Shifts in Suitability Distribution of Deciduous and Citrus Fruit Trees Under Climate Change in South Africa: A Large-Scale Empirical Study

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MSc Dissertation

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Abstract

South Africa is the largest fresh fruit exporter by volume in the Southern Hemisphere. The quality and quantity of fruit produced depend on local climate, soil quality, water quality and availability. Climate change impacts may undermine the potential contributions of important fruit crops toward South Africa's foreign exchange earnings, national food security and local employment. This study assesses the likely impact of climate change on the future suitability of growing citrus and deciduous fruit in South Africa. 5 GCMs from the CORDEX ensemble were used to project future temperature and precipitation under a high- and a low-mitigation Representative Concentration Pathway (RCP4.5 and RCP8.5, respectively) for the periods 2031-2060 (mid-century) and 2071-2100 (end of century). The Ecocrop suitability model was used to project the changes in spatial suitability of 9 crops (oranges, lemons, mandarins, grapefruit, apples, pears, peaches, plums, and table grapes) over South Africa in each of these scenarios. Ecocrop is an empirical model, suited to this large-scale analysis despite known and acceptable point scale inaccuracies, and driven by changes in monthly minimum and mean temperatures and annual precipitation.

The percentage of total land that was suitable for each fruit crop in each case was compared to historical suitability. For all crops, the largest changes in suitability were seen in END-85 due to extreme temperature increases. Large suitability increases were seen for oranges (341%) and lemons (279%), yet grapefruit and mandarins saw minor change (81% and 67% in END-85, respectively). Apples had small decreases in the east and increases over Lesotho highlands, having a net suitable land area of 78% in END-85. Pears had moderate increases over Lesotho highlands and eastern escarpment and moderate decreases in the Lowveld, with a net increase of 126% of the suitable land area in END-85. Peaches and plums had weak decreases over the highveld and eastern escarpment, although the effects were stronger for plums, which gained 159% its suitable land area in END-85. Table grapes experienced negligible change. All of these effects were milder for the mid-century period and under RCP4.5 due to relatively less intense warming and drying. Indirect impacts of climate change include heat stress, water shortages, crop losses due to pest and disease proliferation, and changes in phenology.

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List of acronyms

AIM – AsiaPacific Integrated Model

AR5 – Assessment Report 5

CMIP5 – Coupled Model Intercomparison Project 5

CORDEX – Coordinated Regional Downscaling Experiment

CRU – Climate Research Unit

CSAG – Climate Systems Analysis Group

GCM – Global Circulation Model

FAO – Food and Agriculture Organization

IAMs – Integrated Assessment Models

IPCC – International Panel for Climate Change

KZN – KwaZulu Natal

LTAS – Long Term Adaptation Scenarios

MIP – Model Intercomparison Project

RCM – Regional Climate Model

RCP – Representative Concentration Pathway

SADC – South African Development Community

SRES – Special Report on Emissions Scenarios

WCRP – World Climate Research Programme

1. Introduction

1.1. The role of South Africa's economically important fruits

South Africa's highly diverse landscape and range of agro-ecological conditions allow for its agricultural economy to be one of the world's most diverse, consisting of corporate and private intensive and extensive crop farming systems for vegetable, fruit, nut, and grain production (Midgley et al., 2016). Although the contribution of crop production to local food security is of utmost social importance, the principal economic value is generated from the high-value exports of fresh and processed fruits, wine, indigenous tea, and some livestock products (Midgley et al., 2016). South Africa's well-developed commercial farming, which includes value-added products and niche product opportunities, is the predominant contributor to the country's agricultural economy.

Fruit exports generate significant foreign exchange for the country and profits for local farmers. Grapes, citrus, and deciduous fruit sold in export markets generate a higher unit price than that achieved on the local market (Horticulture - Agribook Digital, 2017). Today, fresh fruit accounts for approximately 35 percent of South African agricultural exports (FPEF, 2020). In 2019, the economic value generated from these fruit exports was $3.3 billion (FPEF, 2020), roughly R 55 billion. Aside from the foreign exchange earnings, the fruit industry also benefits rural communities by creating employment as it is a labour-intensive industry.

