http://www.adpc.net/ece/ACT_Man/ACT-3.3-ForecastQuality.pdf Accessed 08/09/2009.

Miles, M. R., Frederick, R. D. and Hartman, G. L. 2003. *Soybean Rust: Is the U.S.Soybean Crop at Risk?* http://www.apsnet.org/online/feature/rust/. Accessed 13/02/2008.

Morel, W., Scheid, N., Amarilla, V. and Cubilla, L. E. 2004. *SBR in Paraguay*. Bol de Diulgacion No. 44. Ministerio de Agricultura y Granaderia, Centro Regional de Investigacion Agricola, Capitan Miranda, Paraguay.

National Crop Estimates Committee. 2009. *Protein Research Foundation Statistics May 2009* http://www.proteinresearch.net/index.php?dirname=html_docs_030statistics_and_estimates/05100crop_estimates/050002009_season#GRAPH_SOYBEANS Accessed 21/08/2009.

Negus, S. 2007. Asian soybean rust – Canada: First report, (Ontario). *International Society for Infectious Diseases.* http://seedquest.com/News/releases/2007/november/20993.htm. Accessed 12/03/2008.

Nunkumar, A. 2006. *Studies on Phakopsora pachyrhizi, the causal organism of soybean rust.* Unpublished MSc dissertation. University of KwaZulu-Natal., Pietermaritzburg, South Africa.

Pan, Z., Pivonia, S., Pasken, R., Pietrowicz, J. and Yang, X. B. 2004. Simulation of airborne dispersal potentials from Africa to South America and from South America to North America. *Phytopathology* 94: S90.

Pan, Z., Xue, L., Del Ponte, E. M., Andrade, D., Li, X., Pasken, R. and Yang, X. B. 2005. Soybean rust dispersal predication and analysis in the US for 2005 growing season. *Proceedings National Soybean Rust Symposium.* Nashville, USA. http://www.plantmanagamentnetwork.org/infocentrer/topic/soybeanrust/symposium/posters/26.asp. Accessed 30/05/2008.

Parsons, M. J. and Birch, E. B. 1990. The soybean plant and its development. *Soyabeans in Natal.* Pietermaritzburg, South Africa.

Pivonia, S. and Yang, X. B. 2004. Assessment of the year round establishment of soybean rust throughout the world. *Plant Disease* 88: 523-529.

Pivonia, S. and Yang, X. B. 2006. Relating epidemic progress from a general disease model to seasonal appearance time of rusts in the United States: Implications for soybean rust. *Phytopathology* 96: 400-407.

Poonpolgul, S. 2004. Country report: how soybean rust is managed in Thailand. In: Moscardi, F., Hoffmann-Campo, C. B., Saraiva, O. F., Galerani, P. R., Krzyzanowski, F. C., Carrão-Panizzi, M. C. (Eds.) *Proceedings VII World Soybean Research Conference.* 29 February – 5 March 2004, Foz de Iguassu, Brazil: 335-339.

Pretorius, Z. A., Visser, B. and du Preez, P. J. 2007. First report of Asian soybean rust caused by *Phakopsora pachyrhizi* on Kudzu in South Africa. *Plant Disease* 91:1364. Abstract.

Pretorius, Z. A., Kloppers, R. J. and Frederick, R. D. 2001. First report of soybean rust in South Africa. *Plant Disease* 85: 1288.

Pretorius, Z. A. and McLaren, N. W. 2006. *Identification and Control of Soybean Rust.* Agricultural Research Council – Grain crops Institute and the Protein Research Foundation.

Reis, E. M., Satori, A. F. and Camara, R. K. 2004. Modelo climático para a previsão da ferrugem da soja. *Summa Phytopathologica* 30: 209-292.

Roberson, R. 2006. Soybean rust alert system fine tuned. *Southeast Farm Press* 33: 1-3.

Roberts, M. J., Schimmelpfenning, D., Livingston, M.J. and Ashley, E. 2005. Estimating the Value of an Early-Warning System. *Review of Agricultural Economics* 31: 303-332.

Rogers, J. and Redding, J. 2004. *USDA confirms soybean rust in United States.* USDA APHIS News Release No. 0498.04. http://www.usda.gov/wps/portal/!ut/p/_s.7_0_A/7_0_1OB? Accessed 13/02/2008.

Rossi, R. L. 2003. First report of *Phakopsora pachyrhizi*, the casual organism of SBR in the Provence of Misiones, Argentina. *Plant Disease* 68: 828-839.

Schonyers, L. E., Kemerait, R. C., Brock, J., Phillips, D. V., Jost, P. H., Sikora, E. J., Guitierrez-Estrada, A., Mueller, J. D., Marois, J. J., Wright, D. L. and Harmon, C. L. 2006. Asian soybean rust in 2005: A perspective of the south-eastern United States. Online APSnet January 2006 feature. *American Phytopathological Society*. *http://www.apsnet.org/online/feature/sbr/APSnetFeature01_2005.pdf* Accessed 01/09/09.

Schulze, R. E. and Maharaj, M. 2004. *Development of a database of gridded daily temperatures for southern Africa.* WRC Report No. 1156/2/04. Water Research Commission, Pretoria, South Africa.

Schulze, R.E. and Horan, M.J.C. 2009. Methods 1: Delineation of South Africa, Lesotho and Swailand into quinary basins. In: Tadross, M. and Schulze, R.E. (Eds). *Regional aspects of climate change and the secondary impacts on water resources*. WRC Report 1562/1/09, Section 5. Water Research Commission, Pretoria, South Africa.

Schulze, R. E., Warburton, M., Lumsden, T. G. and Horan, M. J. C. 2005. The southern African quaternary catchments database: Refinements to, and links with, the *ACRU* system as a framework for modelling impacts of climate change on water resources. In: Schulze, R. E. (Ed.) *Climate change and water resources in southern Africa: Studies on scenarios, impacts, vulnerabilities and adaptation* Chapter 8, WRC report No. 1430/1/05. Water Research Commission, Pretoria, South Africa: 111-139.

Schulze, R.E., Horan, M.J.C., Kunz, R.P., Lumsden, T.G. and Knoesen, D.M. 2009. Methods 2: Development of southern African quinary catchments database. In: Tadross, M. and Schulze, R.E. (Eds*). Regional aspects of climate change and the secondary impacts on water resources*. Water Research Commission, Pretoria, South Africa, WRC Report 1562/1/09, Section 6.

Schumann, R. A., Meyer, J. H. and van Antwerpen, R. 2000. A review of green manuring practices in sugarcane production. *Proceedings South African Sugar Technology Association* 74: 93-100.

Shanmugasundaram, S. 1999. Epidemiology and control strategies for soybean rust – A knowledge base for Africa. In Smit, M. A. (Ed.) *Proceedings of Workshop on Soybean Rust (Phakopsora pachyrhizi).* ARC Summer Grains Centre, Potchefstroom: 4 - 27.

Sharma N. D. and Mehta, S. K. 1996. SBR in Madhya Pradesh. *Acta Botanica Indica* 24: 115-116.

Shoko, M. D. and Tagwira, F. 2005. Soybean in sugarcane breakcrop systems in Zimbabwe: An assessment of potential nutrient and economic benefits. *Proceedings South African Sugar Technology Association* 79: 192-201.

Sinclair, J. B. 1982. *Compendium of soybean disease.* 2nd ed. American Phytopathological Society, St. Paul, Minnesota, USA.

Singh, R. J., Kollipara, K. P. and Hymowitz, T. 1995. Development of Hybrids between Wild Perennial Soybeans and *Glycine max* (L.) Merr. and Resistance to P*hakopsora pachyrhizi*. In Sinclair, J. B. and Hartman, G. L. (Eds.) *Proceedings of the Soybean Rust Workshop*, 9-11 August 1995. College of Agriculture, Consumer and Environmental Science, National Soybean Research Laboratory Publication Number 1, Urbana, Illinois, USA.

Skelsey, P., Kessel, G.J.T., Holtslag, A.A.M., Moene, A.F. and van der Werf, W. 2008. Regional spore dispersal as a factor in disease risk warnings for potato late blight: A proof of concept. *Agricultural and Forest Meteorology*: Article in Press.

Smit, M. and Rhodes, R. 2009a. Crop rotation with soybean. *The Link.* South African Sugarcane Research Institution 18: 4.

Smit, M. and Rhodes, R. 2009b. The UVS experience. *The Link.* South African Sugarcane Research Institution 18: 5.

Smithers, J. C. and Schulze, R. E. 2000. *Long duration design rainfall estimates for South Africa.* WRC Report No. 811/1/00. Water Research Commission, Pretoria, South Africa.

South African Weather Bureau. 1965. *Climate of South Africa.* WB 28. Department of Transport, Pretoria, South Africa.

Sutherst, R. W. and Maywald, G. F. 1985. A computerized system for matching climates in ecology. *Agriculture, Ecosystems and Environment* 13: 281-299.

Sweets, L. 2002. Soybean Rust: What's the Concern? *Integrated Pest & Crop Management Newsletter* 12:26.

Tan, Y. J., Yu, Z. and Yang, C. Y. 1996. *Soybean Rust*. China Agricultural Press. Beijeng. China.

Tempra, N. 2006. Brazilian Government Underestimated Losses with Rust. *International Society for Infectious Diseases.* http://www.seedquest.com/News/releases/2006/june/16003.htm. Accessed 12/03/2008.

Tichagwa, J. S. 2004. Breeding for resistance to soybean rust in Zimbabwe. In: Moscardi, F., Hoffmann-Campo, C. B., Saraiva, O. F., Galerani, P. R., Krzyzanowski, F. C., Carrão-Panizzi, M. C. (Eds.) *Proceedings VII World Soybean Research Conference.* 29 February – 5 March 2004, Foz de Iguassu, Brazil. 349-353.

Tobler, W. 1970. A computer movie simulating urban growth in the Detroit region. *Economic Geography* 46: 234-240.

Tschanz, A. T. and Tsai, B. Y. 1982. Effect of maturity on soybean rust development. *Soybean Rust Newsletter* 5: 38-41.

United States Department of Agriculture. 2009. *Swaziland yearly meal, soybean production.* http://www.indexmundi.com/agriculture/?country=sz&commodity=soybean-meal&graph=production. Accessed 27/07/2009.

United States Department of Energy. 2009. *Phytozome v4.0: Glycine max.* http://www.phytozome.org/soybean. Accessed 29 October 2009.

van Wyk, Wessel. Protein Research Foundation Soybean Rust Task Team. Lynnwood Ridge, South Africa. Contact details: zenzele@netactive.co.za

Venäläinen, A. and Heikinheimo, M. 2002. Meteorological data for agricultural applications. *Physics and Chemistry of the Earth* 27: 1045-1050.

Wainwright, J. and Mulligan, M. 2004. Modelling and Model Building. In: Wainwright, J. and Mulligan, M. (Eds.) *Environmental Modelling: Finding simplicity in complexity*. John Wiley and Sons. West Sussex, UK: 5-76.

Wang, T. C. and Hartman, G. L. 1992. Epidemiology of Soybean Rust and Breeding for Host Resistance. *Plant Protection Bulletin* 34:109-124.

Warburton, M. L. and Schulze, R. E. 2005. On the southern African rainfall station network and its data for climate change detection and other hydrological studies. In: Schulze, R. E. (Ed.) *Climate change and water resources in southern Africa: Studies on scenarios, impacts, vulnerabilities and adaptation.* Chapter 20. WRC report No. 1430/1/05. Water Research Commission, Pretoria, South Africa: 339-348.

Yang, X. B., Dowler, W. M. and Tschanz, A. T. 1991a. A simulation model for assessing soybean rust epidemics. *Journal of Phytopathology* 133: 187-200.

Yang, X. B., Dowler, W. M. and Royer, M. H. 1991b. Assessing the risk and potential impact of an exotic plant disease. *Plant Disease* 75: 976 – 982.

Yang, X. B., Royer, M. H., Tschanz, A. T. and Tsai, B. Y. 1990. Analysis and quantification of soybean rust epidemics from seventy-three sequential planting experiments. *Phytopathology* 80: 1421-1427.

Yorinori, J. T. 2004. Country report and rust control strategies in Brazil. In: Moscardi, F., Hoffmann-Campo, C. B., Saraiva, O. F., Galerani, P. R., Krzyzanowski, F. C., Carrão-Panizzi, M. C. (Eds.) *Proceedings VII World Soybean Research Conference.* 29 February – 5 March 2004, Foz de Iguassu, Brazil: 447-455.

APPENDIX A

Appendix A shows the map series of index values illustrating the long term climatic vulnerability for KwaZulu-Natal to soybean rust infection.

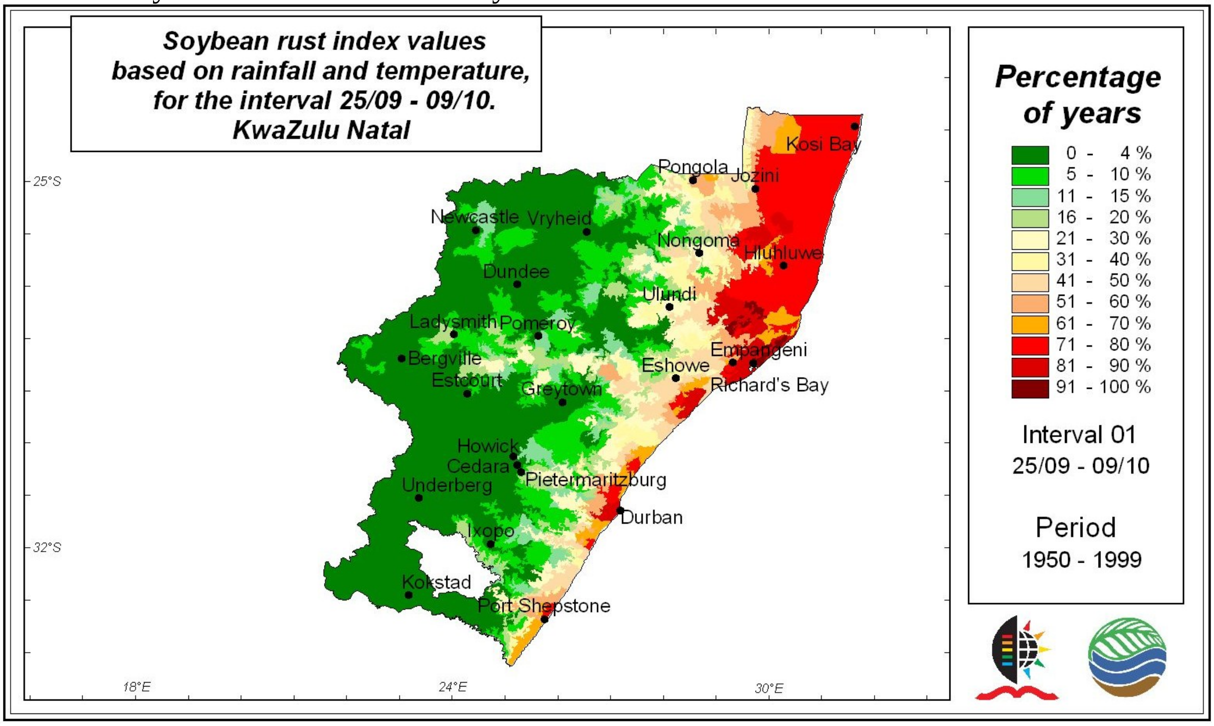

Figure A1 Soybean rust climatic susceptibility map, based on index values, for the beginning of October in KwaZulu-Natal, South Africa.

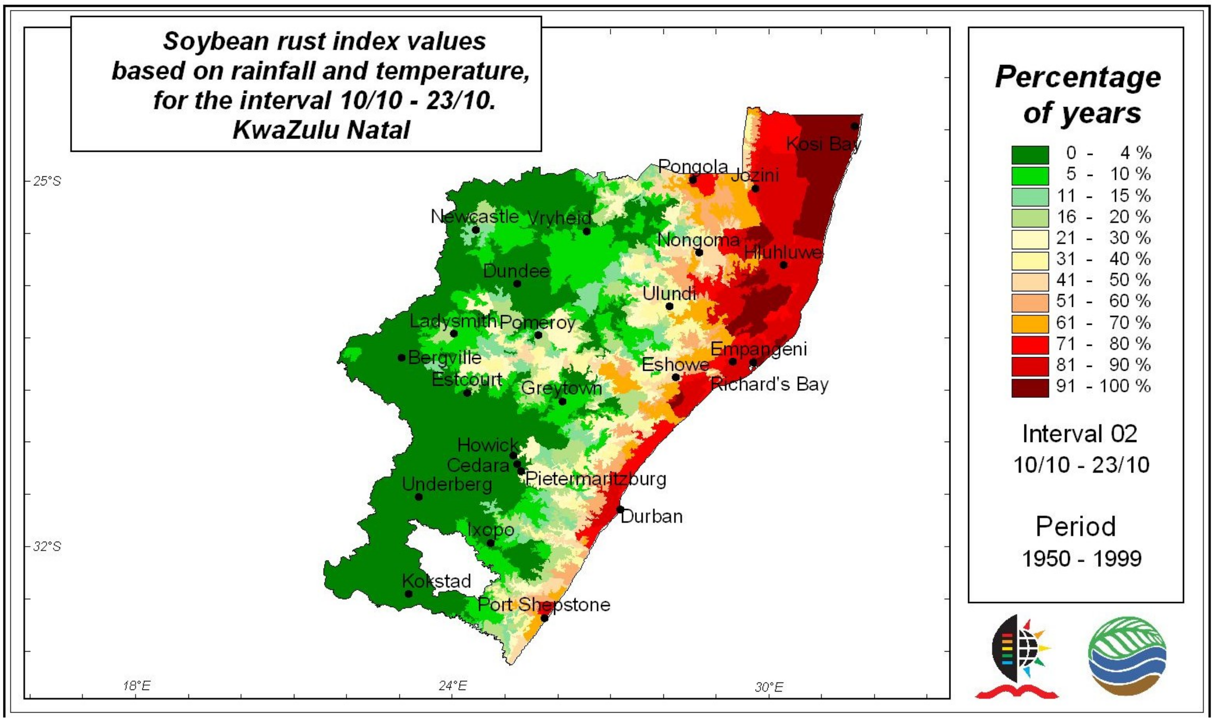

Figure A2 Soybean rust climatic susceptibility map, based on index values for the middle of October in KwaZulu-Natal, South Africa.

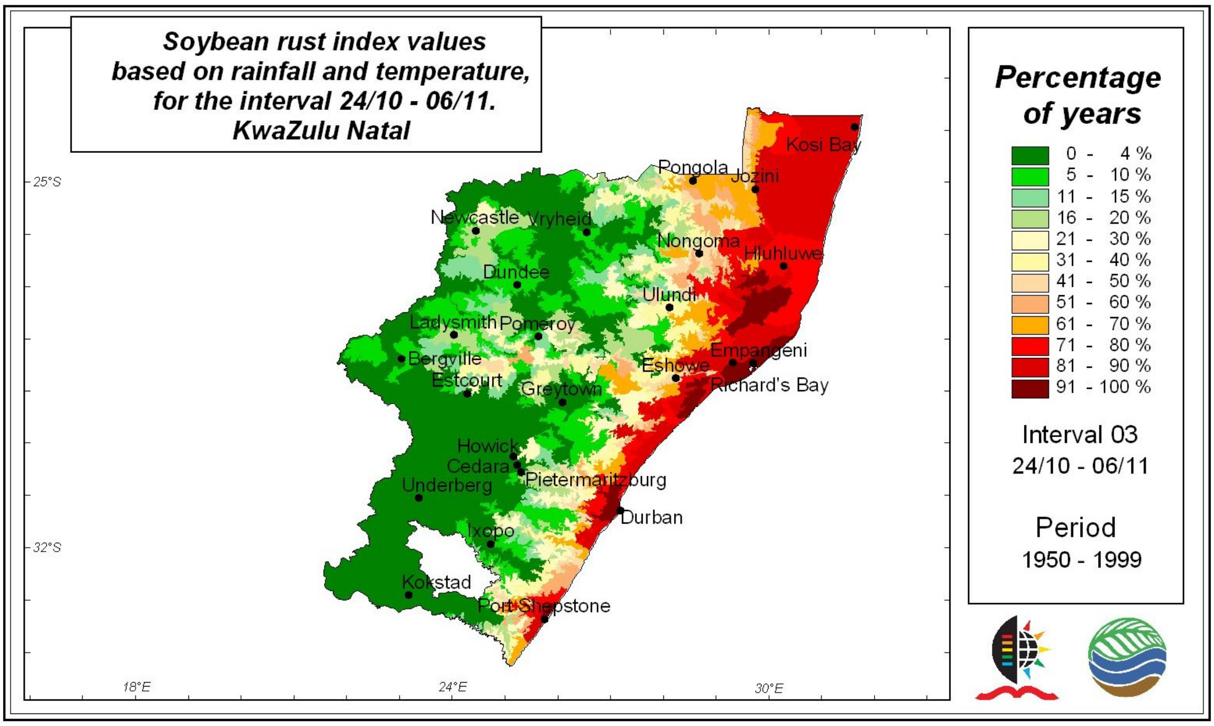

Figure A3 Soybean rust climatic susceptibility map, based on index values, for the end of October and beginning of November in KwaZulu-Natal., South Africa.

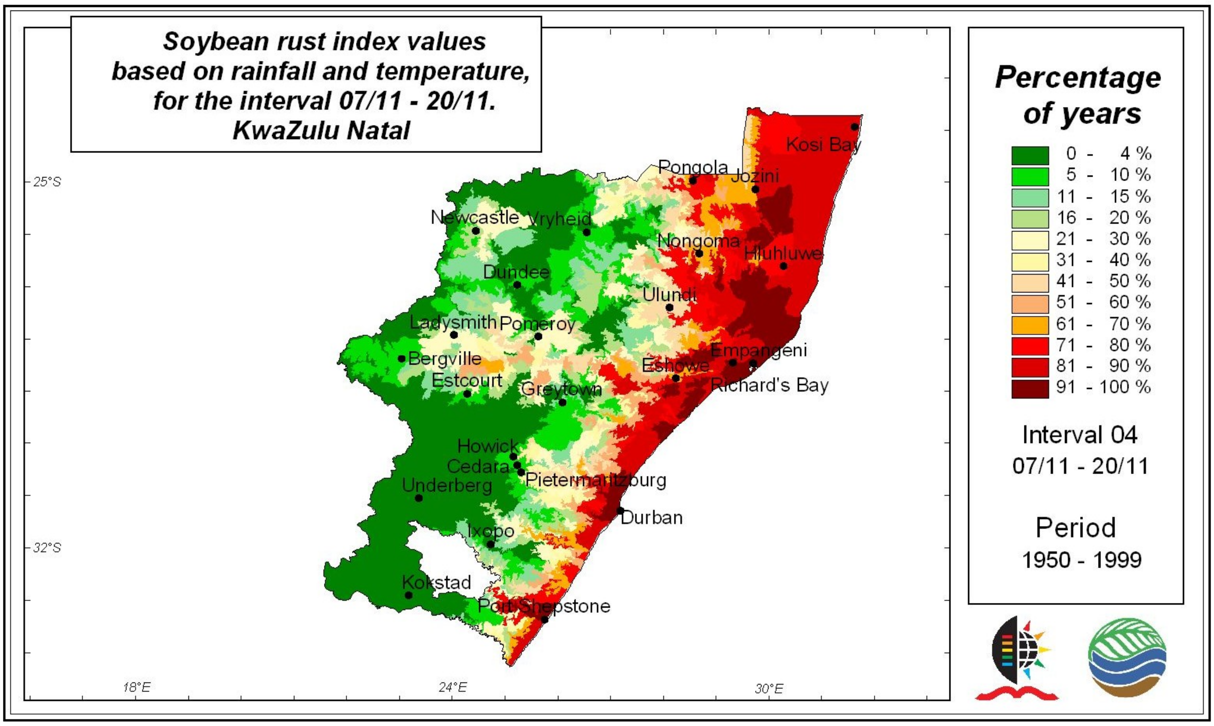

Figure A4 Soybean rust climatic susceptibility map, based on index values, for the middle of November in KwaZulu-Natal, South Africa.

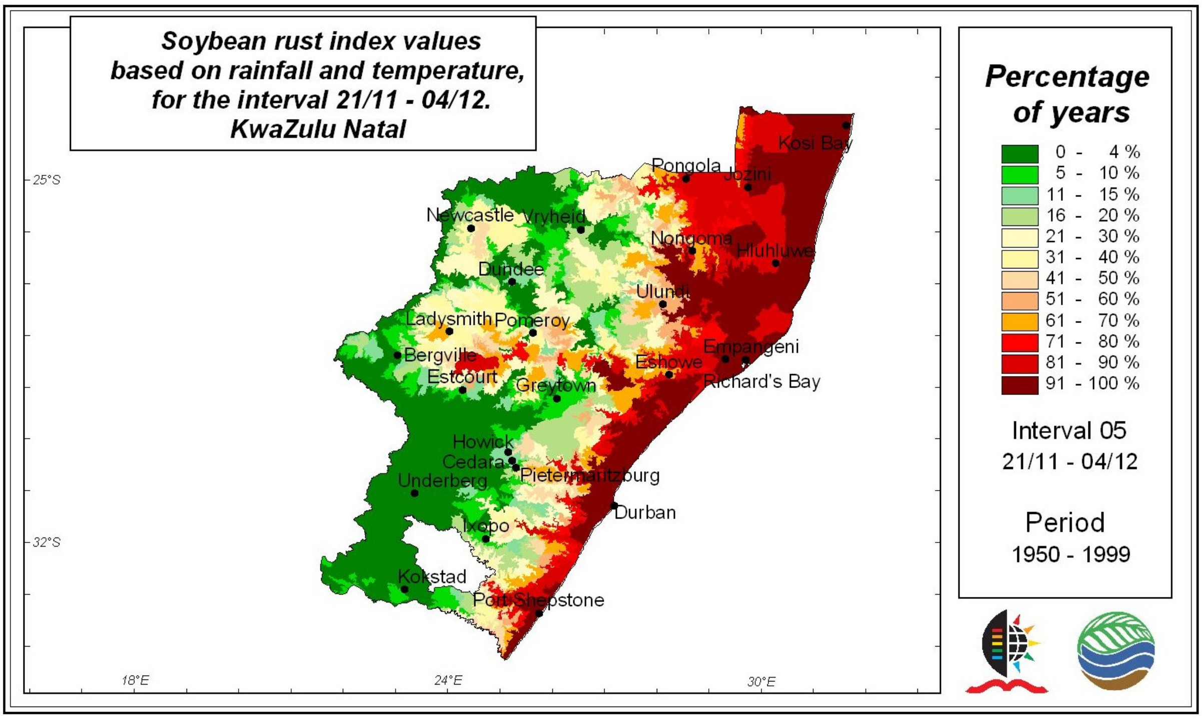

Figure A5 Soybean rust climatic susceptibility map, based on index values, for the end of November in KwaZulu-Natal, South Africa.