South Africa is the largest fresh fruit exporter by volume in the Southern Hemisphere (FPEF, 2020). The greatest contributor to South Africa's fruit exports is citrus, making up 61 percent of the fruit exports (FPEF, 2019). Other major fruit exports include deciduous fruit (pome fruit, stone fruit, and table grapes, contributing 19%, 3% and 14% of fruit exports respectively), subtropical fruit and exotic fruit (3%); exported to 111 countries, primarily the UK, Europe, Russia and the Middle East (FPEF, 2020).

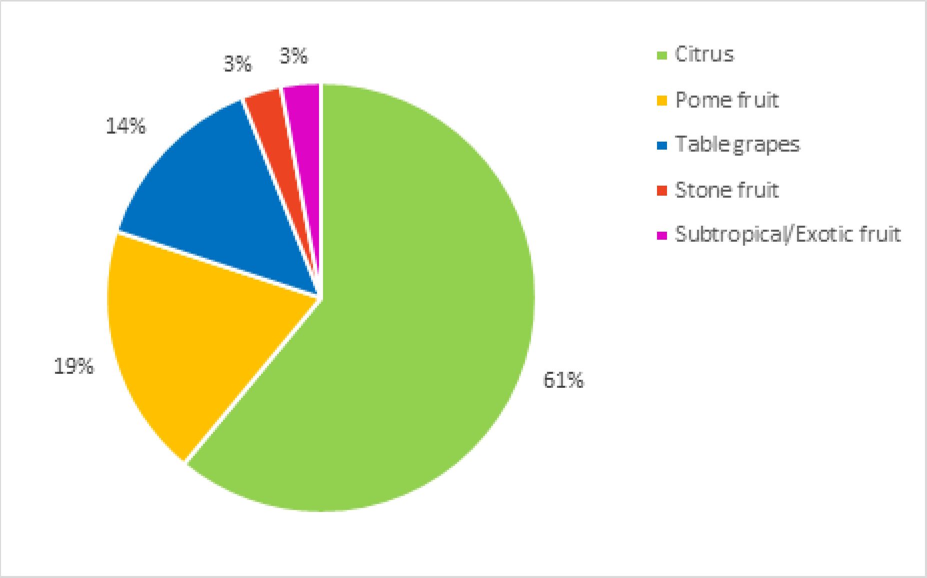


Figure 1: Proportion of South African fruit exports in 2019 (Adapted from FPEF, 2020)

South Africa is the second largest citrus exporting country, after Spain, and the largest in the Southern Hemisphere – accounting for over 60 percent of exports from the Southern Hemisphere (Citrus Production South Africa, 2020). South African citrus is mainly exported to Europe, the UK, the Middle East as well as to Asia and North America. It is also sold locally and exported to neighbouring African countries. In 2017, the citrus industry contributed R 19.1 billion to the country's agricultural economy (DAFF, 2018a). The citrus industry alone employs over 100 000 people working in orchards and packing houses, and an estimated 1 million households rely on the citrus industry to support their livelihood (DAFF, 2018a).

Deciduous fruit comprises pome fruit (apples and pears), stone fruit (peaches, nectarines, plums and apricots) and grapes. The deciduous fruit industry contributed R 19.4 billion to South Africa's agricultural economy in the 2016/2017 season, 28 percent (R 5.5 billion) of which was from apples, 14 percent (R 2.7 billion) was from pears, 6.8 percent (R 1.4 billion) from peaches, and 6 percent (R 1.2 billion) from plums. (DAFF, 2017a; DAFF, 2017b; DAFF, 2018b; DAFF, 2018c). In 2018, 45 percent of total deciduous fruit production was exported (Hortgro, 2018). South Africa is the Southern Hemisphere's second largest apple exporter, after Chile. The apple industry contributes considerably to national agricultural exports, with roughly half of apples produced being exported, and the remainder being sold locally or processed (Midgley, 2016). The majority of apples are exported to other African countries, followed by Europe and Asia.

Aside from the value of its exports, the deciduous fruit industry creates employment for many South Africans. In 2017, the apple industry alone employed over 27 000 people directly and had an estimated 109 000 dependents (DAFF, 2018b). Direct employment within the pear industry was estimated at 13 000 people and 52 000 dependents (DAFF, 2018c). In 2016, direct employment within the peach industry was 8 000, with 32 000 dependents (DAFF, 2017a); and 6 500 direct employees with 26 000 dependents within the plum industry (DAFF, 2017b).