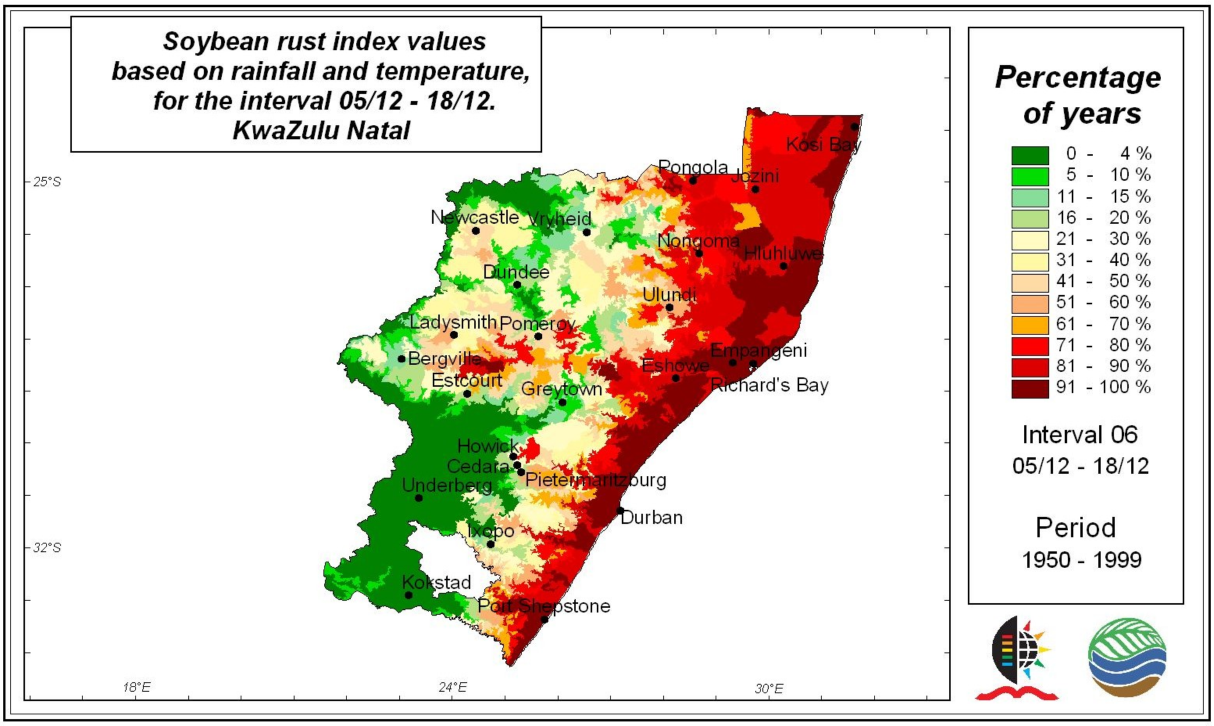

Figure A6 Soybean rust climatic susceptibility map, based on index values, for the beginning of December in KwaZulu-Natal, South Africa.

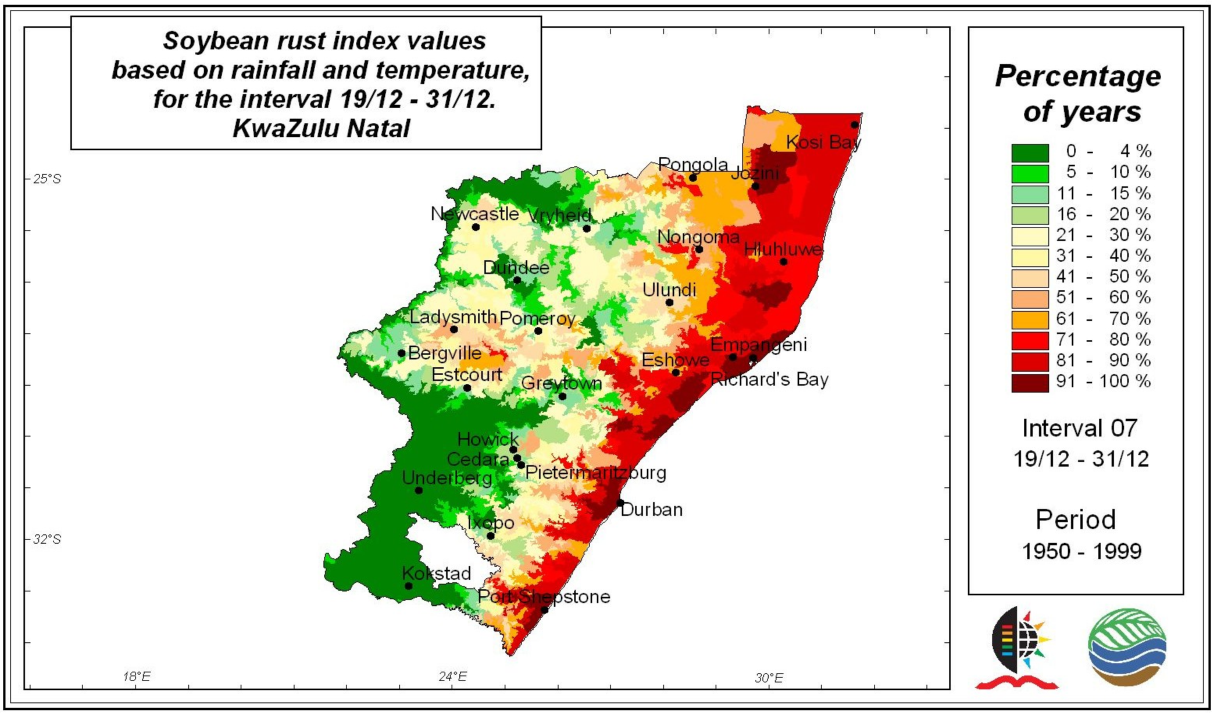

Figure A7 Soybean rust climatic susceptibility map, based on index values, for the end of December in KwaZulu-Natal, South Africa.

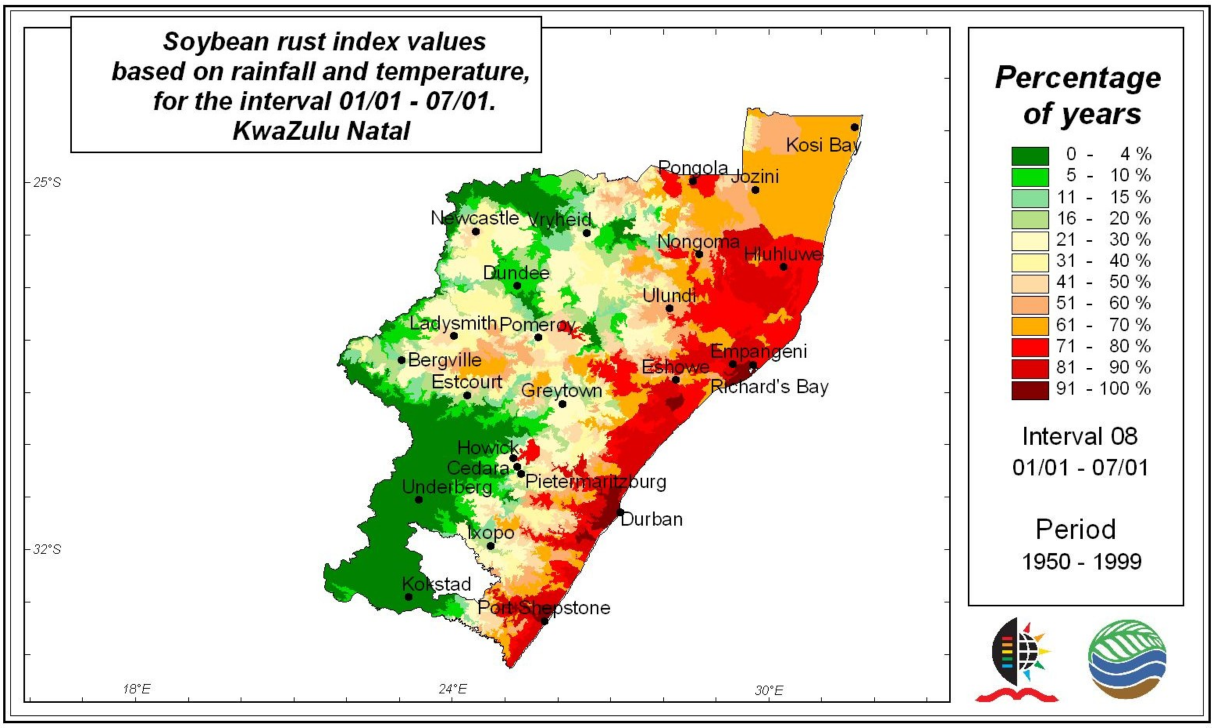

Figure A8 Soybean rust climatic susceptibility map, based on index values, for week 1 of the year in KwaZulu-Natal, South Africa.

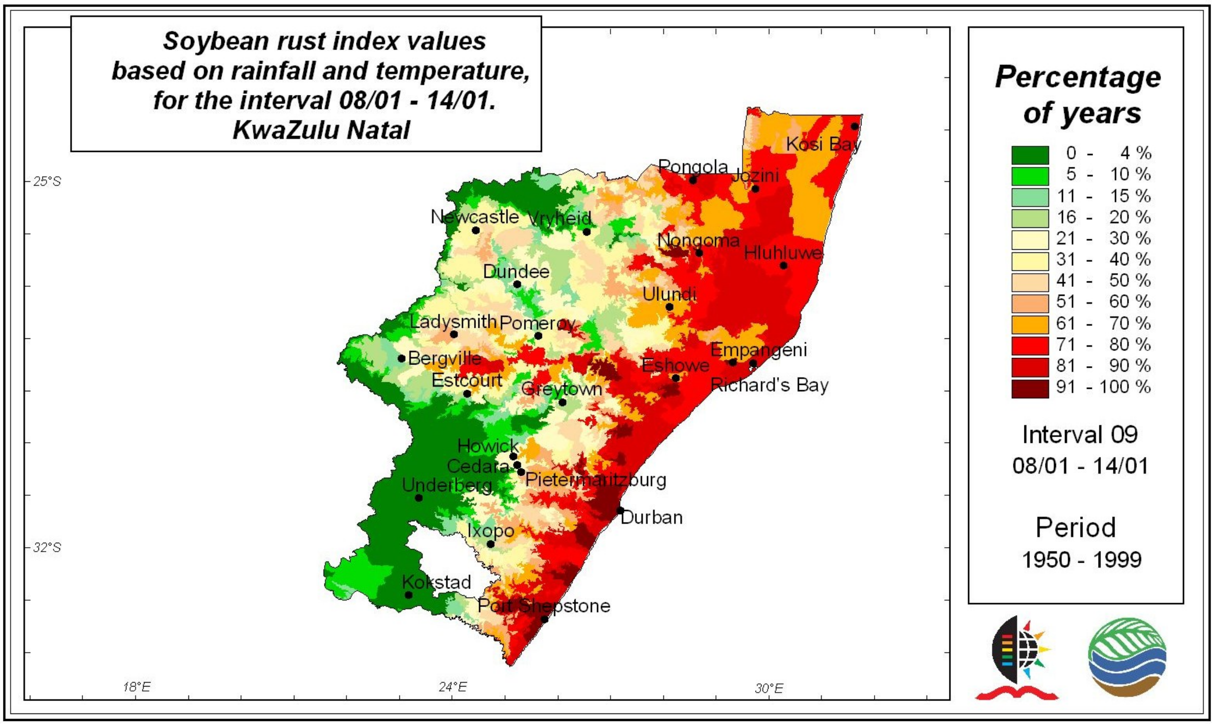

Figure A9 Soybean rust climatic susceptibility map, based on index values, for week 2 of the year in KwaZulu-Natal, South Africa.

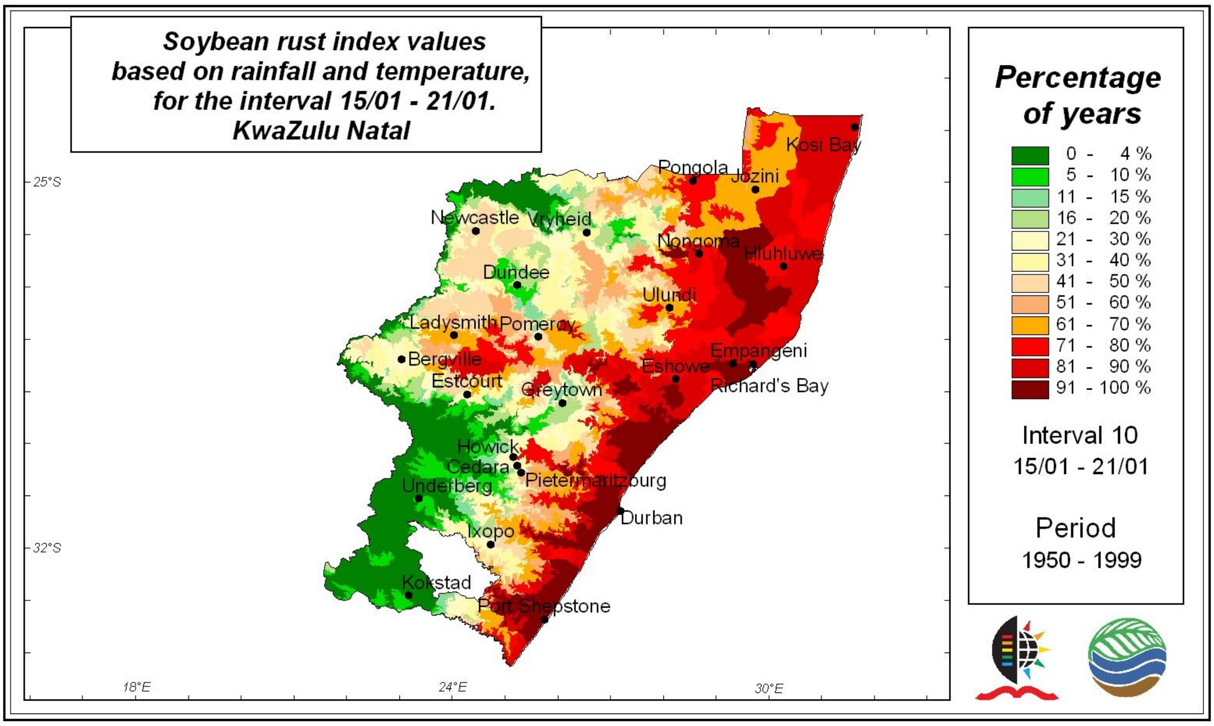

Figure A10 Soybean rust climatic susceptibility map, based on index values, for week 3 of the year in KwaZulu-Natal, South Africa.

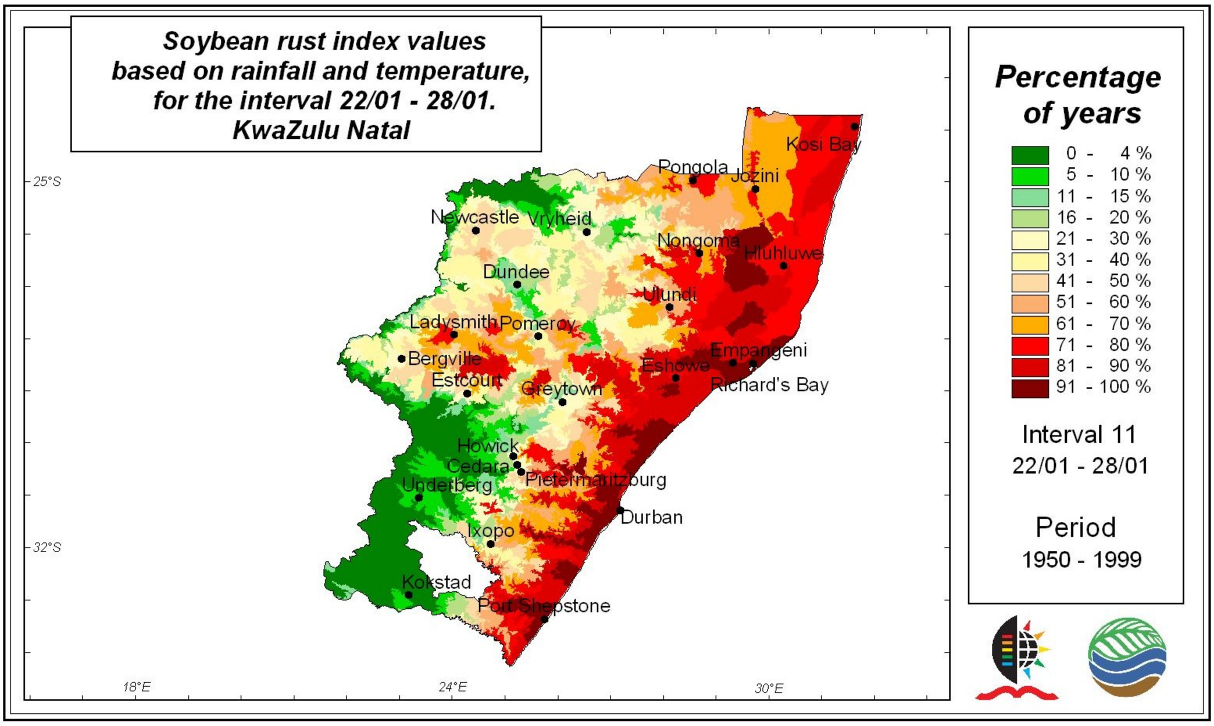

Figure A11 Soybean rust climatic susceptibility map, based on index values, for week 4 of the year in KwaZulu-Natal, South Africa.

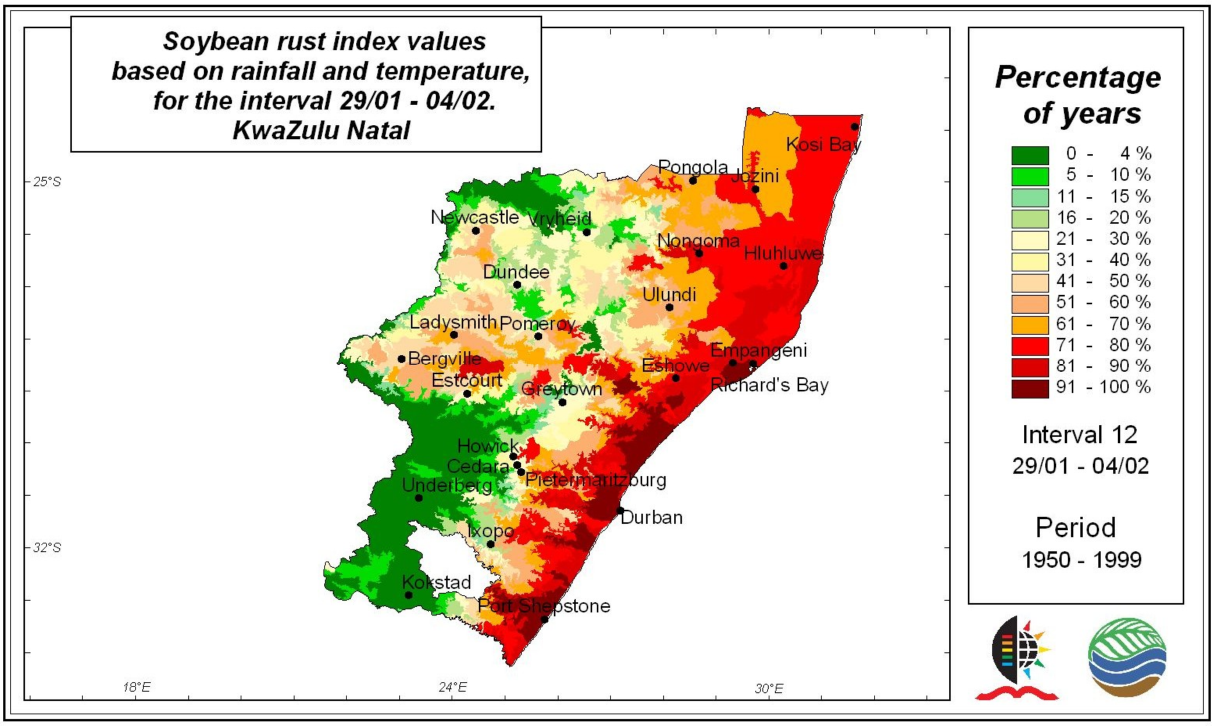

Figure A12 Soybean rust climatic susceptibility map, based on index values, for week 5 of the year in KwaZulu-Natal, South Africa.

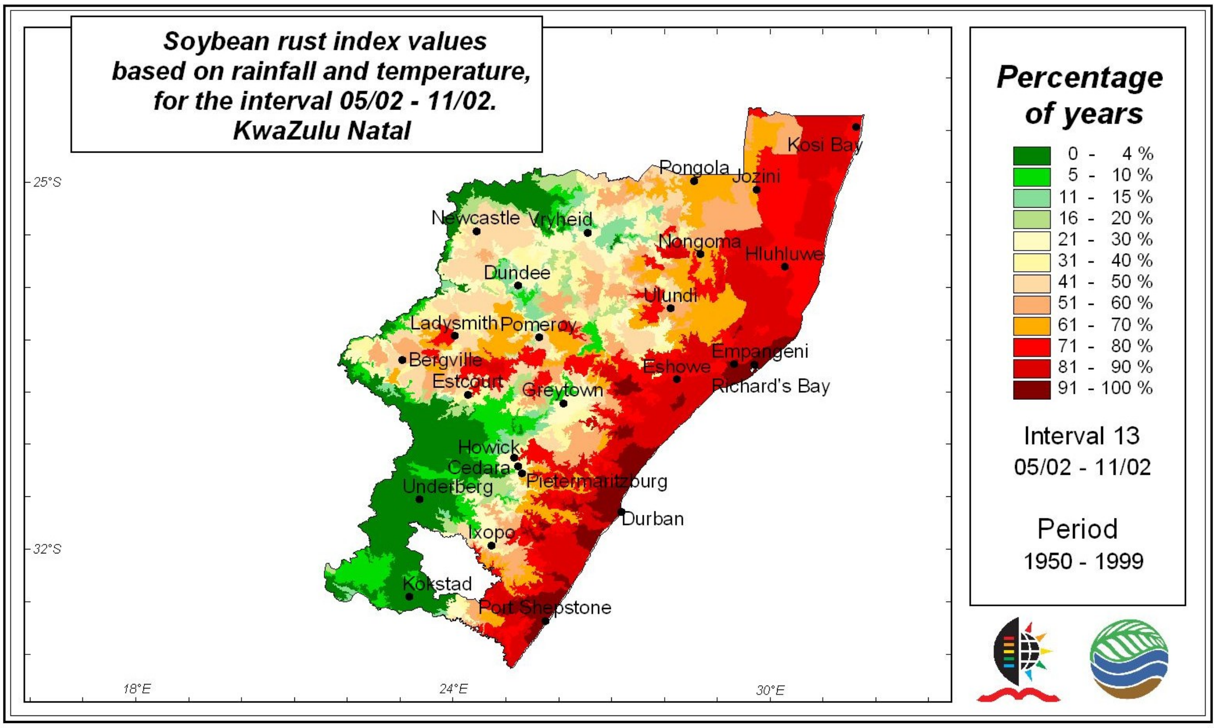

Figure A13 Soybean rust climatic susceptibility map, based on index values, for the week 6 of the year in KwaZulu-Natal, South Africa.

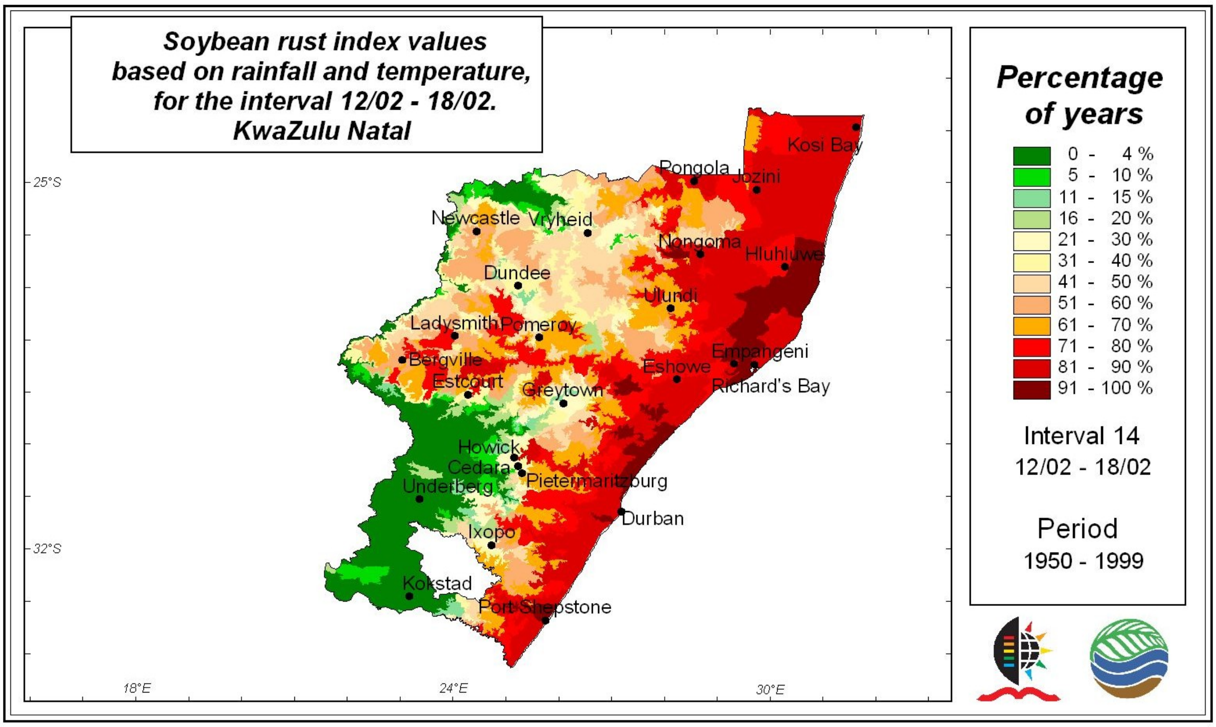

Figure A14 Soybean rust climatic susceptibility map, based on index values, for week 7 of the year in KwaZulu-Natal, South Africa.

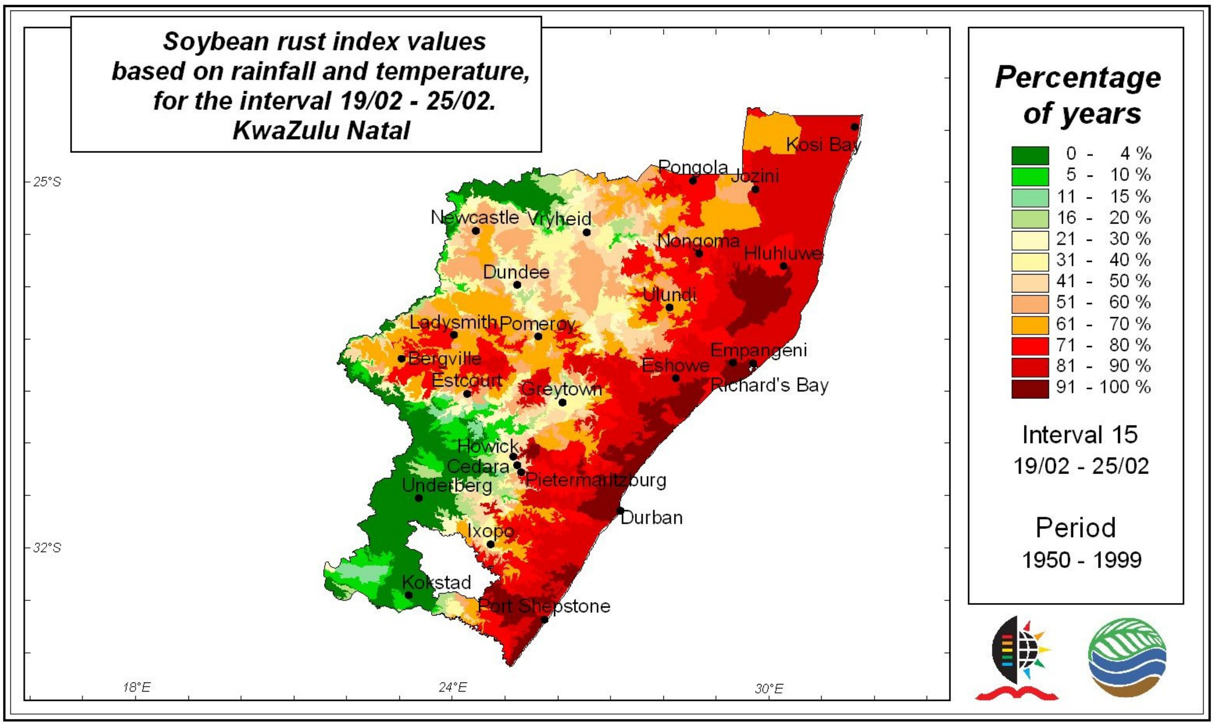

Figure A15 Soybean rust climatic susceptibility map, based on index values, for week 8 of the year in KwaZulu-Natal, South Africa.

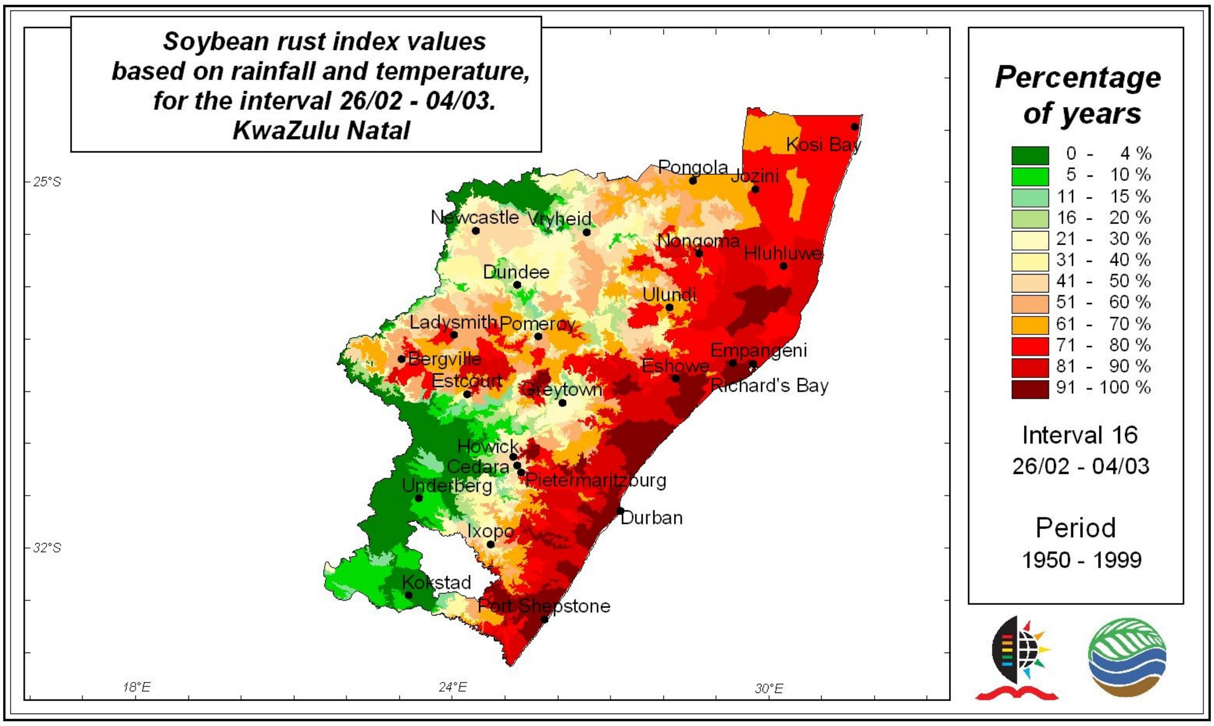

Figure A16 Soybean rust climatic susceptibility map, based on index values, for the week 9 of the year in KwaZulu-Natal, South Africa.

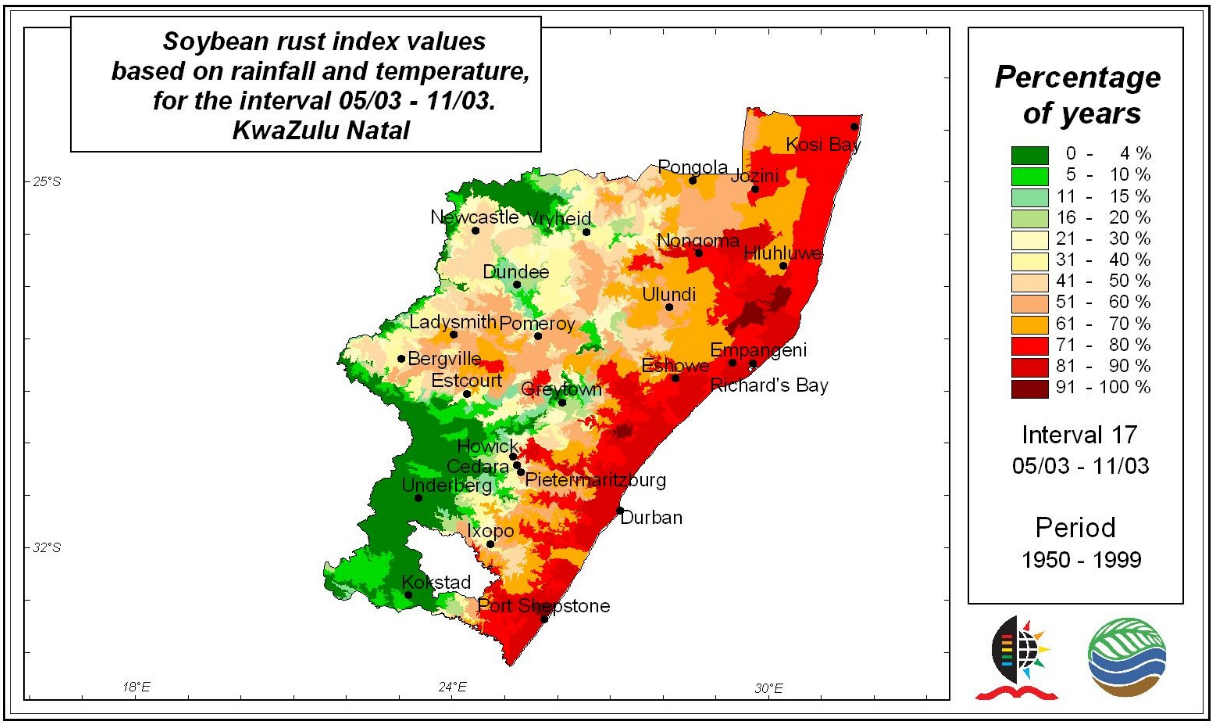

Figure A17 Soybean rust climatic susceptibility map, based on index values, for week 10 of the year in KwaZulu-Natal, South Africa.

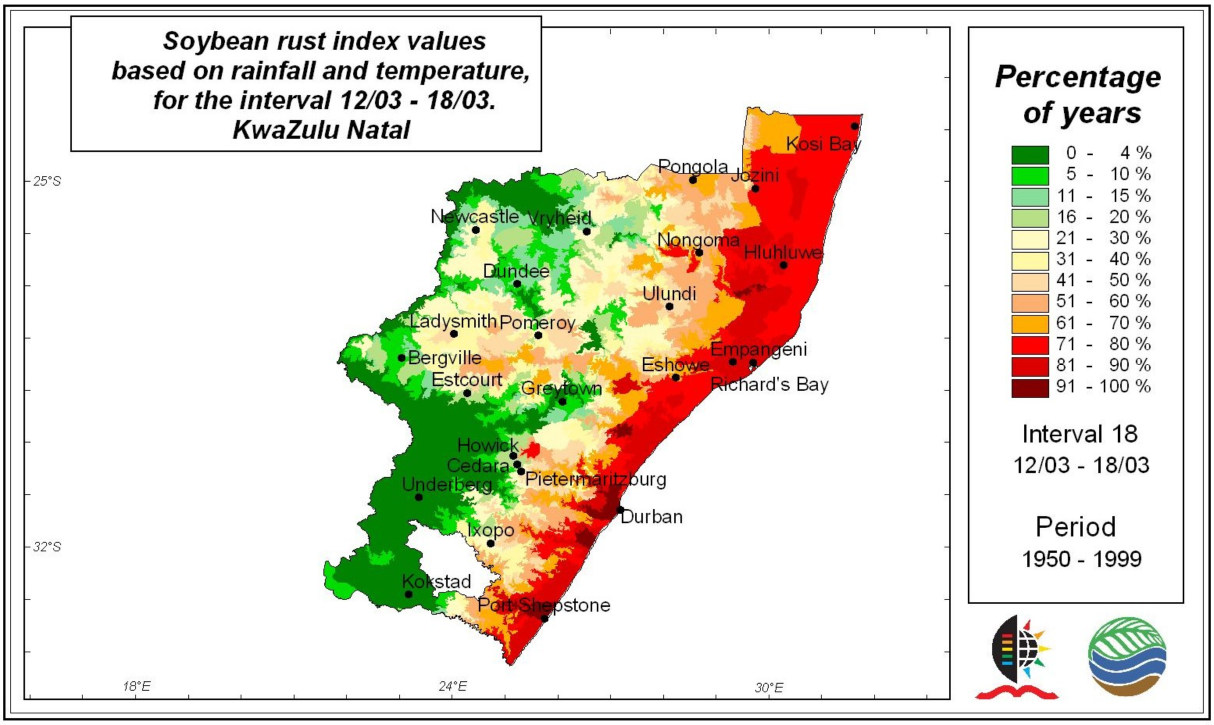

Figure A18 Soybean rust climatic susceptibility map, based on index values, for week 11 of the year in KwaZulu-Natal, South Africa.

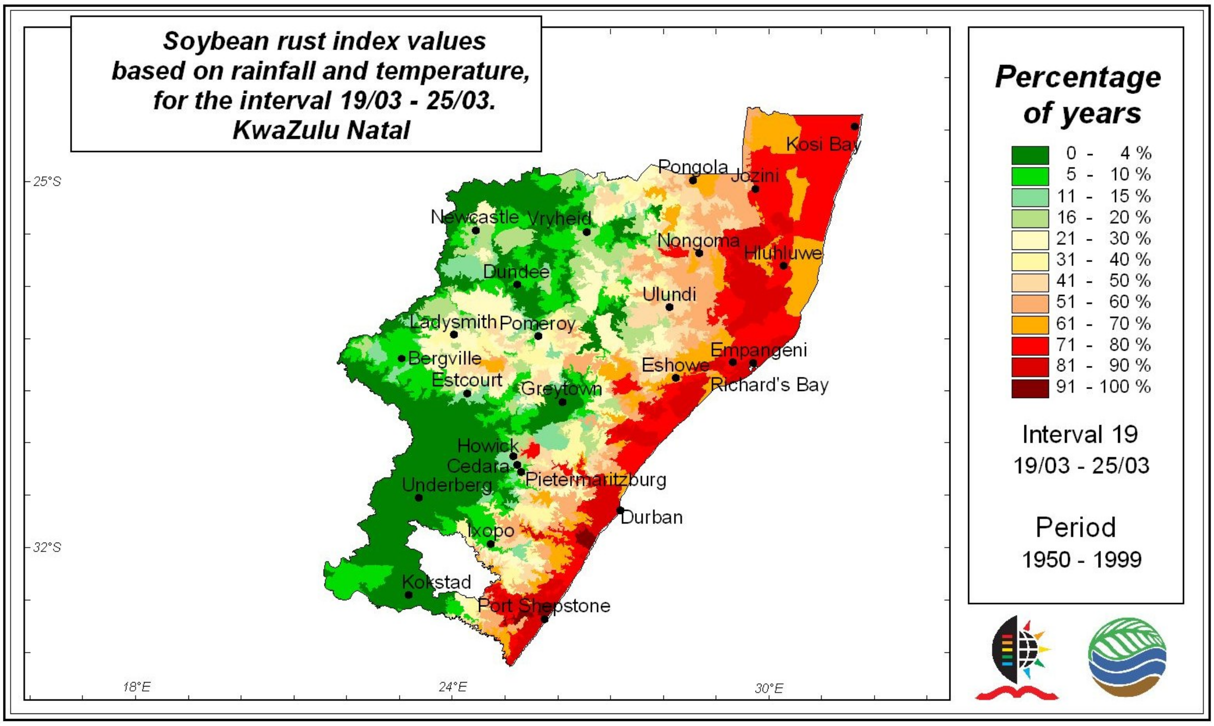

Figure A19 Soybean rust climatic susceptibility map, based on index values, for week 12 of the year in KwaZulu-Natal, South Africa.

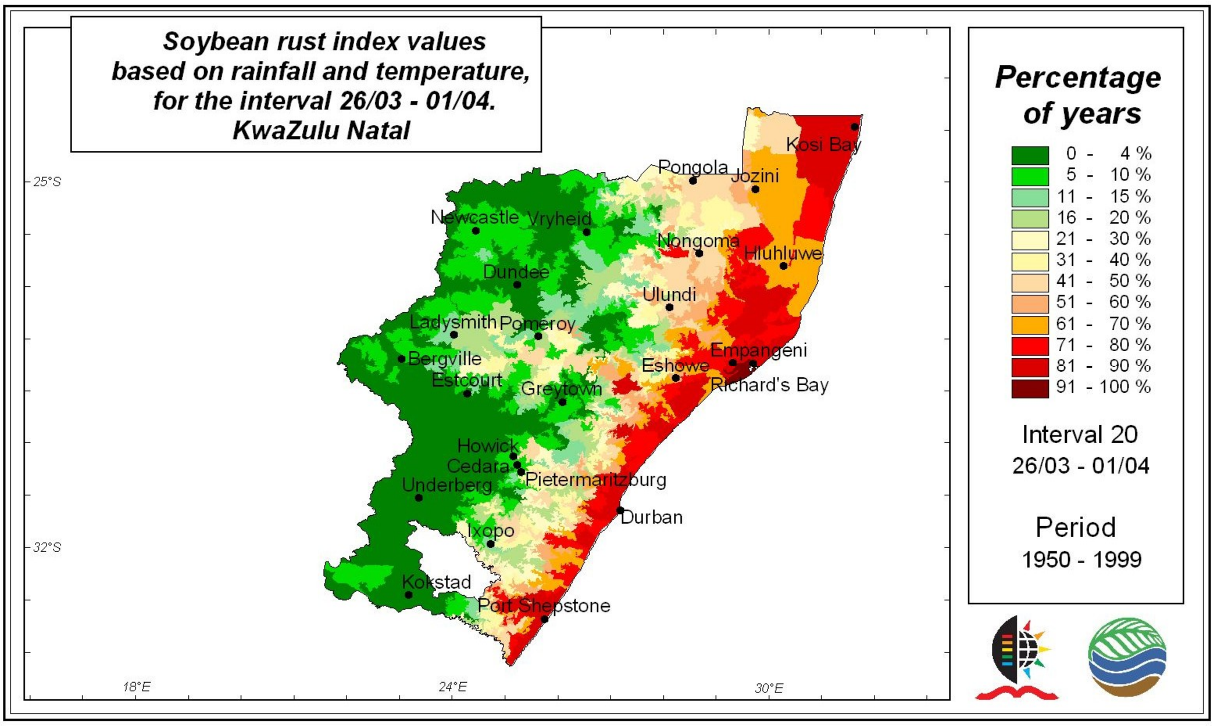

Figure A20 Soybean rust climatic susceptibility map, based on index values, for week 13 of the year in KwaZulu-Natal, South Africa.

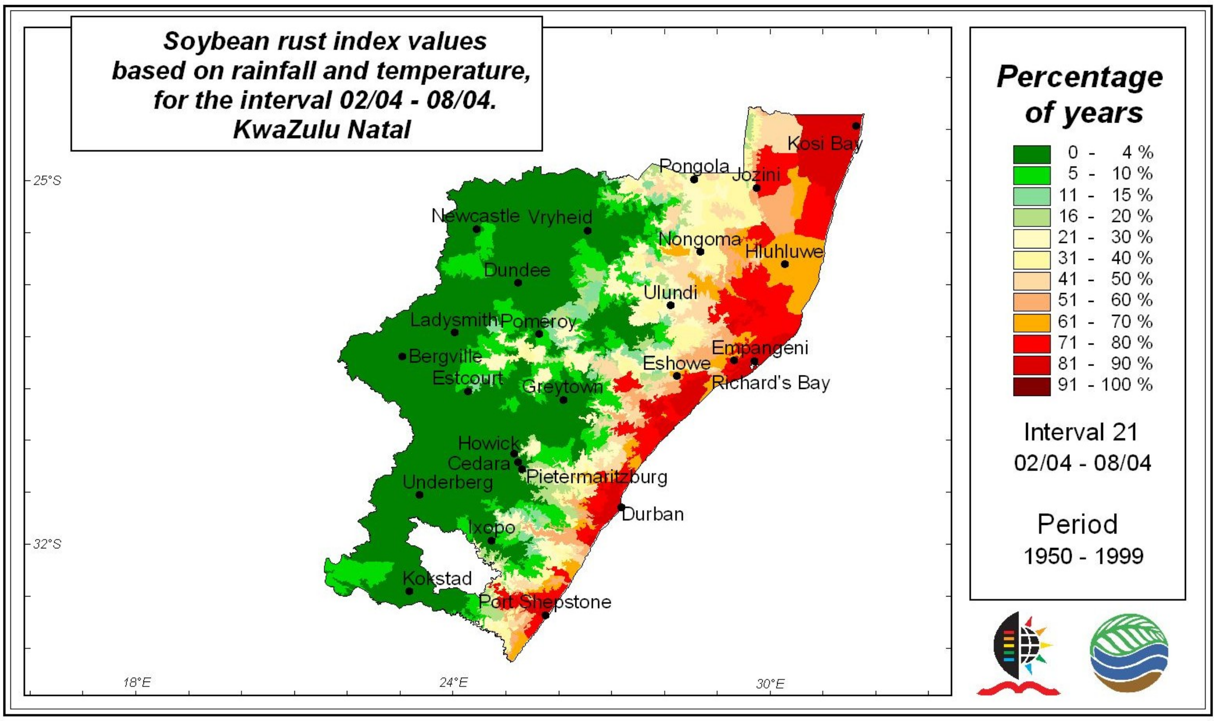

Figure A21 Soybean rust climatic susceptibility map, based on index values, for week 14 of the year in KwaZulu-Natal, South Africa.

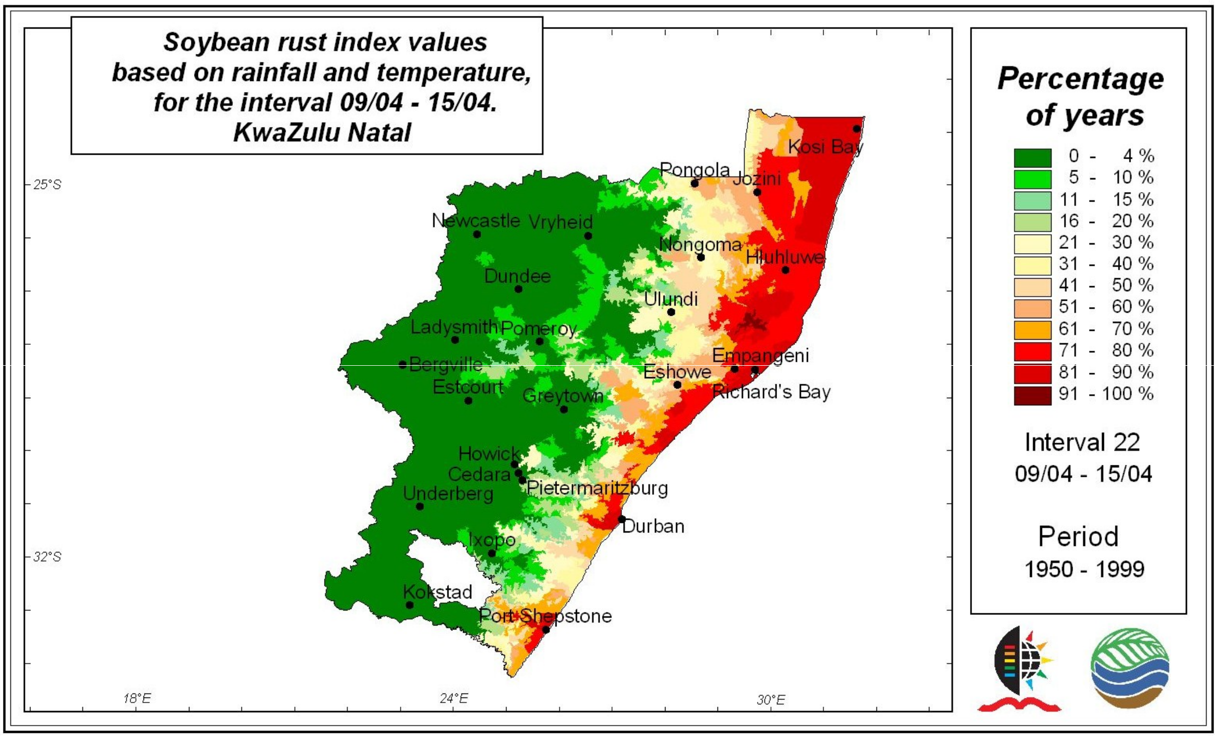

Figure A22 Soybean rust climatic susceptibility map, based on index values, for week 15 of the year in KwaZulu-Natal, South Africa.

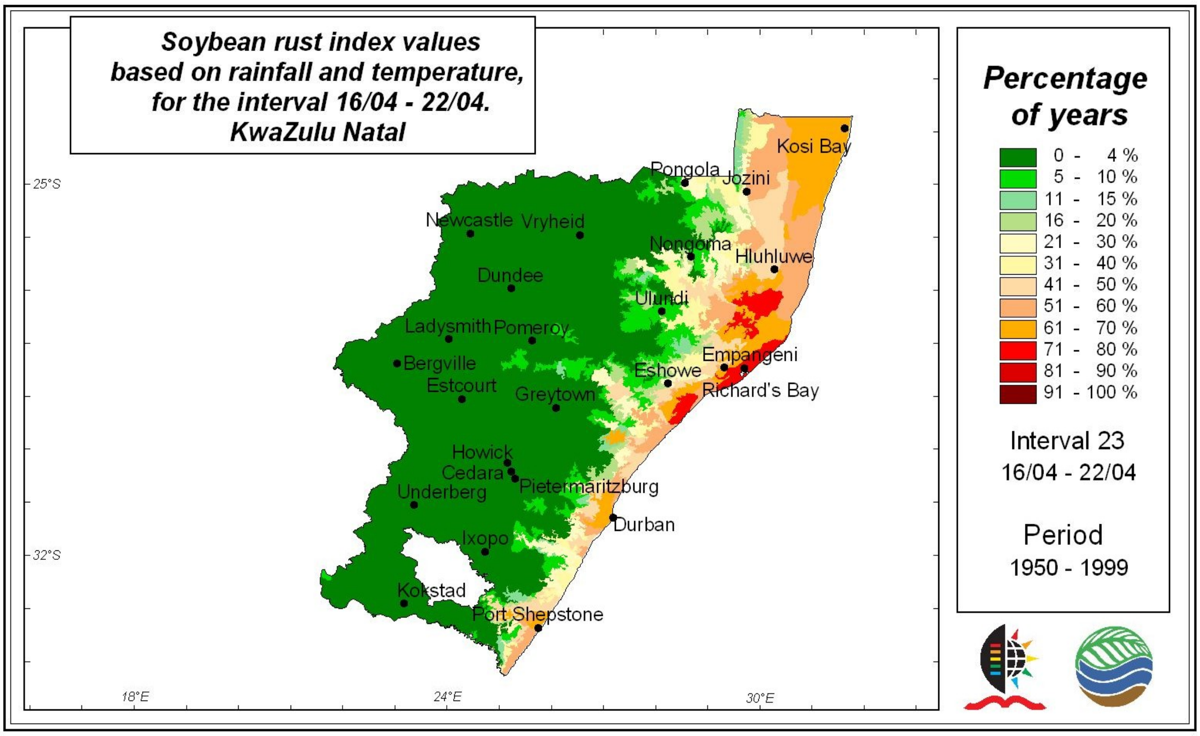

Figure A23 Soybean rust climatic susceptibility map, based on index values, for week 16 of the year in KwaZulu-Natal, South Africa.

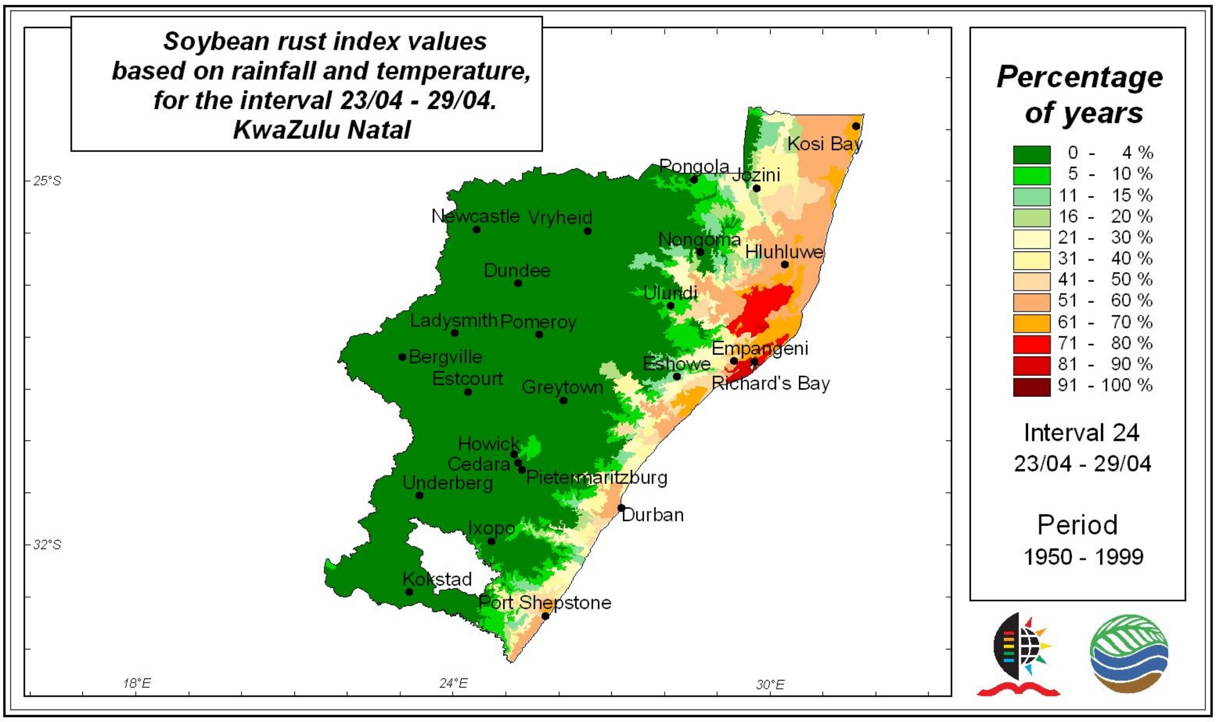

Figure A24 Soybean rust climatic susceptibility map, based on index values, for week 17 of the year in KwaZulu-Natal, South Africa.

APPENDIX B

Appendix B shows the map series of index values illustrating the long term climatic vulnerability for the northern soybean production areas to soybean rust infection.