Attributable to their foreign exchange earnings and employment creation, table grapes are one of South Africa's most imperative deciduous fruits grown (DAFF, 2017c). The industry produces grapes mainly for the export market and is growing rapidly. South Africa has been producing and exporting table grapes for more than a century and is considered the oldest and most reliable supplier of table grapes to the Northern Hemisphere (DAFF, 2017c). About 90 percent of grapes produced in South Africa are exported, primarily to Europe and the UK (Horticulture - Agribook Digital, 2017), to be sold in traditional markets. The table grape industry contributed R7.1 billion to South Africa's agriculture economy in the 2015/2016 season and employed 43,000 workers on a seasonal basis in 2017, with 180 000 dependents (DAFF, 2017c).

The fresh fruit that the country exports is of a higher quality than the fruit sold on the local market (Midgley et al., 2016). Although yield variability is often problematic, variability in fruit quality often causes greater complications as it affects fruit prices. Fruit that does not meet export-level quality standards needs to be sold on the local market or processed (juiced, dried, or canned). This shift causes disruptions and pressurizes prices to drop, drastically reducing profits. South Africa's fruit industry is highly dependent on exports, and thus needs to maintain global competitiveness (Midgley, 2016). Unpredictable weather patterns associated with climate change contribute to uncertainty of yields and quality, increasing the price volatility of agricultural products (Midgley et al., 2016).

1.2. Climate change impacts on South African agriculture

Climate change is a reality that poses significant environmental, social, and economic risks and challenges on a global scale. South Africa's agricultural sector faces numerous challenges and risks and has been presented with new and very significant threats due to climate change (Midgley et al., 2016). Climate change is already negatively affecting global crop production and is expected to continue doing so unless adaptive measures are taken (IPCC, 2014). The Intergovernmental Panel on Climate Change (IPCC)'s Fifth

Assessment Report (AR5) says with high confidence that food security – encompassing production, access and price stability – is potentially threatened by climate change; and that water availability and supply, food security, infrastructure and agricultural incomes in rural areas are expected to experience major impacts, including shifts in the production areas of crops (IPCC, 2014).

Fruit production quality and quantity depend on local climate, soil quality, water quality and availability. Climate change includes changes in temperature, precipitation, atmospheric carbon dioxide concentration, and the frequency and intensity of extreme weather events such as drought and extreme rainfall. The IPCC reveals, through reviewing numerous studies, that the negative impacts of climate change on crops have outweighed the positive ones (IPCC, 2014). Whereas short-term effects include greater climate variability and more severe and prolonged extreme events, the long-term impact will also result in shifts in mean climatic states. Both long- and short-term effects will impact agricultural productivity and suitability, including those of crops, livestock, and fisheries. Increased climate variability and climate extremes associated with climate change will impact water quality and availability through shifts in rainfall seasonality, more frequent and severe storms, floods, and droughts affecting soil moisture, runoff, and evaporation rate from reservoirs and dams (Department of Environmental Affairs, 2017; Midgley et al., 2016). Irrigation demands are also expected to increase. South Africa's recent drought (2015-2018) had associated crop losses and water restrictions, impacting food and water security (Department of Environmental Affairs, 2017). Water resources are already stressed, and water use for agricultural purposes is not assured. Rising temperatures and the increasingly variable rainfall will increase the demand for water, leaving even less for irrigation (Midgley et al., 2016). Furthermore, water quality (which is negatively impacted by warming and variable/extreme rainfall) is a chief concern and poses a significant risk to the quality of crops, particularly to high-value export crops, such as the ones we are concerned with here.

Potential climate change impacts on agriculture in southern Africa also include more frequent and longer dry spells, as well as increased temperatures that will put fruit crops under greater and/or more frequent heat stress, and increasingly favourable conditions for the prevalence of wildfires (Midgley et al., 2016). Other climate change impacts on agriculture in southern Africa also include the possibility of increased frequency and intensity of hailstorms and windstorms (Midgley et al., 2016) which can damage fruit crops. As a developing country, South Africa is particularly vulnerable to climate change impacts, due to its lack of adaptive capacity and its enhanced warming (Niang et al., 2014). Consequently, South Africa is heavily challenged with the task of advancing economic growth whilst using sustainable resources to respond to climate change. In terms of agriculture, the impacts of climate change will be felt most in greater variability of crop production and quality, and hence in price and income (Midgley, 2016), although this applies mostly to field crops. Problems with fruit production and quality may arise due to seasonal shifts in rainfall, temperature, and humidity. Drought conditions could challenge farmers in areas where rising summer temperatures cause soils to become drier. In some places, water supply may be reduced which leaves less water for irrigation when more is needed. Irrigated horticultural crops may therefore be threatened by insufficient water for irrigation, pests and diseases, and heat stress caused by warm production regions getting even hotter. On the other hand, temperature changes may result in some regions becoming more suited for horticultural production, depending on the crop's optimum growing conditions (Midgley et al., 2016).

The growing concern around climate change and its significant effect on crops requires crop and climate modelling to assess crop responses and to provide the necessary information to support farmers and policymakers in strategic decision-making regarding cultivar selection, planting dates, irrigation scheduling, etc., as well as climate change mitigation and adaptation (Fischer et al., 2005). Plant biophysical processes such as respiration, photosynthesis, growth, reproduction, and water use are impacted by increased temperatures and carbon dioxide levels associated with climate change (Oteng-Darko et al., 2012). Attempts to measure the impacts of climate change on agriculture must invariably rely on models that translate changes in climate to changes in agricultural outcomes (Lobell and Asseng, 2017). Because of the complex interactions between climate, crop physiology, and human management at the farm to regional level, studies assessing the impacts of climate change on agriculture involve the use of computer simulations that link climate model predictions with crop models and land management decision tools (Fischer et al., 2005). The combination of climate and crop models enables the simulation of long- and short-term impacts of climate change on crops. While a well-known suite of models focus on the biophysical characteristics of the crops and how those characteristics will respond under future climate (typically process-based models), this study utilizes another method using an empirical approach which focuses on the environment rather than the crop. The nature of such approach is known for inconsistent accuracy of biophysical indicators at point-based scale, but high ability to represent large spatial and temporal variability. We acknowledge this characteristic, and will focus on drawing value out of the relative changes in time and space rather than specific location or temporal accuracy.

1.3. Rationale for this study

Climate change impacts may undermine the potential contributions of important fruit crops toward South Africa's foreign exchange earnings, national food security and local employment. Stakeholders need to plan for, and respond to, climate risks to agricultural productivity, food security and socio-economic development, which requires further understanding and research assessing the scope of these impacts. This study aims to generate information about how potential climate change scenarios will impact the statistical climatic suitability of farming citrus and deciduous fruit in South Africa, to improve decision-making and spatial planning regarding which fruit crops, their cultivars, and farming practices should be implemented in which areas to foster a climate-resilient agricultural industry in South Africa.

Past related research on climate change impacts on the suitability of annual trees such as those examined in this study include a GIS-based suitability modelling of sago palms in the Philippines using Ecocrop (Makinano-Santillan and Santillan, 2015), potential shifts in optimal growing areas of selected commercial trees including pine trees, gum trees and pecan nuts (Shulze and Kunz, 1995). Jayathilaka et al., 2011, assessed climate change effects on suitability of major plantation crops in Sri Lanka, specifically that of tea, rubber, and coconut trees. Vanalli et al., 2021 studied the shift in peach tree's thermal niches in France due to climate change. Recently, World Agroforestry created a climate change atlas for Africa of tree species prioritised for forest landscape restoration in Ethiopia using habitat suitability models (Kindt et al., 2021). Most agricultural research conducted in South Africa focuses on staple field crops such as maize, wheat, beans, sorghum etc. (Blanc, 2012; Cairns et al., 2013; Ramirez-Villegas et al., 2013; Piikki et al., 2017; Egbebiyi et al., 2019), as these crops are most widely grown and consumed, yet little attention has been given to climate-sensitive fruit crops which generate significant foreign exchange and job creation in the rural sector.

1.4. Aim and objectives

This study aims to assess the long-term impact of climate change on the large-scale suitability of growing citrus and deciduous fruit in South Africa in the 21st century.