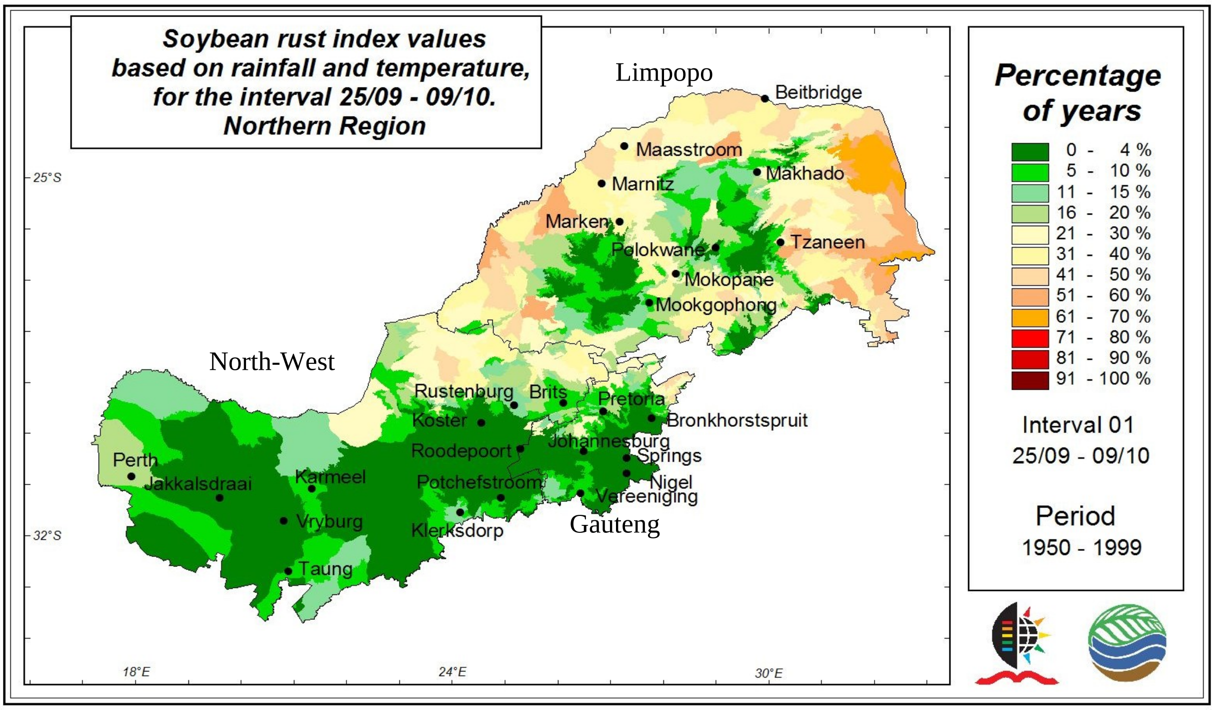

Figure B1 Soybean rust climatic susceptibility map, based on index values, for the beginning of October in the northern soybean producing areas, South Africa.

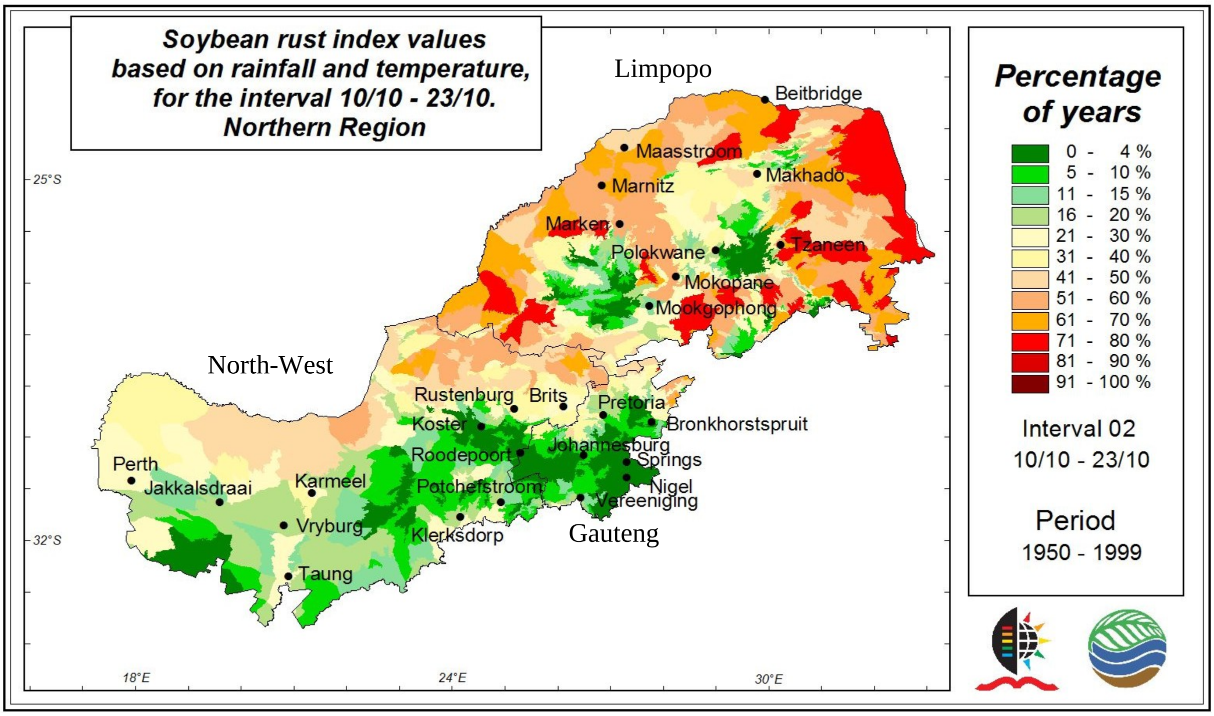

Figure B2 Soybean rust climatic susceptibility map, based on index values, for the middle of October in the northern soybean producing areas, South Africa.

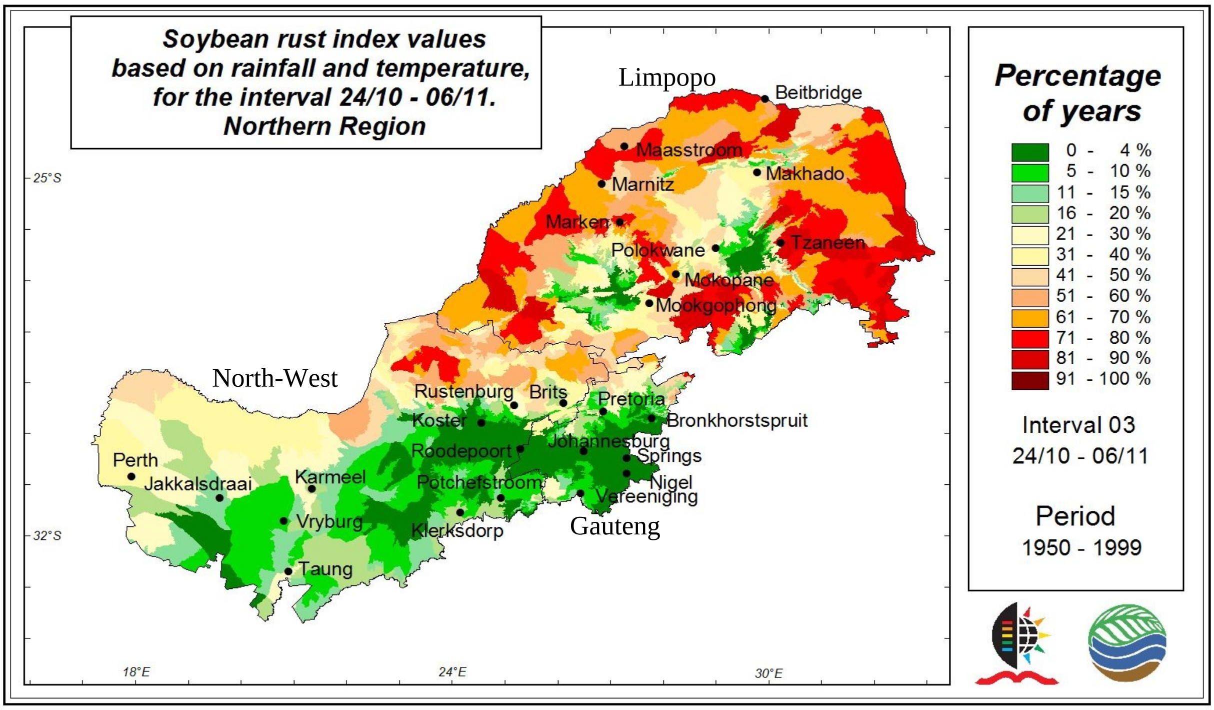

Figure B3 Soybean rust climatic susceptibility map, based on index values, for the in the end of October and beginning of November in the northern soybean producing areas, South Africa.

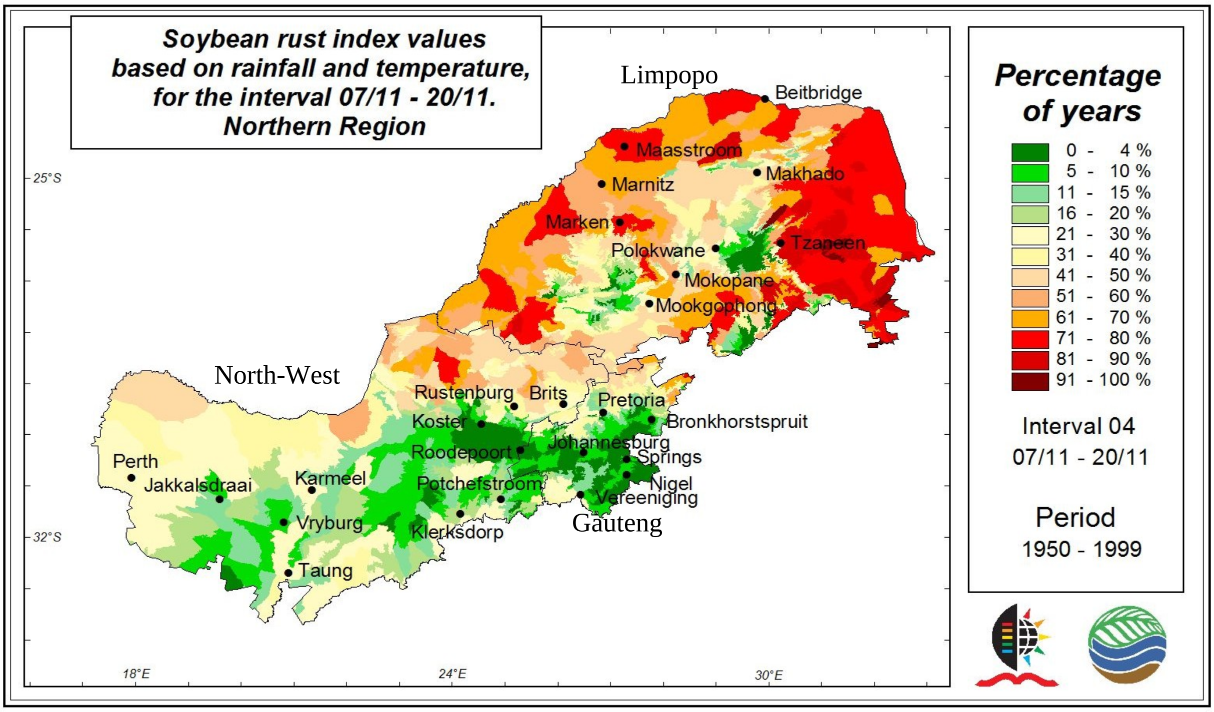

Figure B4 Soybean rust climatic susceptibility map, based on index values, for the middle of November in the northern soybean producing areas, South Africa.

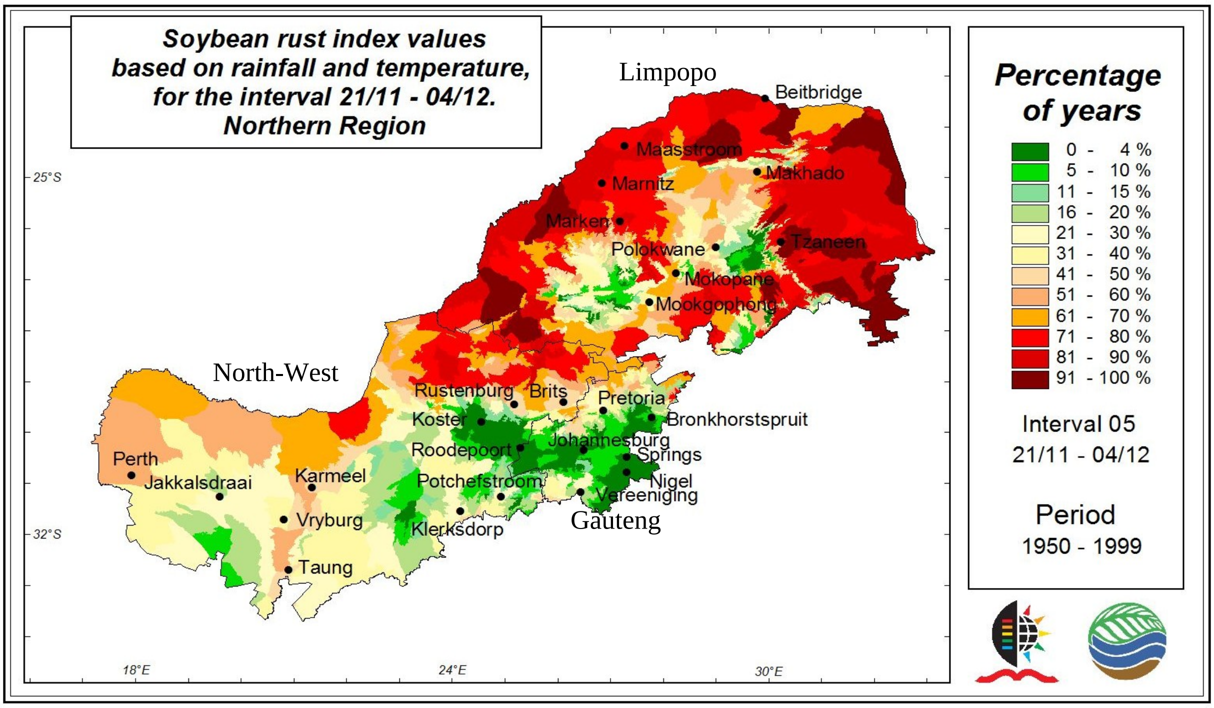

Figure B5 Soybean rust climatic susceptibility map, based on index values, for the end of November in the northern soybean producing areas, South Africa.

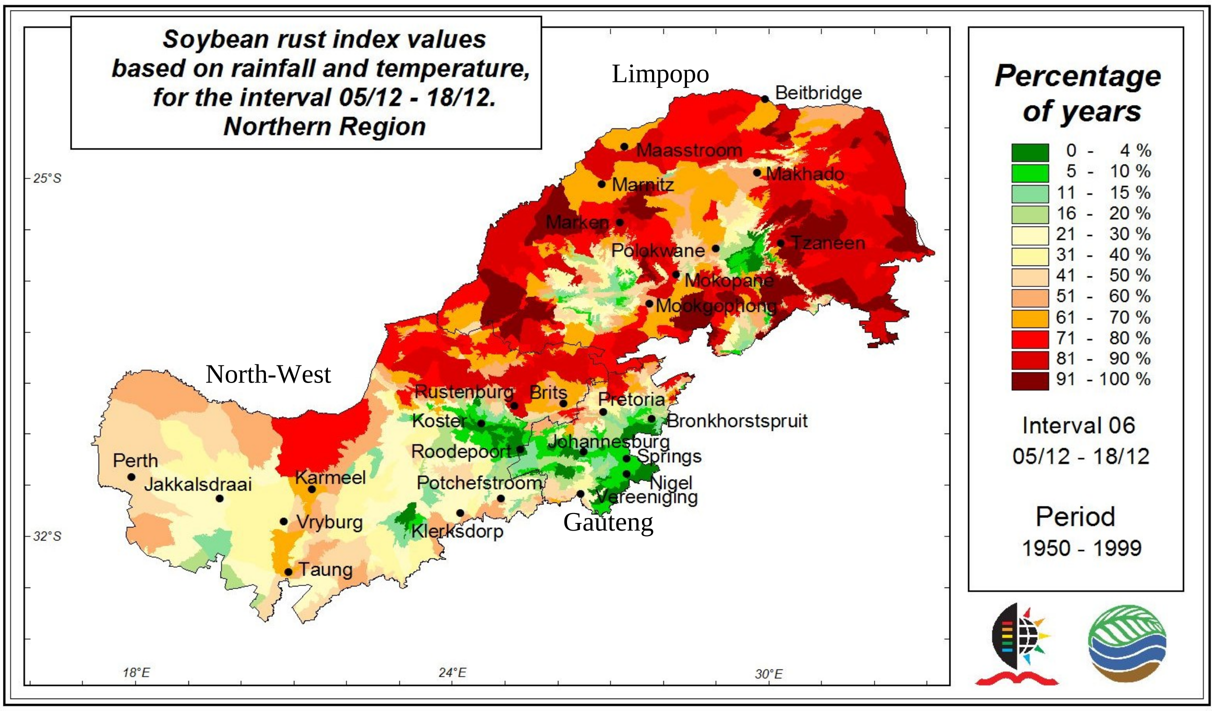

Figure B6 Soybean rust climatic susceptibility map, based on index values, for the beginning of December in the northern soybean producing areas, South Africa.

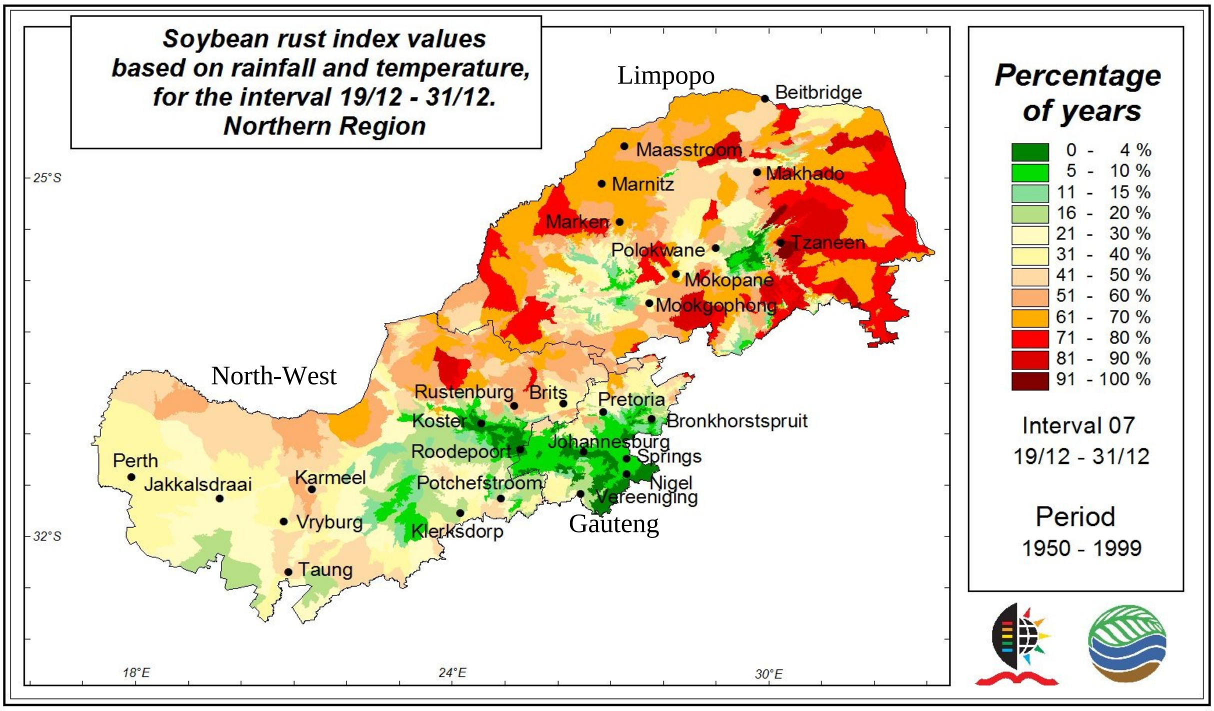

Figure B7 Soybean rust climatic susceptibility map, based on index values, for the end of December in the northern soybean producing areas, South Africa.

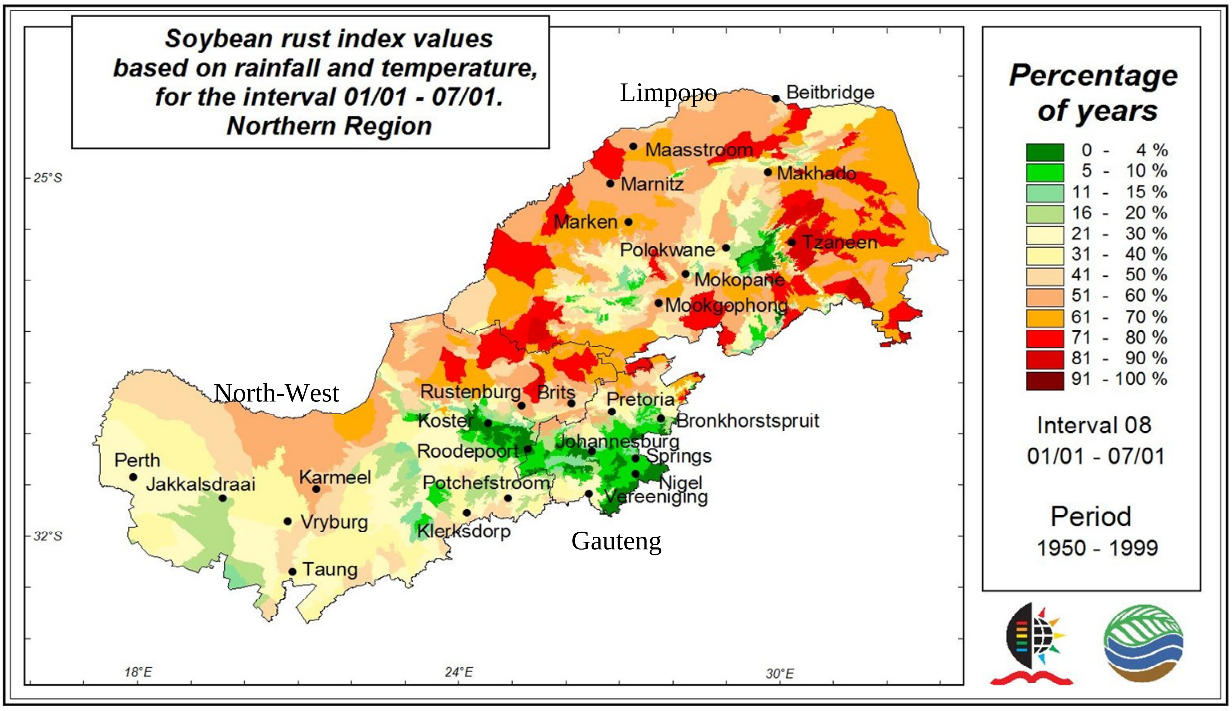

Figure B8 Soybean rust climatic susceptibility map, based on index values, for week 1 of the year in the northern soybean producing areas, South Africa.

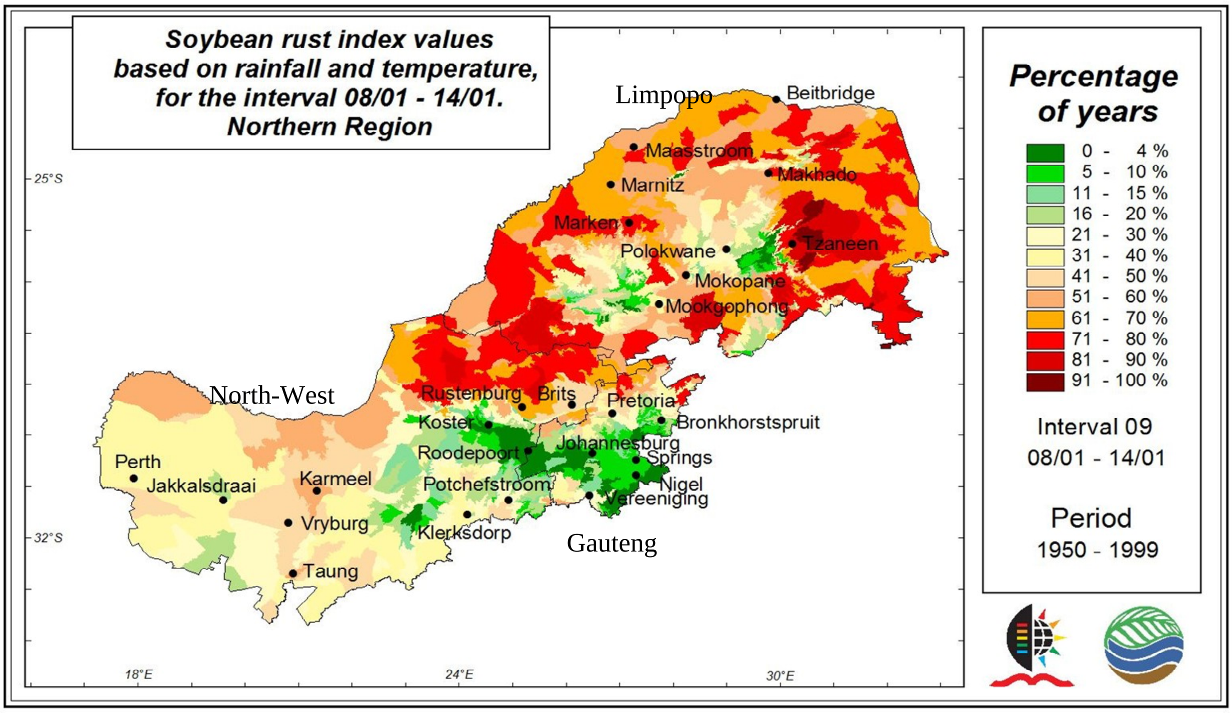

Figure B9 Soybean rust climatic susceptibility map, based on index values, for week 2 of the year in the northern soybean producing areas, South Africa.

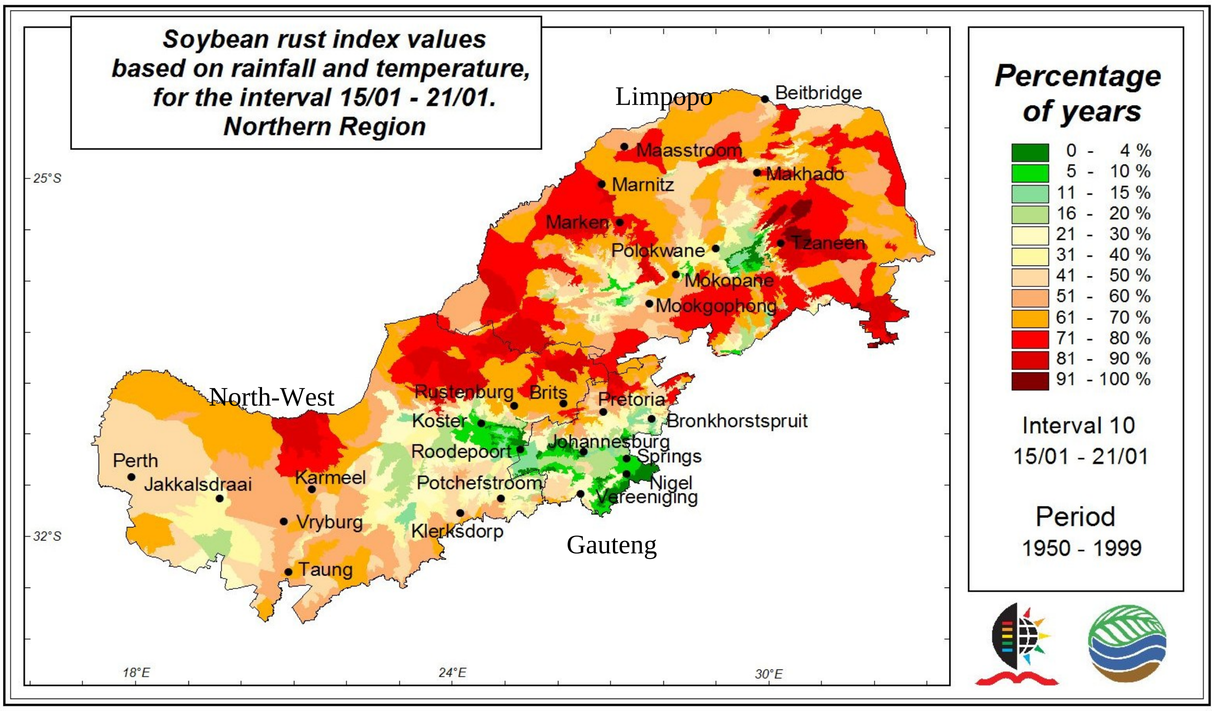

Figure B10 Soybean rust climatic susceptibility map, based on index values, for week 3 of the year in the northern soybean producing areas South Africa.

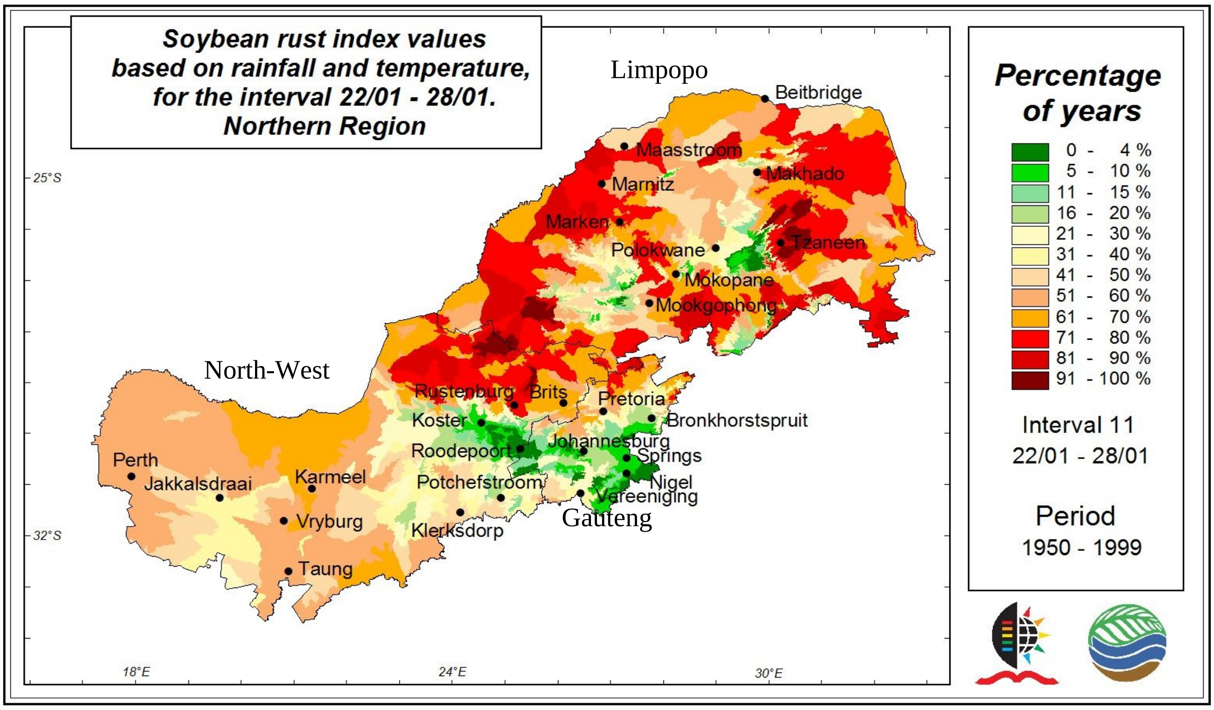

Figure B11 Soybean rust climatic susceptibility map, based on index values, for week 4 of the year in the northern soybean producing areas, South Africa.

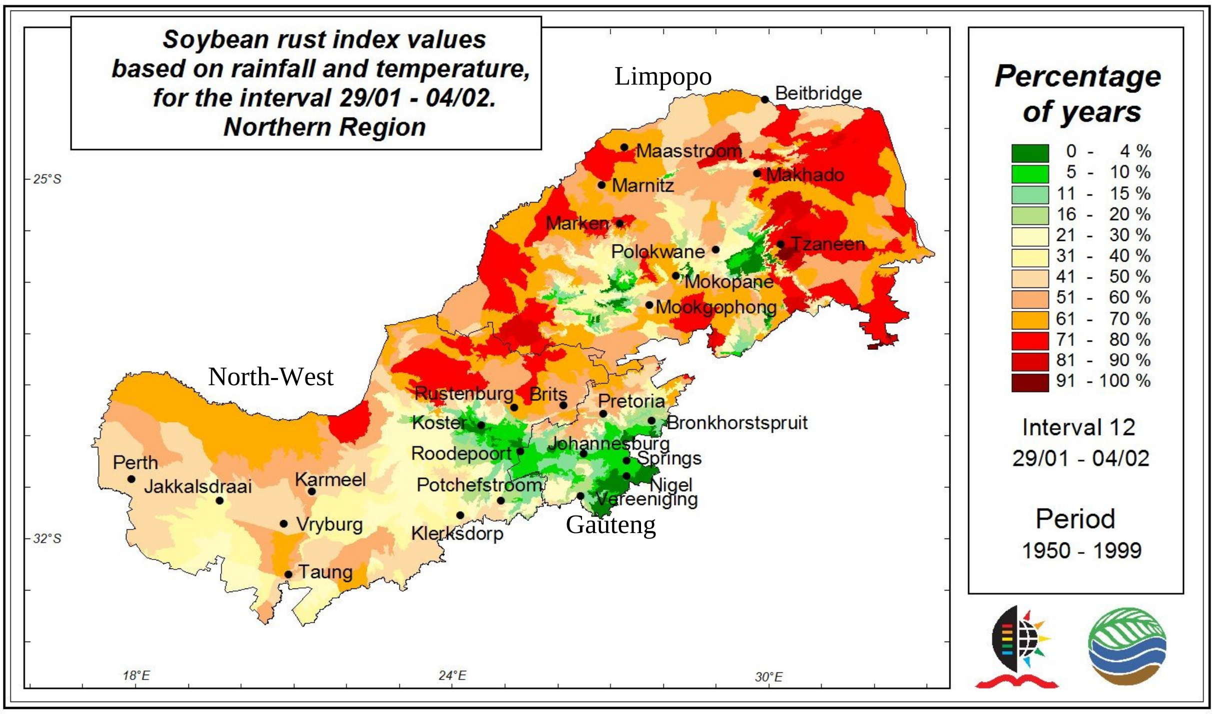

Figure B12 Soybean rust climatic susceptibility map, based on index values, for week 5 of the year in the northern soybean producing areas, South Africa.

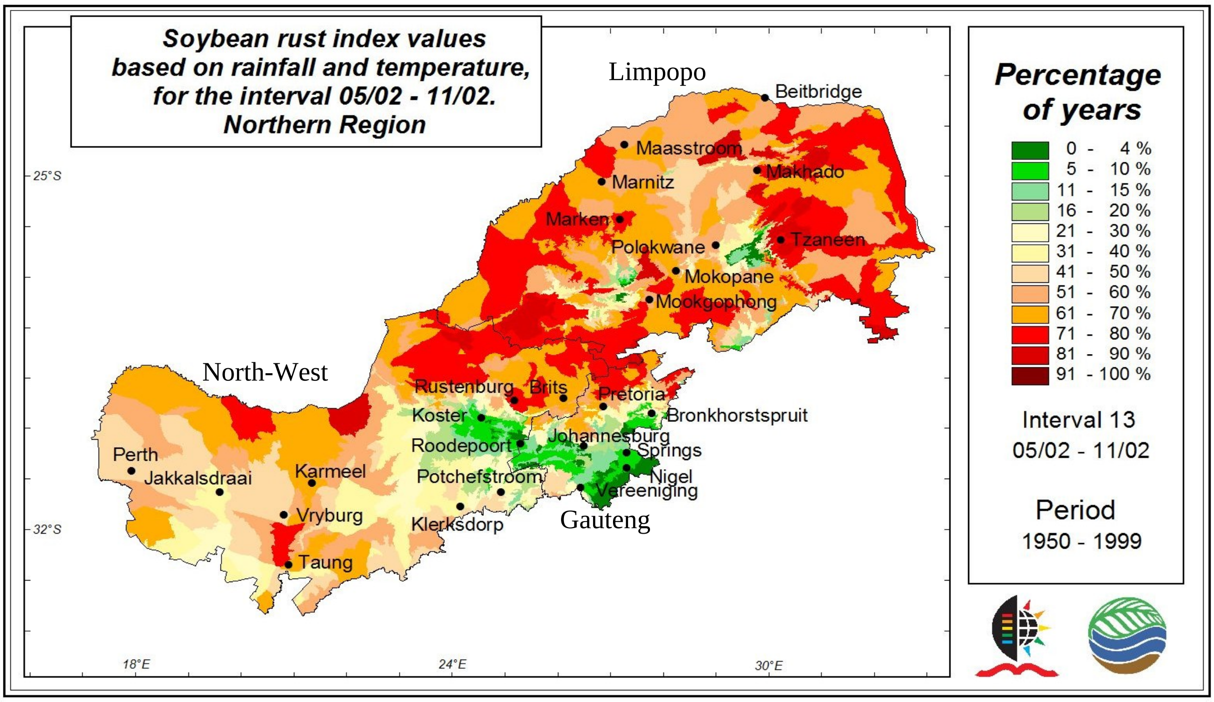

Figure B13 Soybean rust climatic susceptibility map, based on index values, for week 6 of the year in the northern soybean producing areas, South Africa.

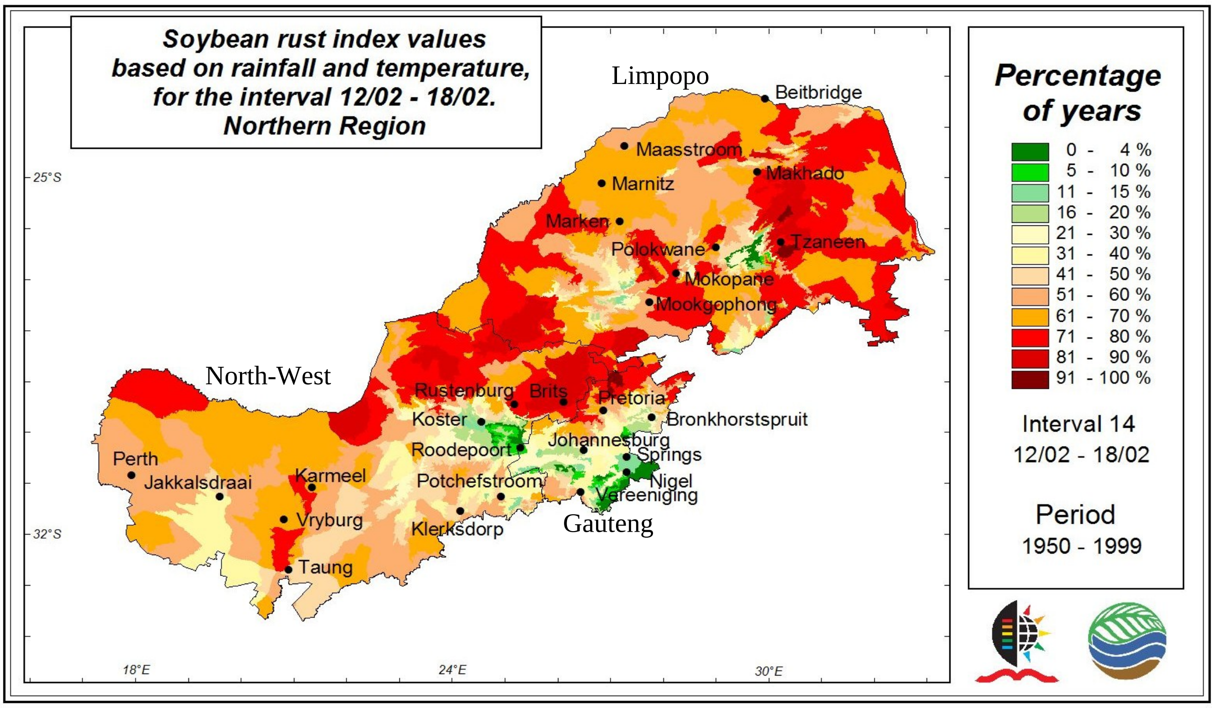

Figure B14 Soybean rust climatic susceptibility map, based on index values, for week 7 of the year in the northern soybean producing areas, South Africa.

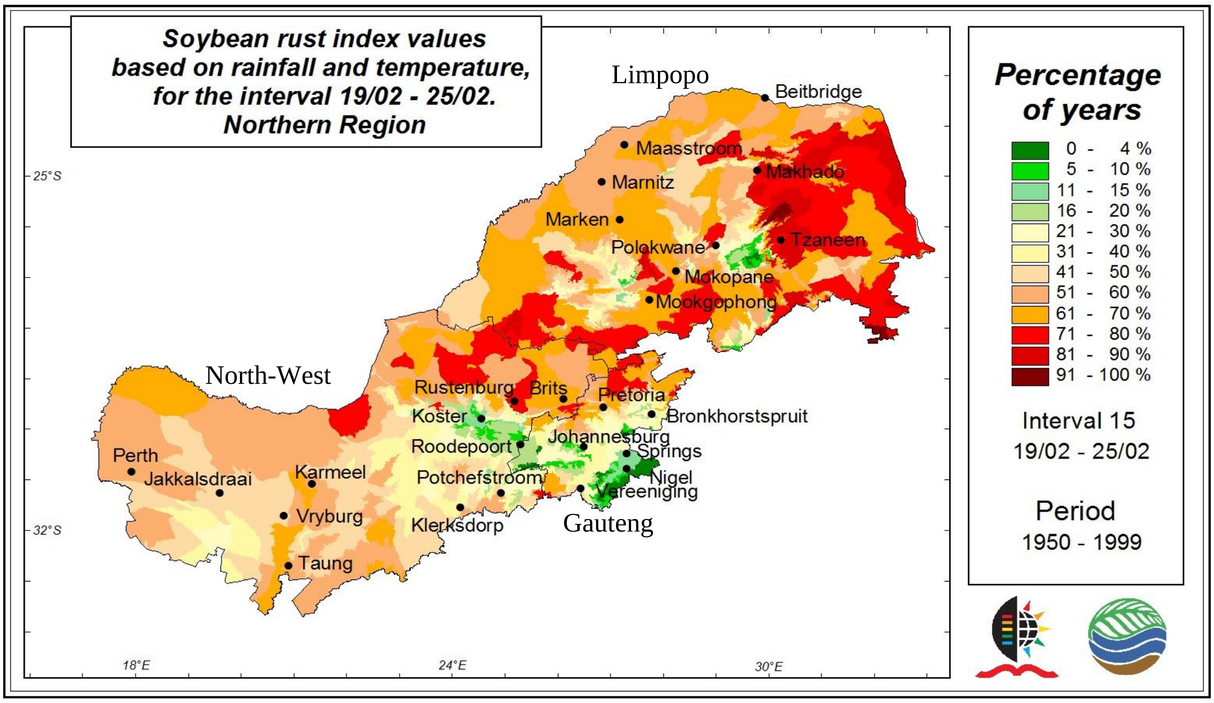

Figure B15 Soybean rust climatic susceptibility map, based on index values, for week 8 of the year in the northern soybean producing areas, South Africa.

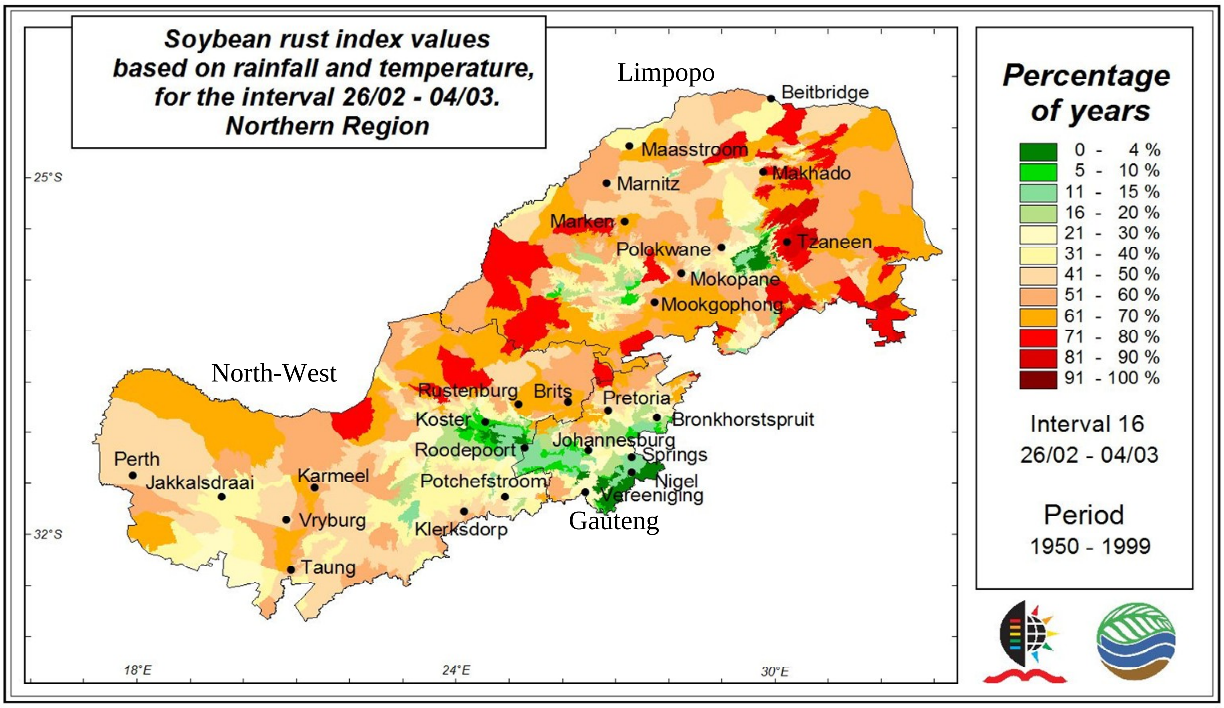

Figure B16 Soybean rust climatic susceptibility map, based on index values, for week 9 of the year in the northern soybean producing areas, South Africa.

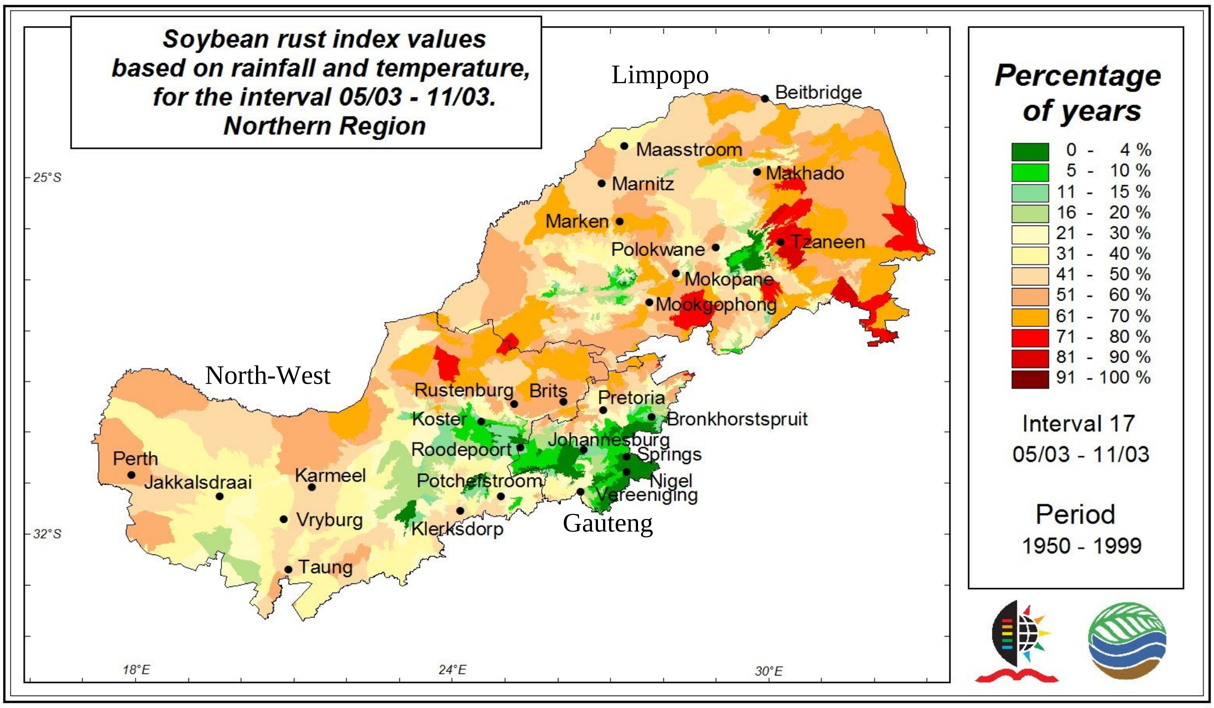

Figure B17 Soybean rust climatic susceptibility map, based on index values, for week 10 of the year in the northern soybean producing areas, South Africa.

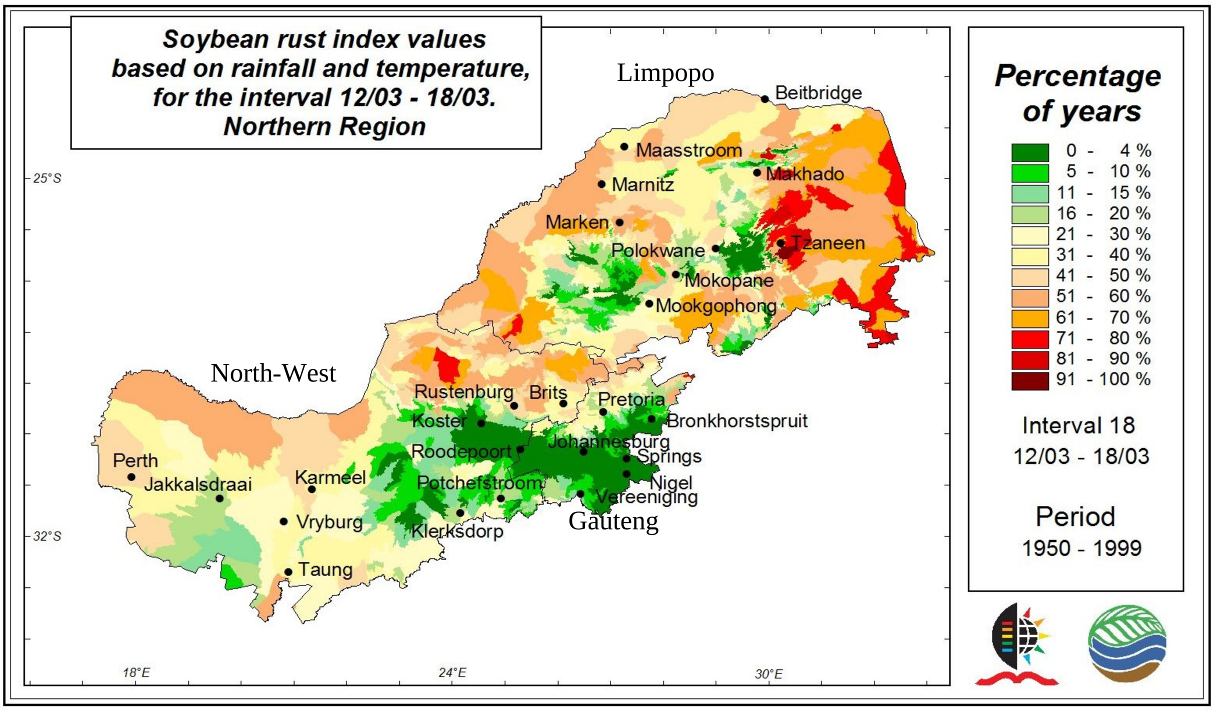

Figure B18 Soybean rust climatic susceptibility map, based on index values, for week 11 of the year in the northern soybean producing areas, South Africa.

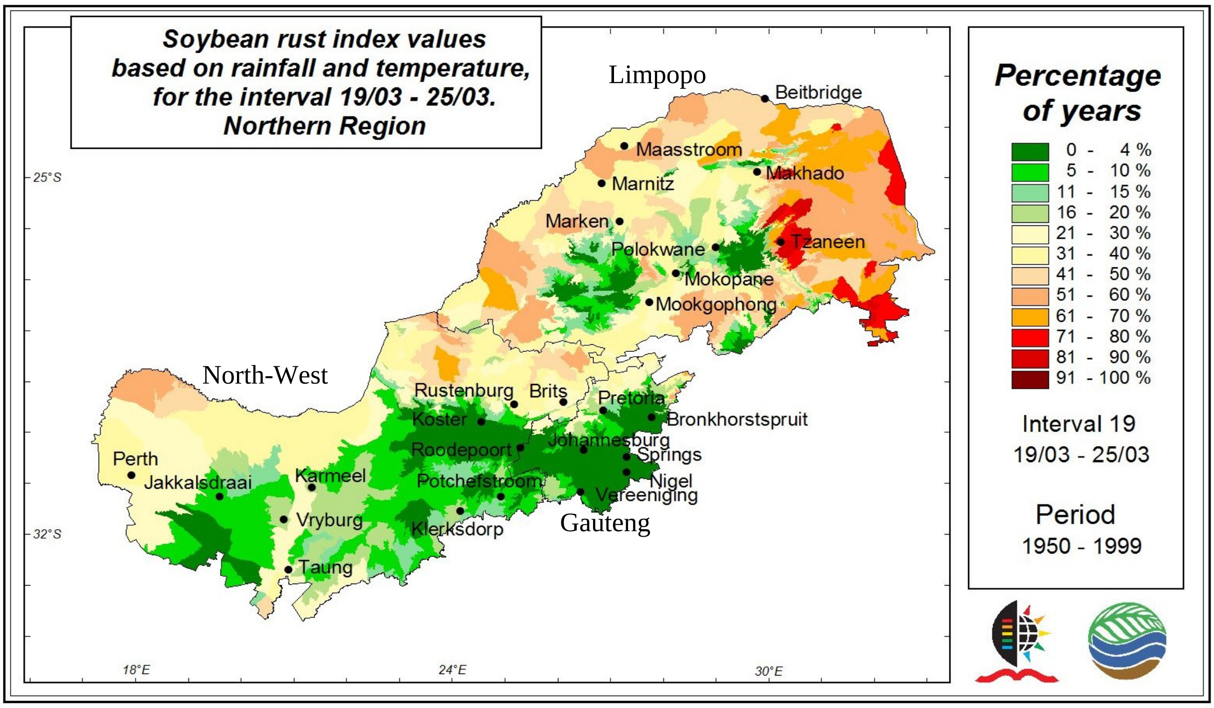

Figure B19 Soybean rust climatic susceptibility map, based on index values, for week 12 of the year in the northern soybean producing areas, South Africa.

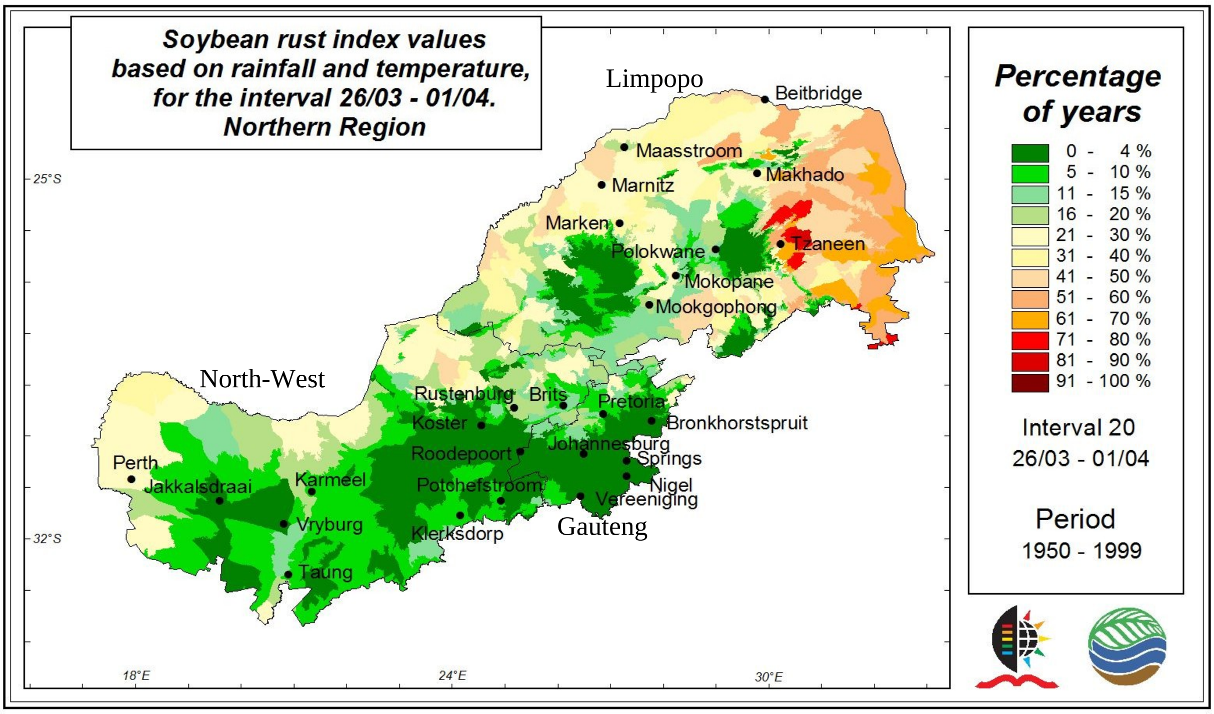

Figure B20 Soybean rust climatic susceptibility map, based on index values, for week 13 of the year in the northern soybean producing areas, South Africa.

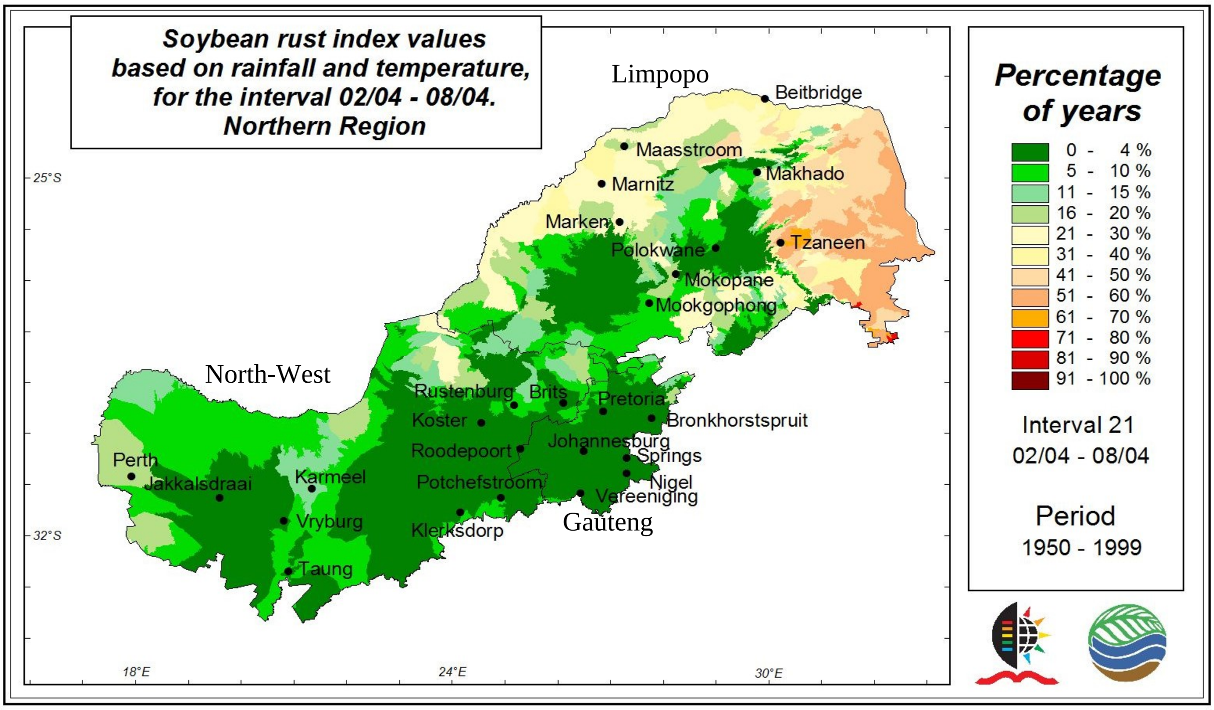

Figure B21 Soybean rust climatic susceptibility map, based on index values, for week 14 of the year in the northern soybean producing areas, South Africa.

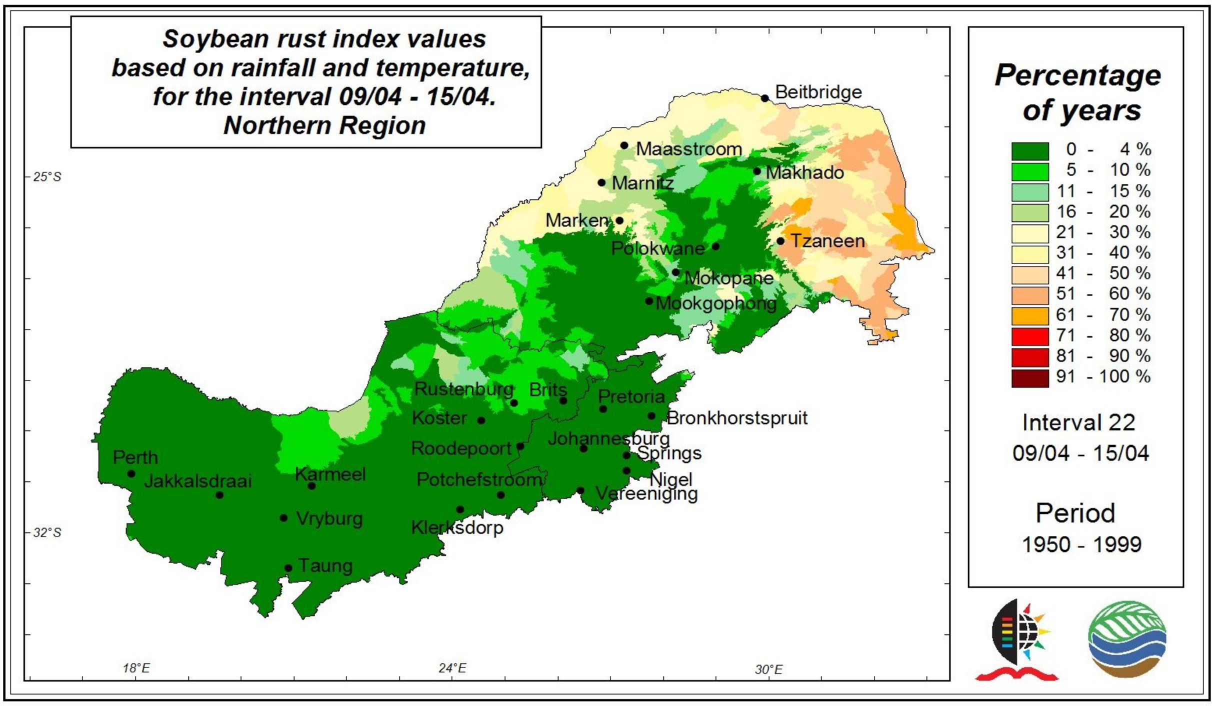

Figure B22 Soybean rust climatic susceptibility map, based on index values, for week 15 of the year in the northern soybean producing areas, South Africa.

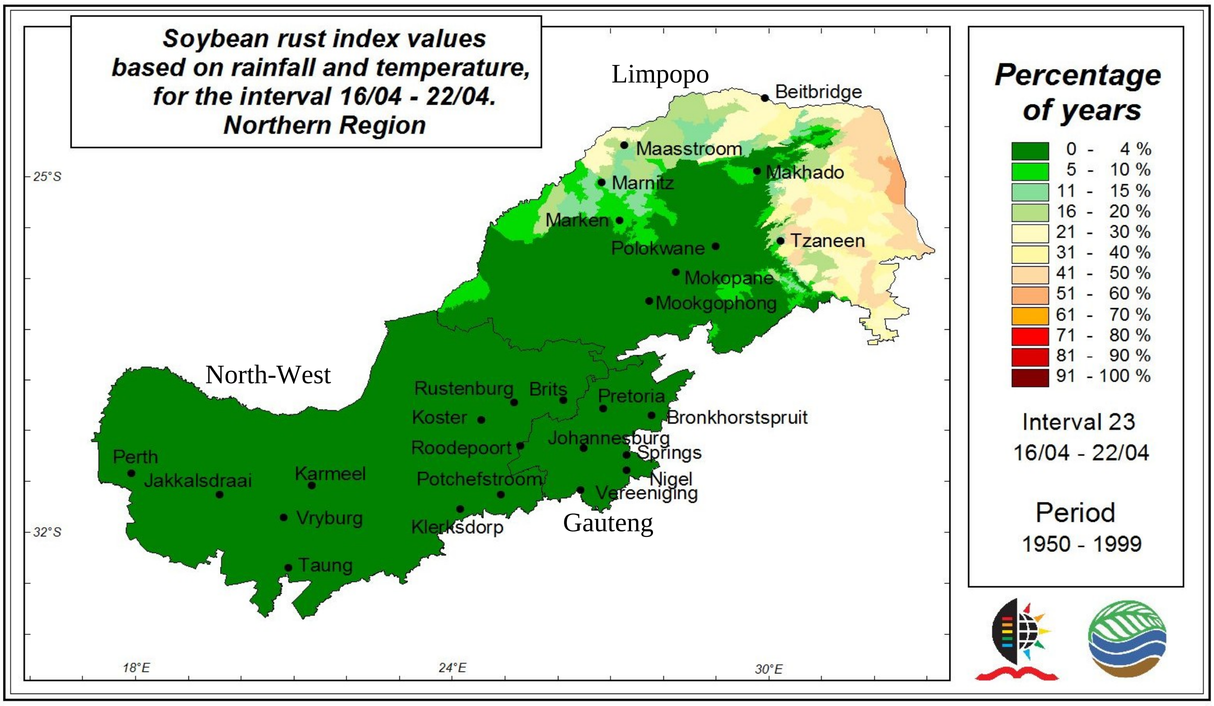

Figure B23 Soybean rust climatic susceptibility map, based on index values, for week 16 of the year in the northern soybean producing areas, South Africa.

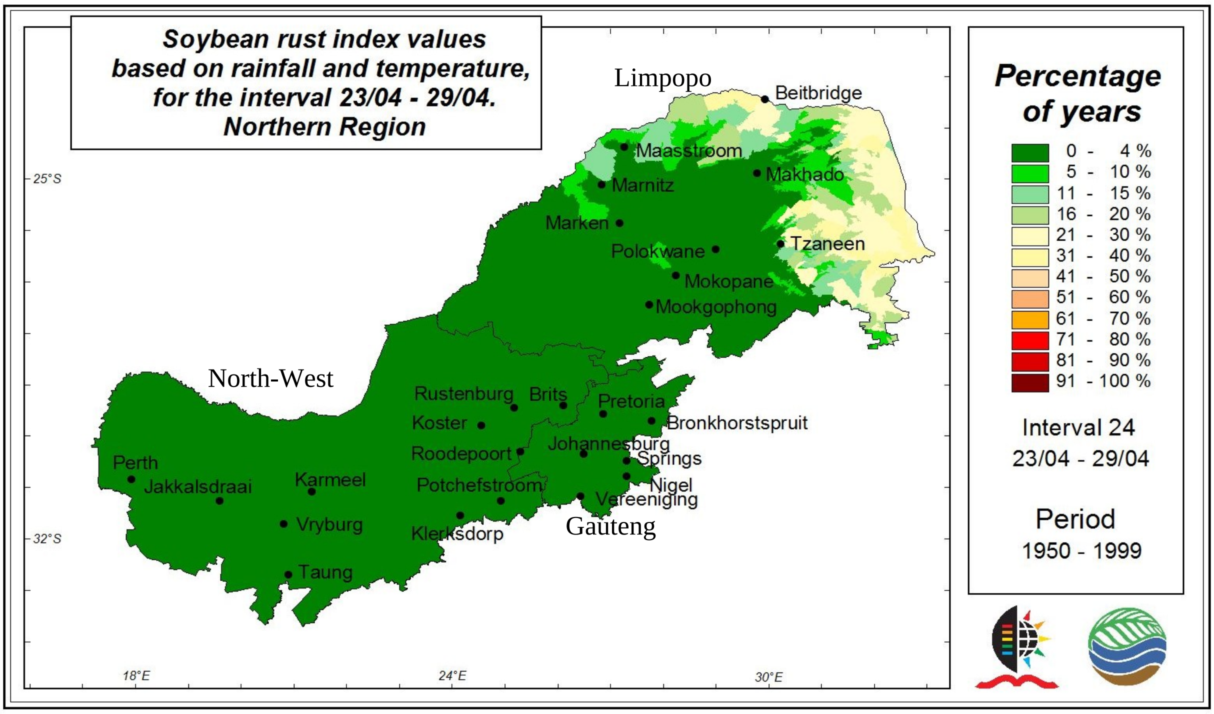

Figure B24 Soybean rust climatic susceptibility map, based on index values, for week 17 of the year in the northern soybean producing areas, of South Africa as well Swaziland and Lesotho to soybean rust infection.

APPENDIX C

Appendix C shows the map series of index values illustrating the long term climatic vulnerability for the central soybean production areas of South Africa as well Swaziland and Lesotho to soybean rust infection.

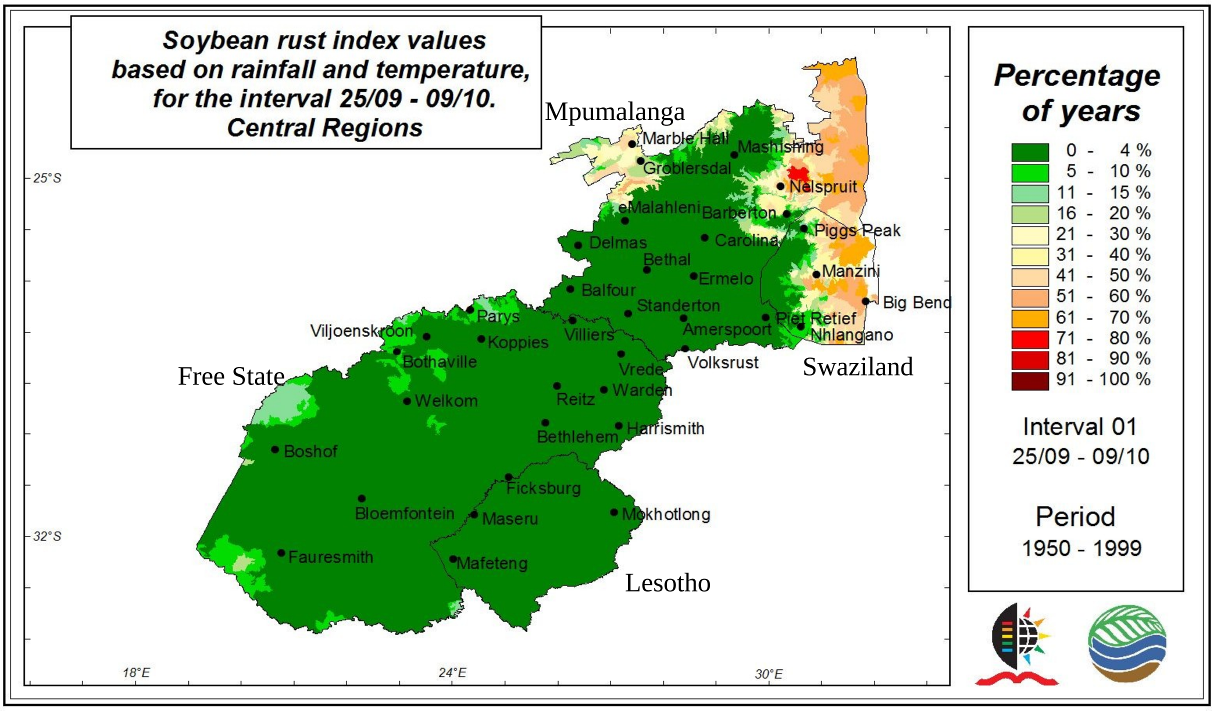

Figure C1 Soybean rust climatic susceptibility map, based on index values, for the beginning of October in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

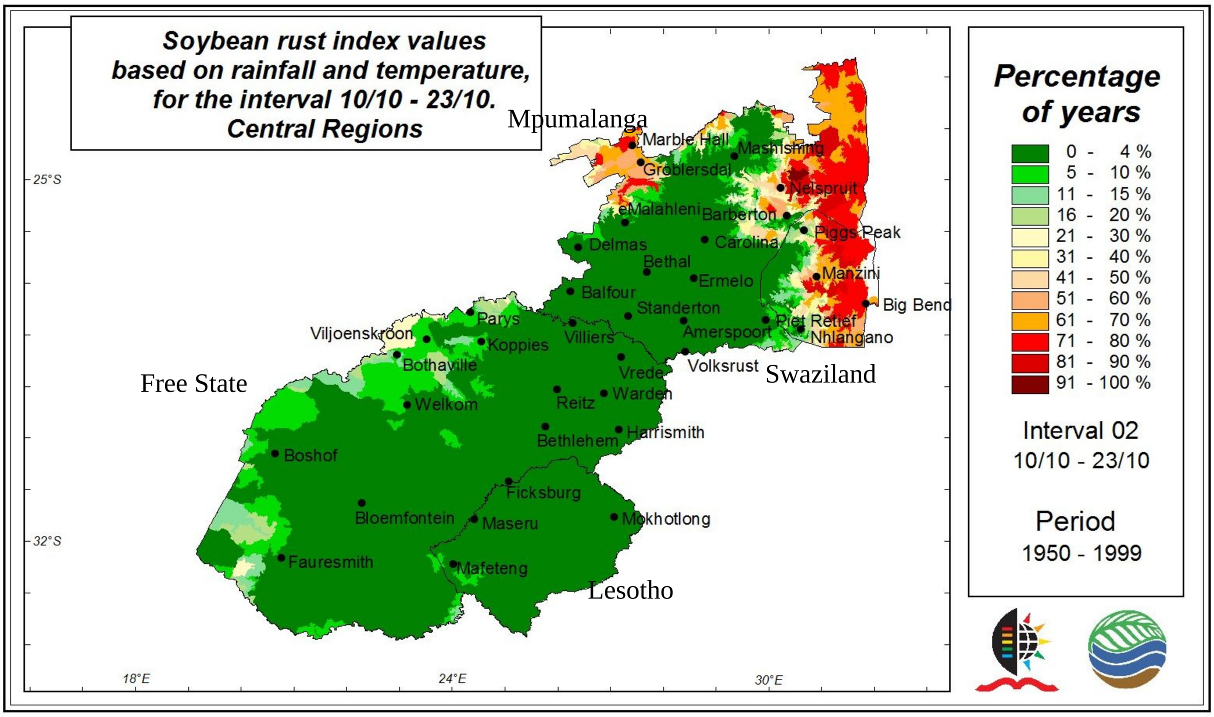

Figure C2 Soybean rust climatic susceptibility map, based on index values, for the middle of October in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

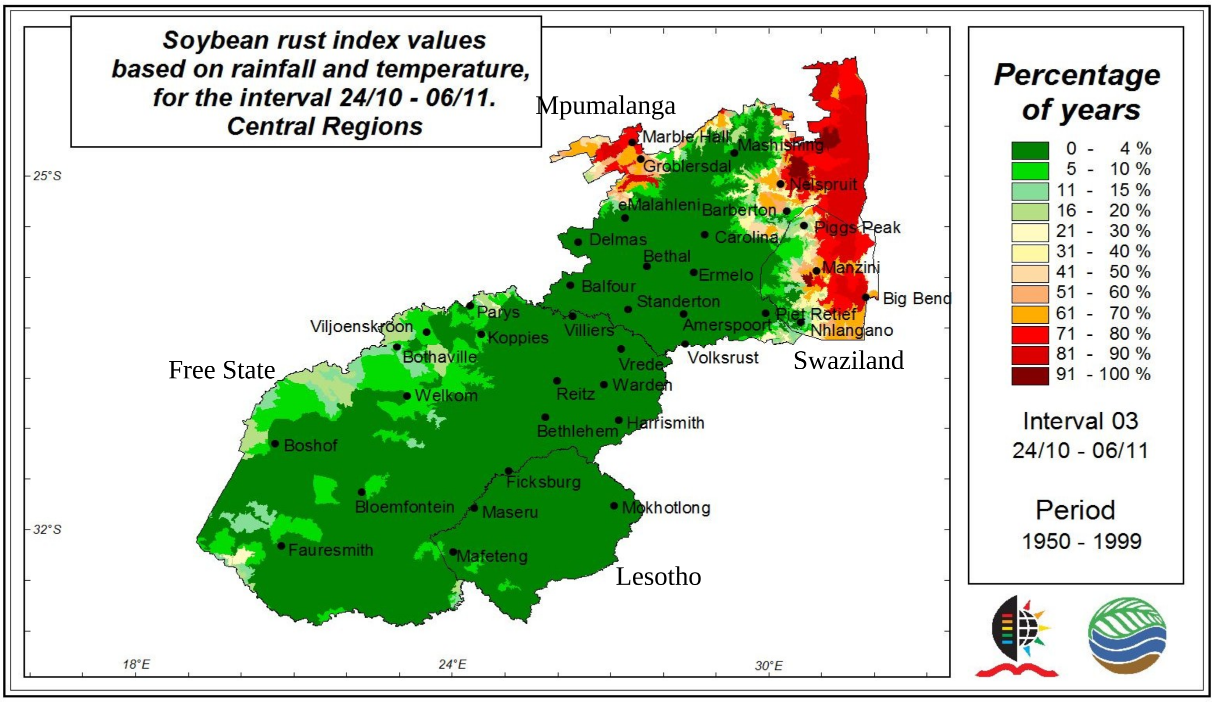

Figure C3 Soybean rust climatic susceptibility map, based on index values, for the in the end of October and beginning of November central soybean producing areas of South Africa, as well Swaziland and Lesotho.

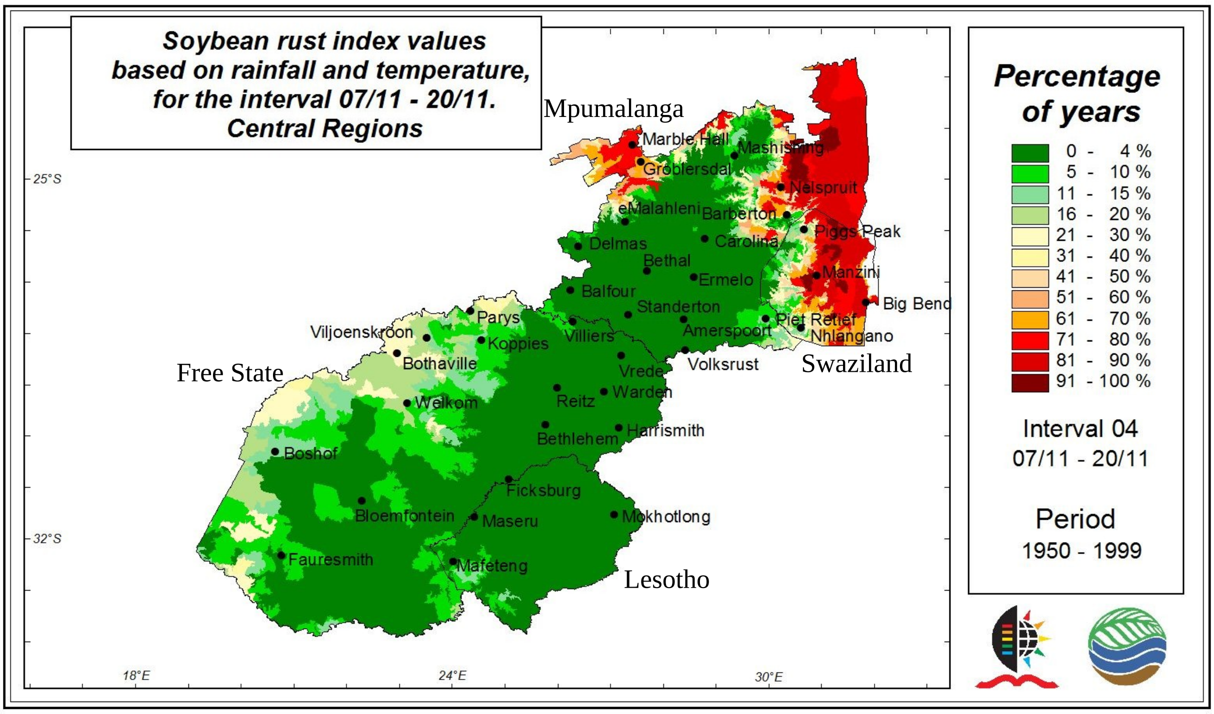

Figure C4 Soybean rust climatic susceptibility map, based on index values, for the middle of November in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

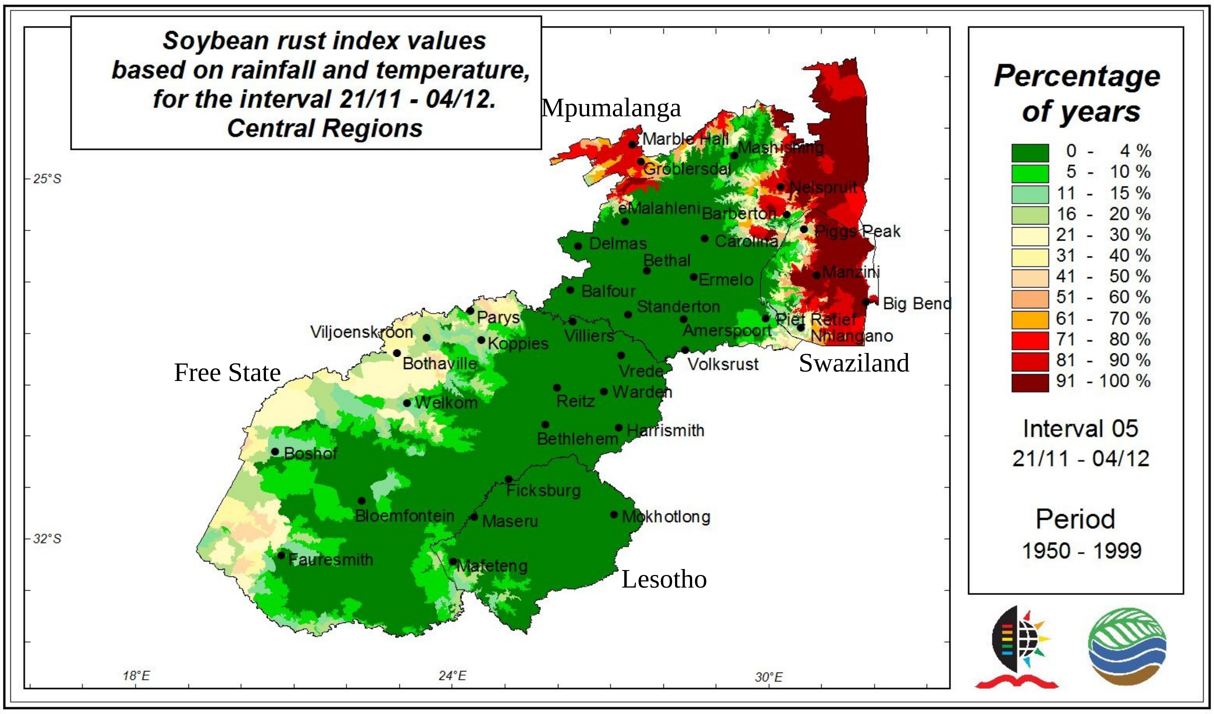

Figure C5 Soybean rust climatic susceptibility map, based on index values, for the end of November in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

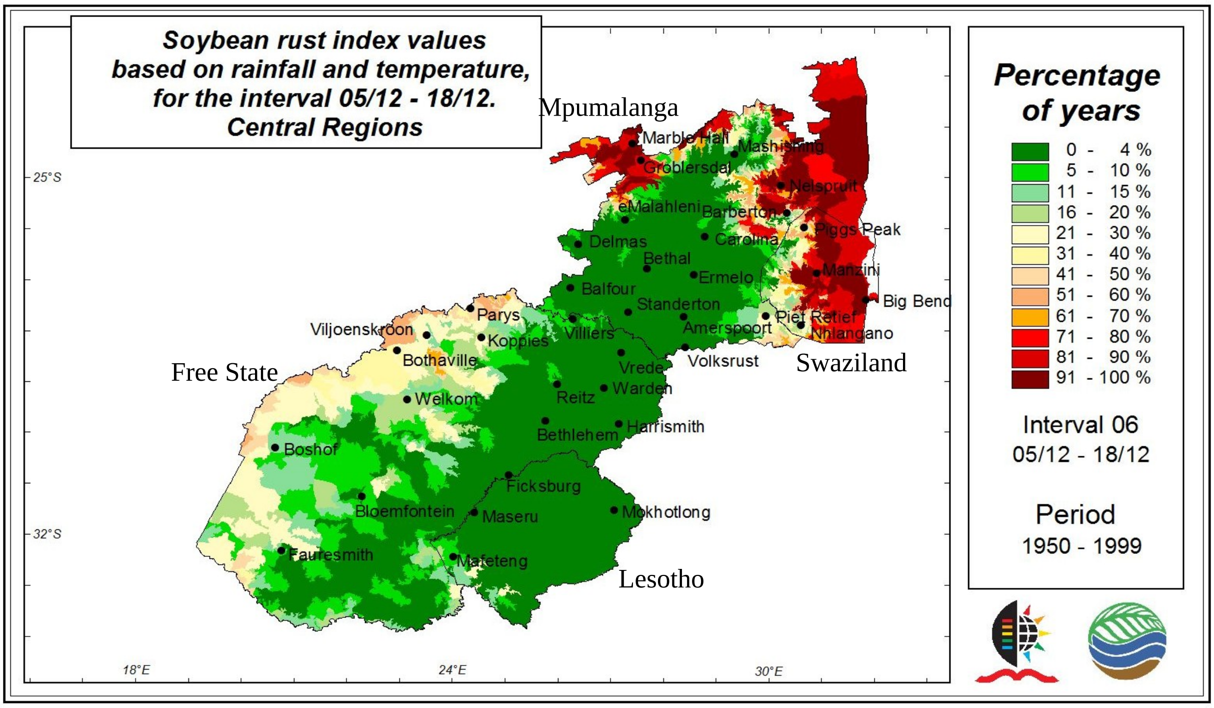

Figure C6 Soybean rust climatic susceptibility map, based on index values, for the beginning of December in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

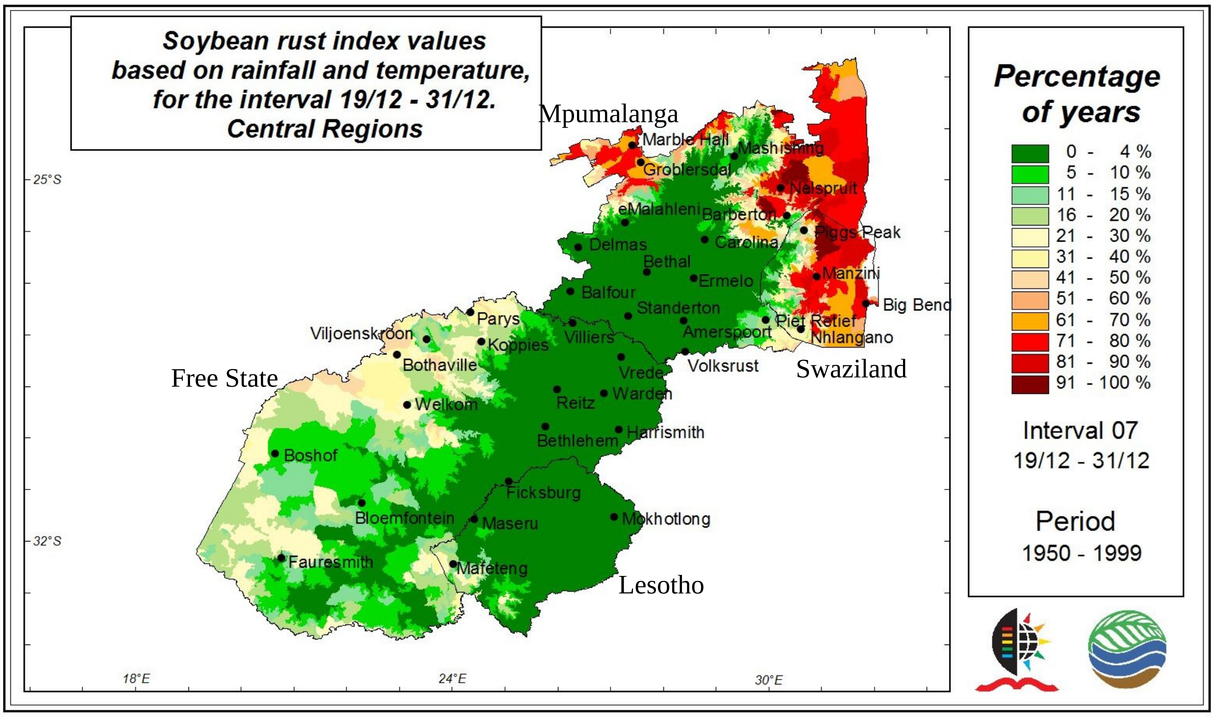

Figure C7 Soybean rust climatic susceptibility map, based on index values, for the end of December in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

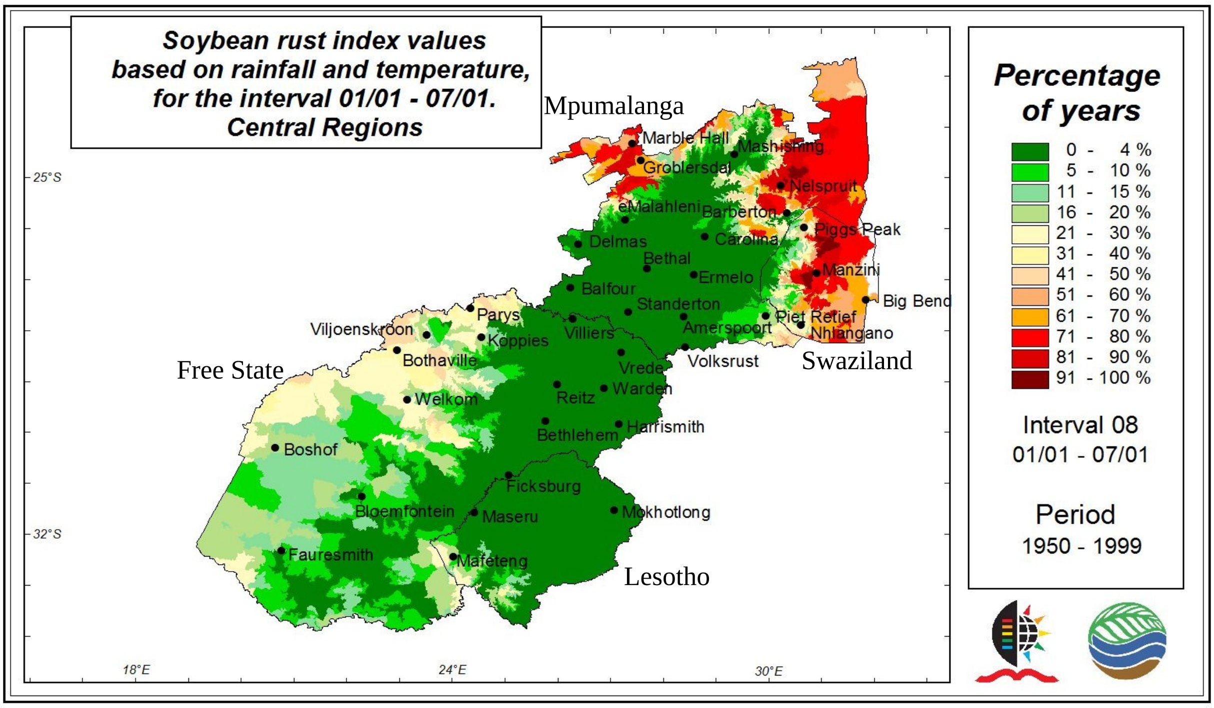

Figure C8 Soybean rust climatic susceptibility map, based on index values, for week 1 of the year in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

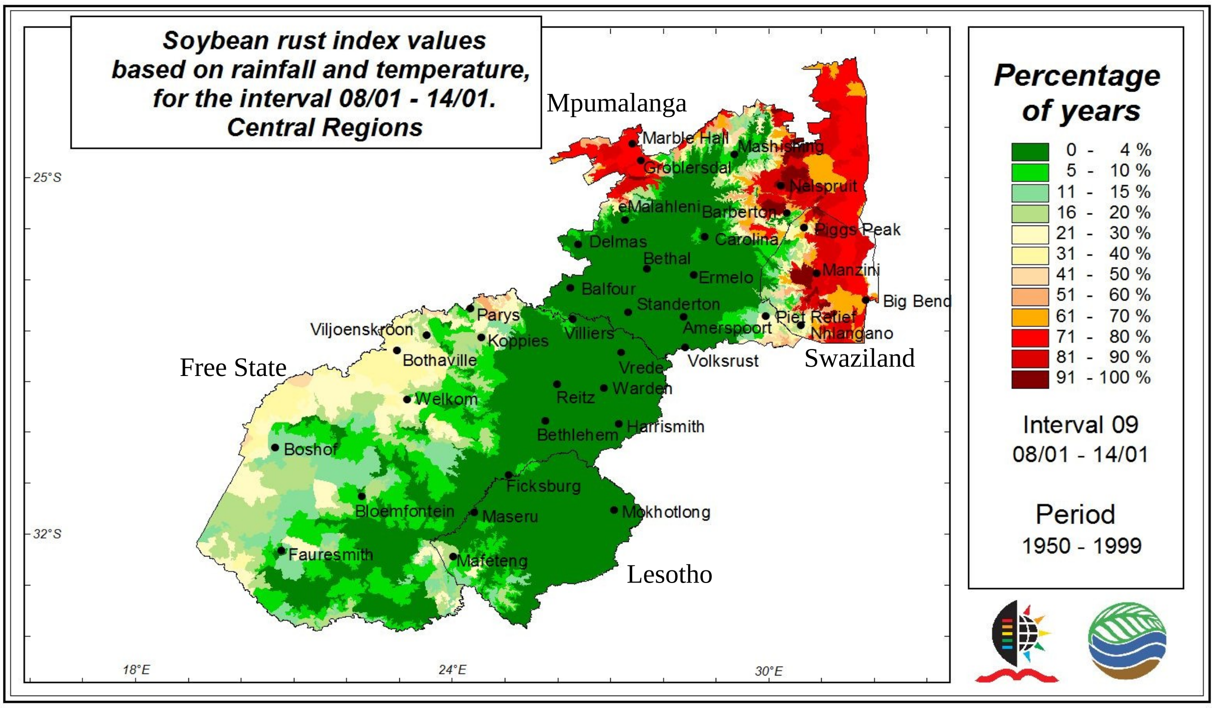

Figure C9 Soybean rust climatic susceptibility map, based on index values, for week 2 of the year in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

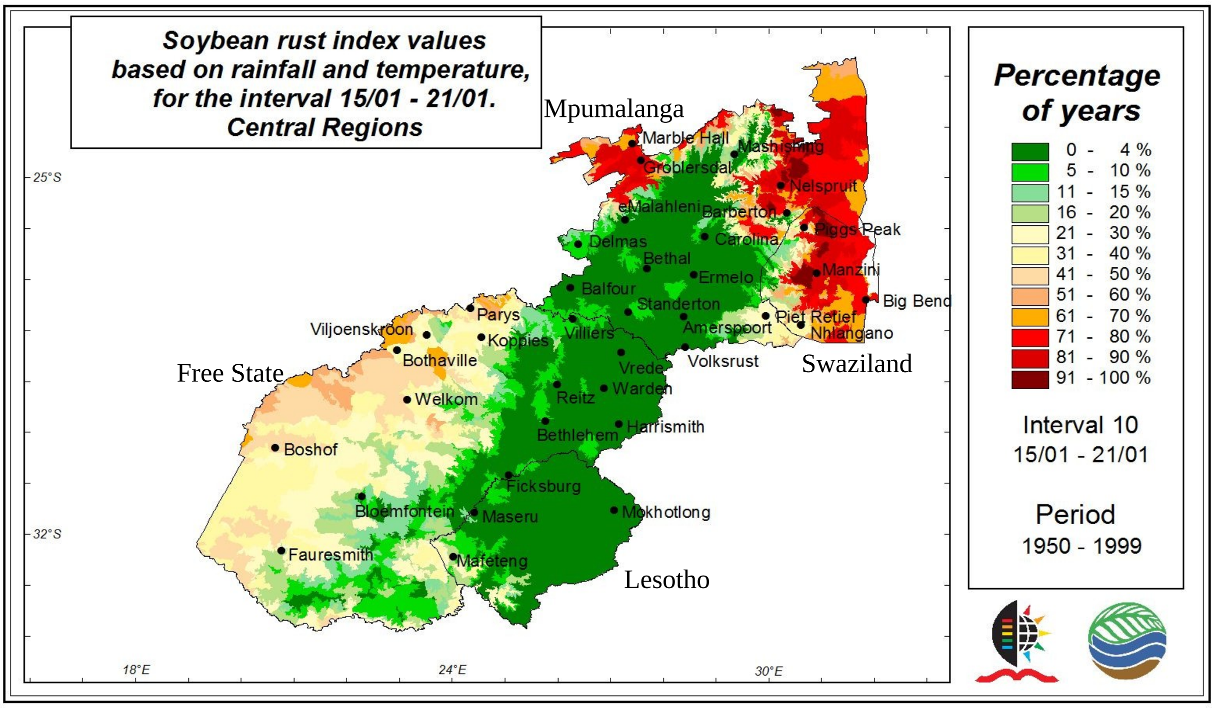

Figure C10 Soybean rust climatic susceptibility map, based on index values, for week 3 of the year in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

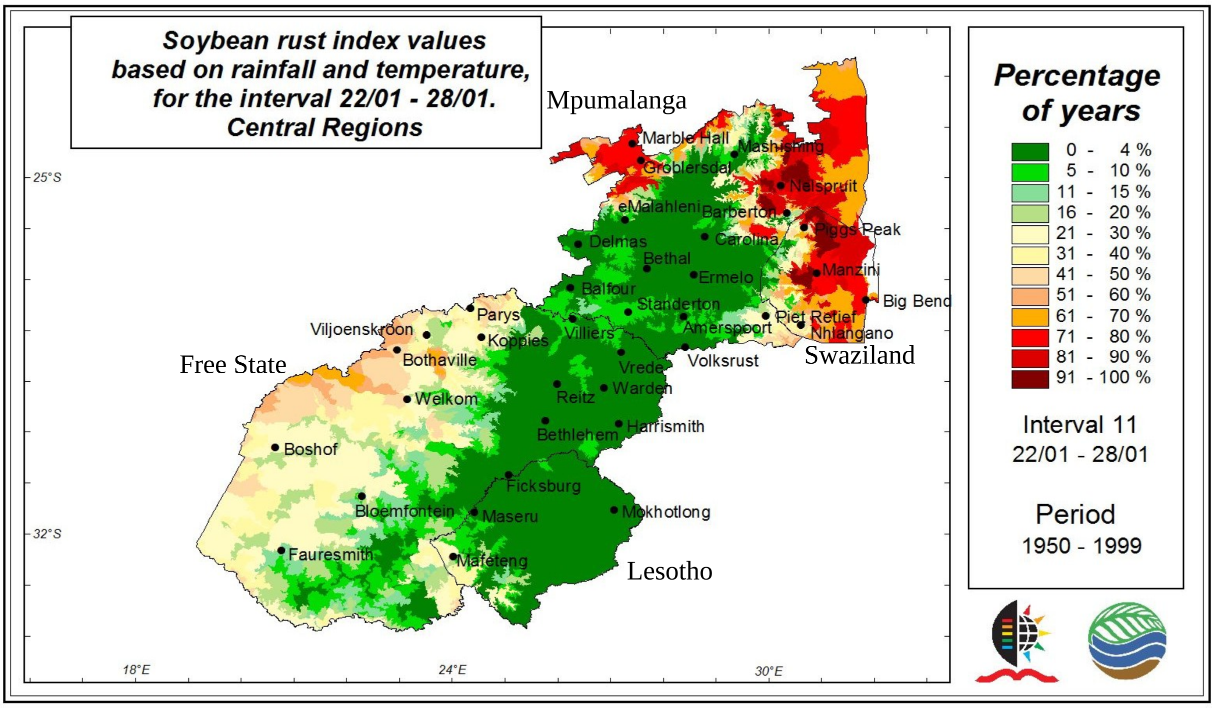

Figure C11 Soybean rust climatic susceptibility map, based on index values, for week 4 of the year in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

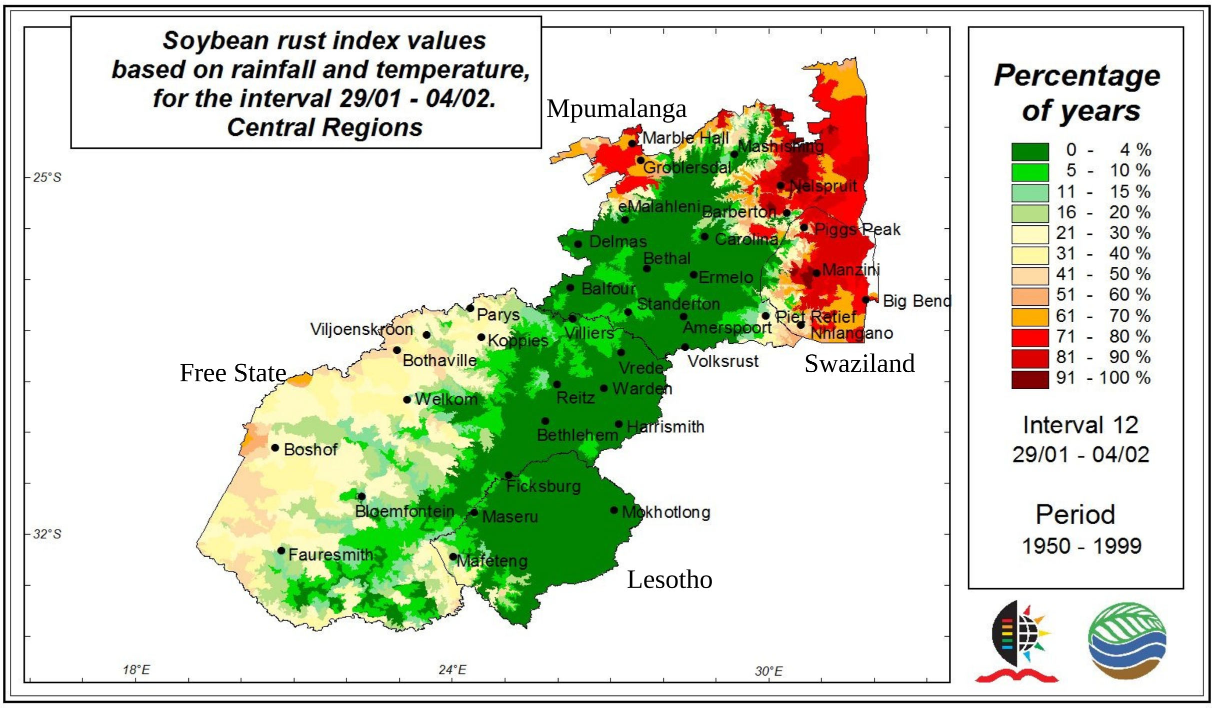

Figure C12 Soybean rust climatic susceptibility map, based on index values, for week 5 of the year in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

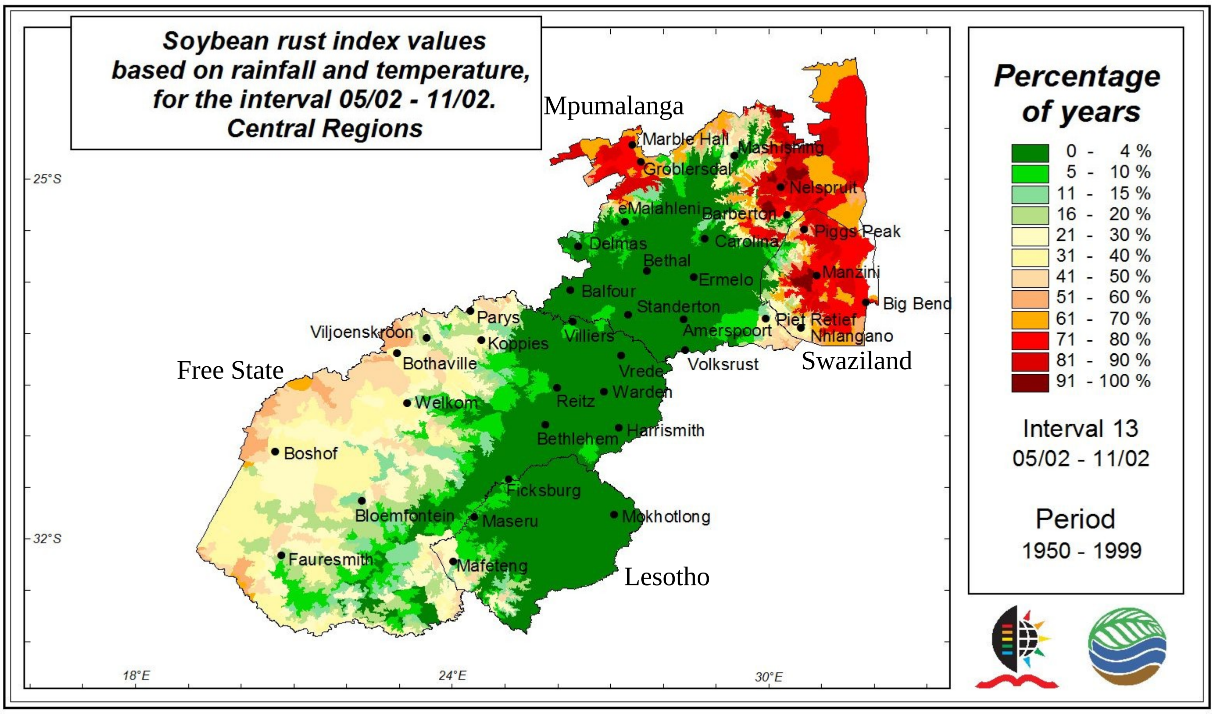

Figure C13 Soybean rust climatic susceptibility map, based on index values, for week 6 of the year in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

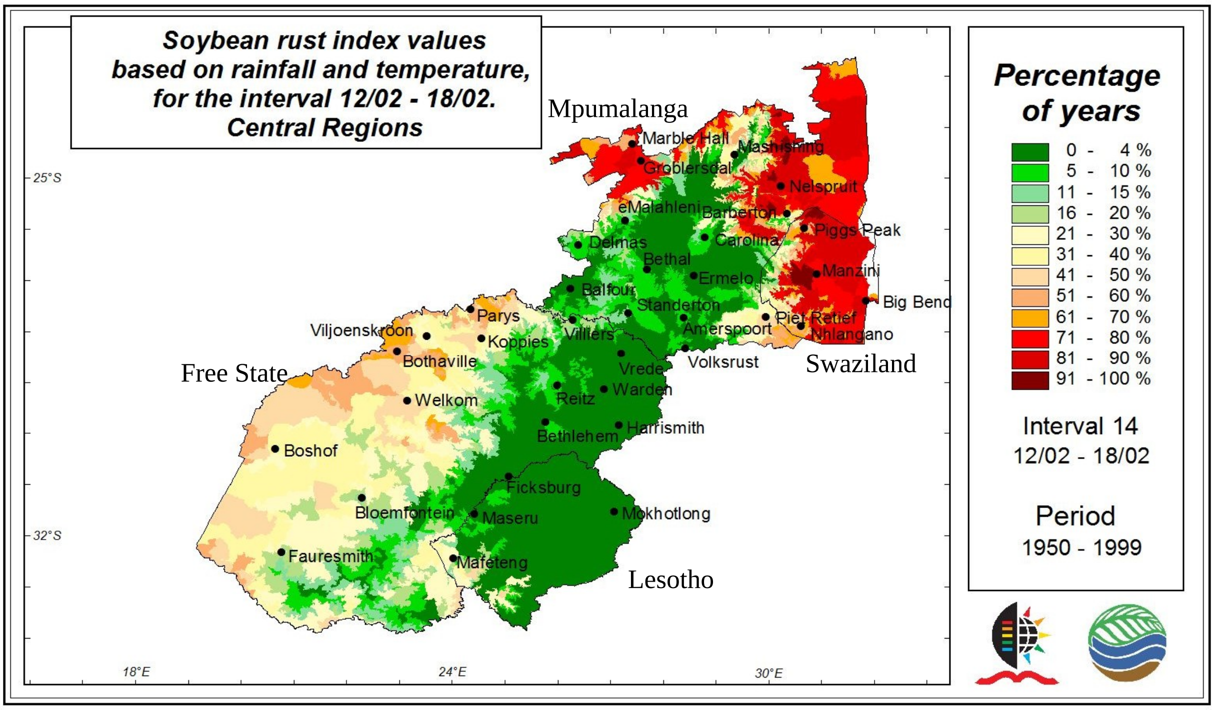

Figure C14 Soybean rust climatic susceptibility map, based on index values, for week 7 of the year in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

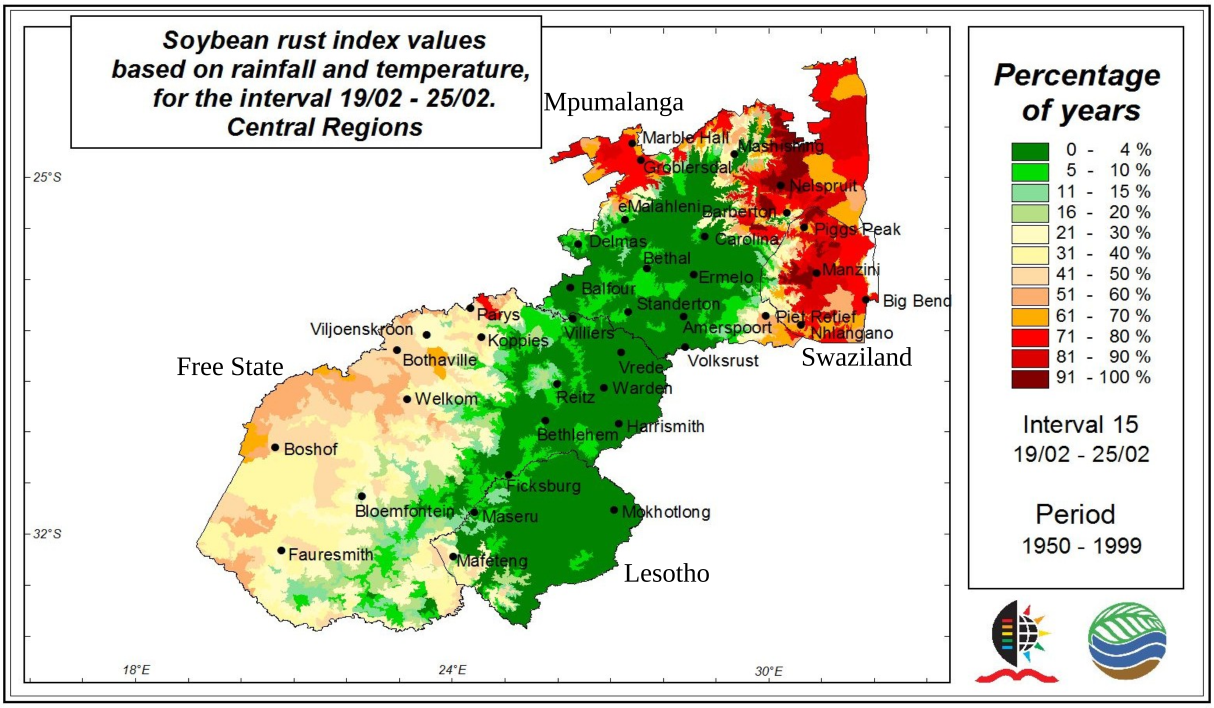

Figure C15 Soybean rust climatic susceptibility map, based on index values, for week 8 of the year in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

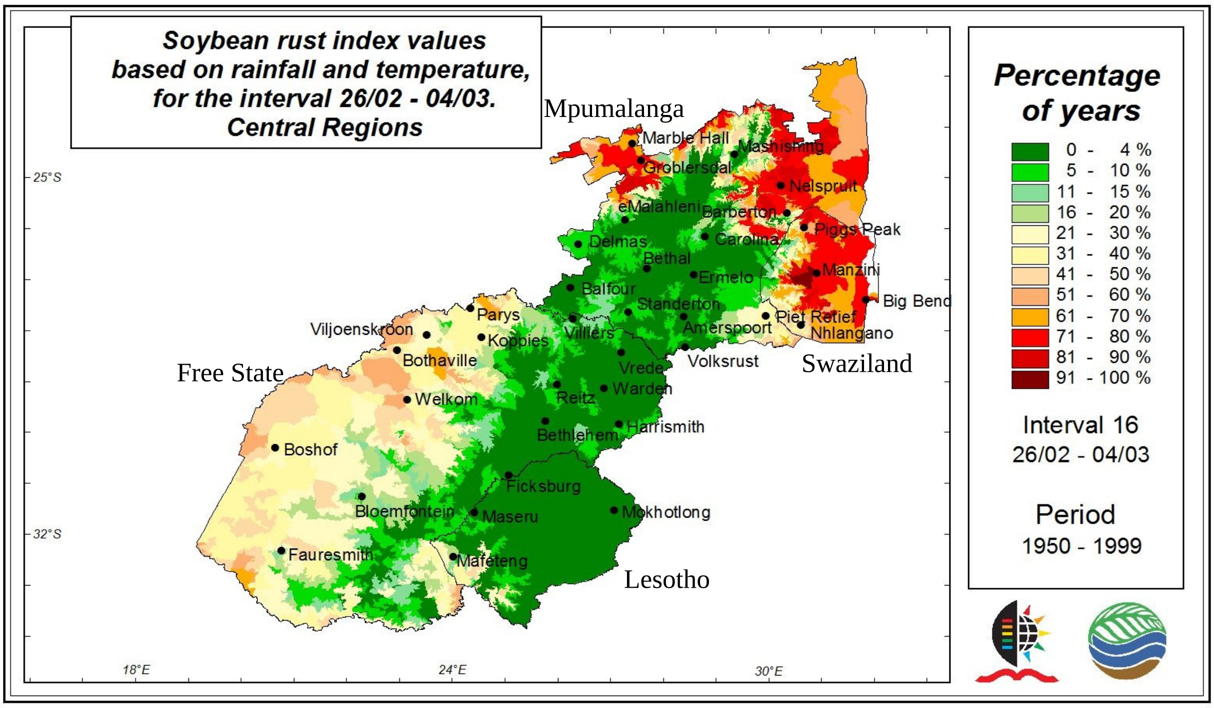

Figure C16 Soybean rust climatic susceptibility map, based on index values, for week 9 of the year in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

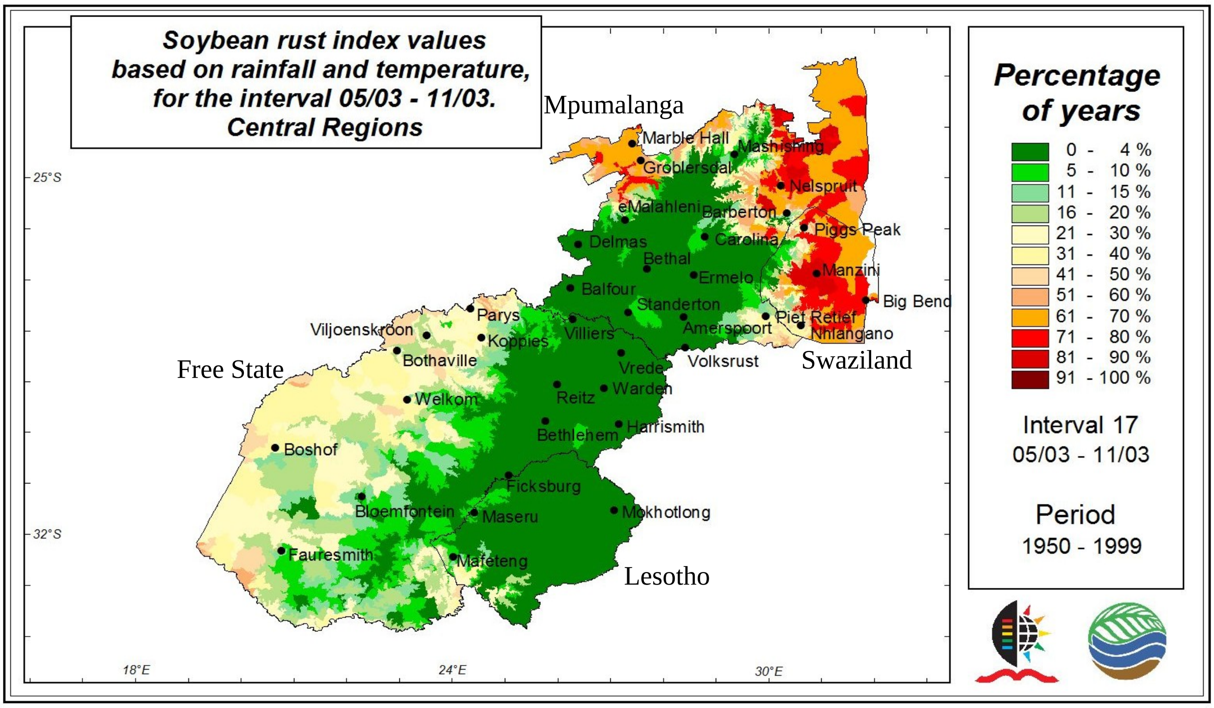

Figure C17 Soybean rust climatic susceptibility map, based on index values, for week 10 of the year in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

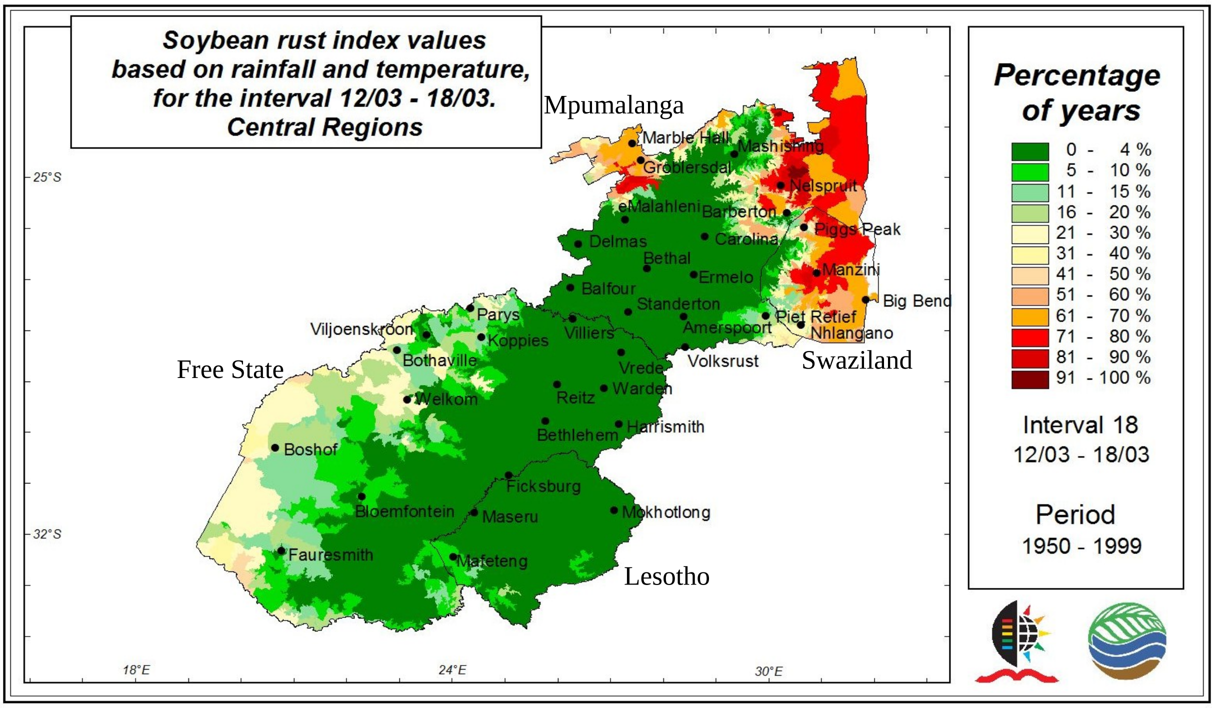

Figure C18 Soybean rust climatic susceptibility map, based on index values, for week 11 of the year in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

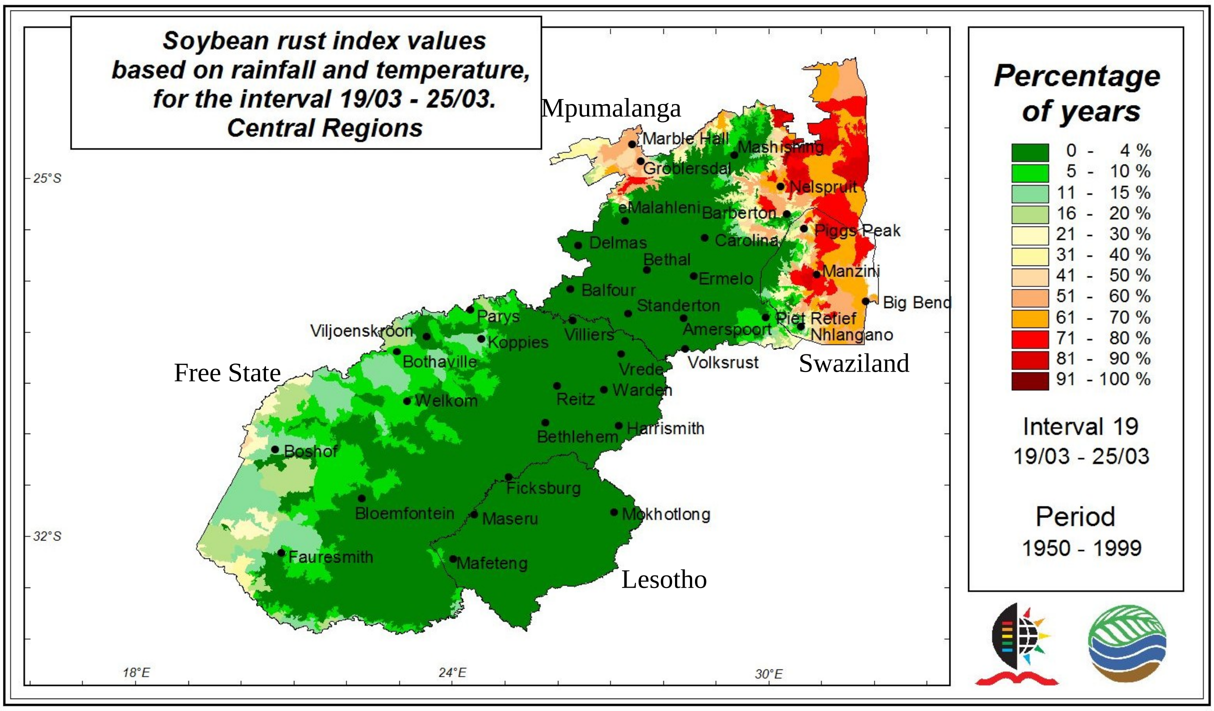

Figure C19 Soybean rust climatic susceptibility map, based on index values, for week 12 of the year in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

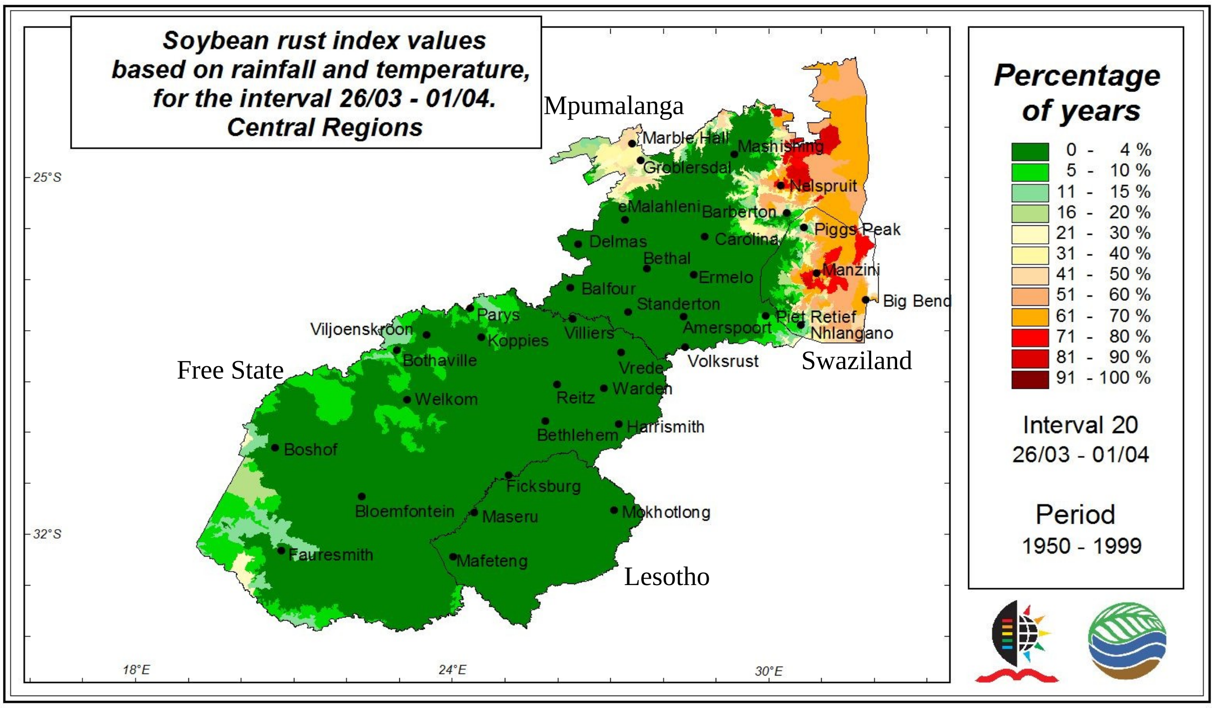

Figure C20 Soybean rust climatic susceptibility map, based on index values, for week 13 of the year in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

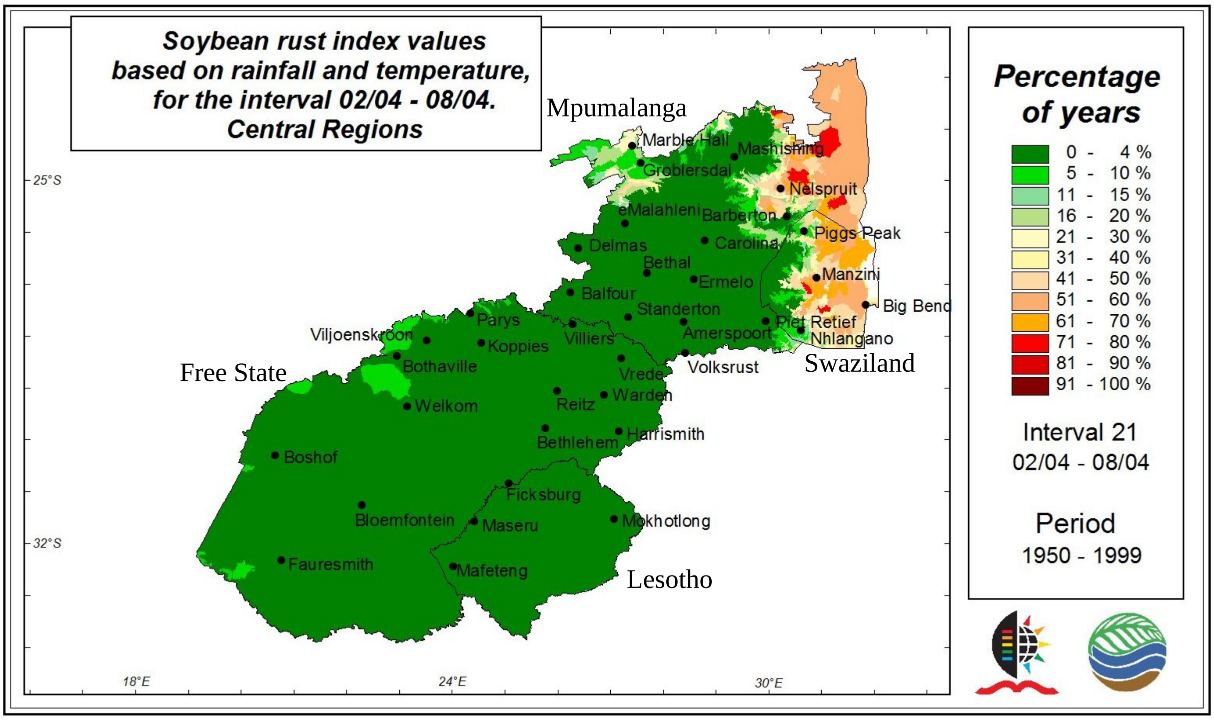

Figure C21 Soybean rust climatic susceptibility map, based on index values, for week 14 of the year in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

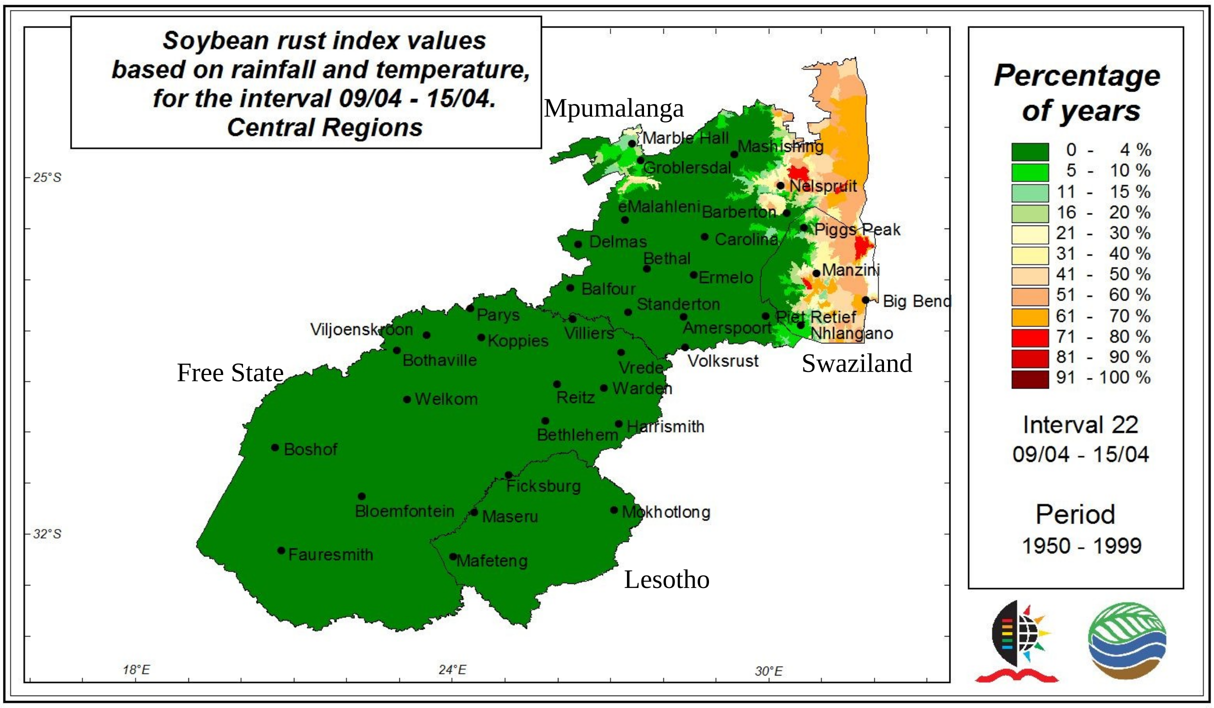

Figure C22 Soybean rust climatic susceptibility map, based on index values, for week 15 of the year in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

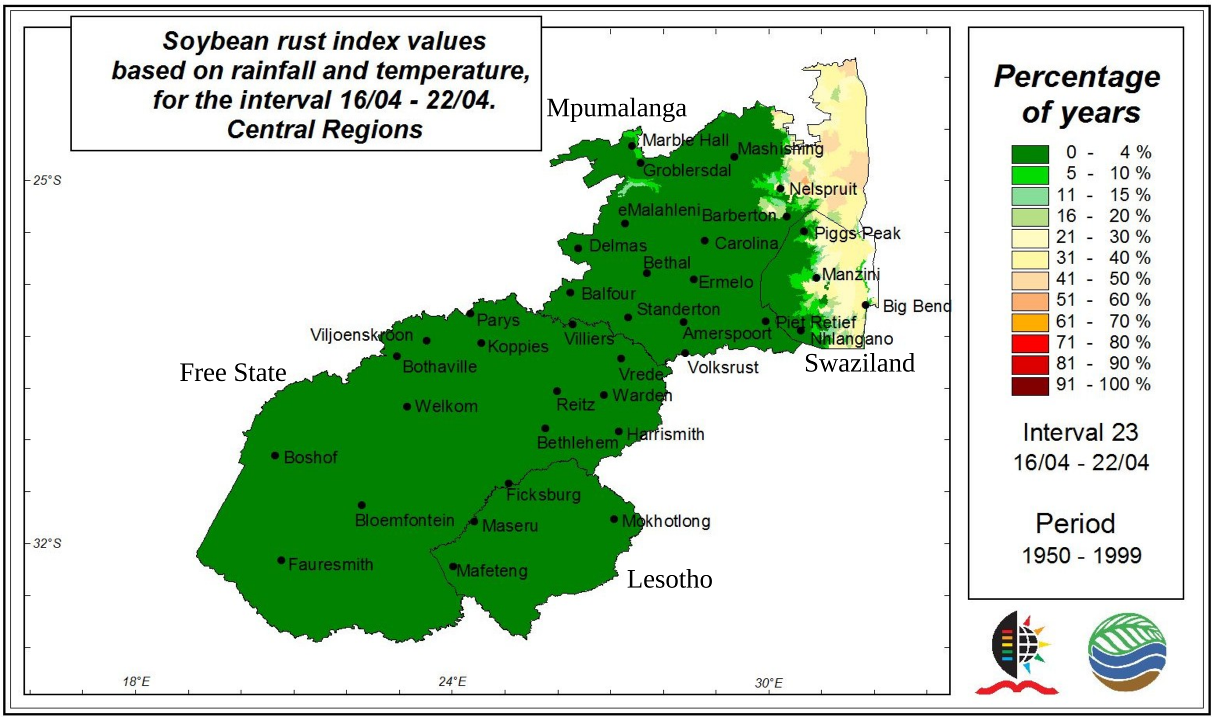

Figure C23 Soybean rust climatic susceptibility map, based on index values, for week 16 of the year in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.

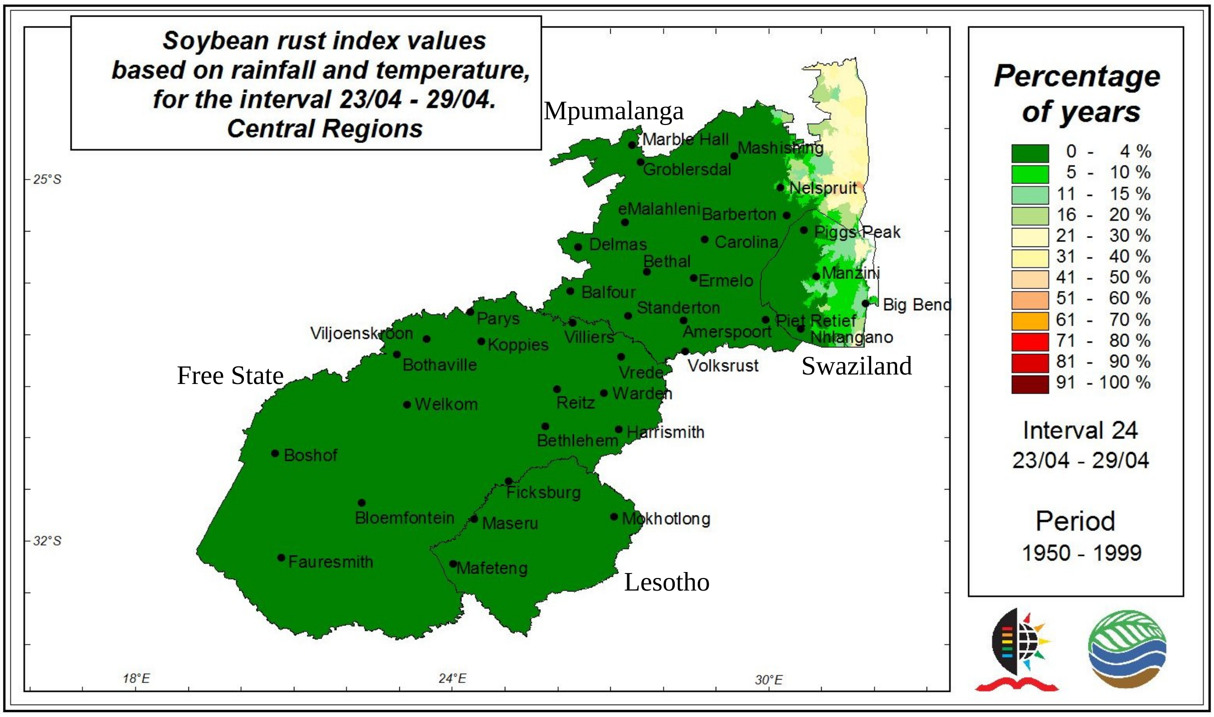

Figure C24 Soybean rust climatic susceptibility map, based on index values, for week 17 of the year in the central soybean producing areas of South Africa, as well Swaziland and Lesotho.