Objectives:

- To review the climatic requirements for farming citrus, pome fruit, stone fruit, and table grapes, and the effect climate change may directly and indirectly have on crop suitability;
- To analyse changes in South African climate in the 21st century under high and low emission scenarios (Representative Concentration Pathways RCP8.5 and RCP4.5); and,
- To analyse large spatial and large temporal changes in suitability of fruit crops under different climate change scenarios

2. Literature review

2.1. Agroclimatology of major fruit crops

Crop growth, production and geographic distribution are greatly dependent on the environment. Growth and suitability are limited by environmental factors such as light, moisture, temperature, nutrients, and soil properties. South African climate varies from subtropical to Mediterranean, allowing for a range of farming opportunities, and providing ideal conditions for a variety of fruit to be grown. Various soil types across South Africa have differing physical characteristics such as drainage, density, texture, depth, and porosity; upon which the growth, development and production of crops depend. These soil properties determine the extent of water uptake by the plant roots, and the depth of the root system. The country's biodiverse landscape ensures that a wide range of products such as grains, fruit and wine are produced at an exceptional quality and can be exported due to high international demand. Citrus fruit, deciduous fruit and subtropical fruit are grown throughout most of South Africa, however, the Western Cape is the predominant horticultural region.

Figure 2: Map of fruit-growing regions in South Africa (FPEF, 2019)

Table 1 outlines the absolute and optimum temperature and moisture requirements of the crops in this study.

Table 1: Crop ecological requirements (source: FAO-Ecocrop database)

		Crop								
Climate variable		Apple	Pear	Sweet orange	Mandarin	Lemon	Grapefruit	Peach	Plum	European wine grape
Gdur	Growing duration (days)	180 - 320	180 - 270	180 - 365	60 - 365	210 - 365	60 - 365	240 - 270	180 - 220	160 - 270
T_{KILL}	Killing temperature (°C)	-2	-26	0	0	-2	0	0	-2	0
T_{MIN}	Minimum temperature (°C)	8	10	13	12	12	13	7	6	10
T_{OPMIN}	Optimum minimum temperature (°C)	14	20	20	23	15	18	20	18	18
T_{OPMAX}	Optimum maximum temperature (°C)	27	35	30	34	28	32	33	33	30
T_{MAX}	Maximum temperature (°C)	33	37	38	38	36	42	35	36	38
R_{MIN}	Minimum rainfall (mm)	500	400	450	300	300	300	750	600	400
R_{OPMIN}	Optimum minimum rainfall (mm)	700	600	1200	1200	1000	1500	900	900	700
R_{OPMAX}	Optimum maximum rainfall (mm)	2500	900	2000	1800	2300	2300	1100	1500	850
R_{MAX}	Maximum rainfall (mm)	3200	2100	2700	4000	4000	4000	1600	1800	1200

Citrus fruit

Citrus (Rutaceae) plants produce important fruit crops such as oranges, soft citrus (or easy peelers, such as naartjies and mandarins), lemons, limes, and grapefruit. Citrus production is the largest fruit industry in South Africa. The success of a commercial citrus farm depends on the climate of the region, the location of the orchard, the soil, the appropriate choice of citrus cultivar, and the cultivation practices. The main citrus cultivation areas are Hoedspruit, Letsitele and Vhembe in Limpopo; Onderberg. Malelane and Nelspruit in Mpumalanga; Ceres, Boland and Citrusdal in the Western Cape; Patensie and the Sundays River Valley in Eastern Cape; and Pongola and the midlands of KwaZulu-Natal. South Africa has a total of around 86 744 hectares under citrus cultivation (Citrus Growers Association, 2020). The cultivation areas differ greatly in climatic conditions, and different varieties are suited to each environment. The Western Cape and Eastern Cape are the cooler citrus growing areas where Navel oranges and lemons are best suited, as well as most of the soft citrus/easy peelers. Farms in the Western and Eastern Cape are generally smaller, and citrus is packed by private co-operatives in massive packing facilities (DAFF, 2018a). The warmer climate in Mpumalanga, Limpopo and KwaZulu-Natal is better suited to farming Valencia oranges and grapefruit. Farms in these provinces are larger and the fruit is packed in smaller, privately owned facilities (DAFF, 2018a).

Citrus requires a warm subtropical climate and is sensitive to freezing temperatures and frost, although some varieties can withstand freezing temperatures (National Department of Agriculture, 2000). The optimum temperature for citrus growth is 25 - 30°C (Abobatta, 2019). The coldest month should not have minimum average temperatures below 2 to 3°C if no protection is provided. Citrus production is can also be limited by lack of water, and farming of citrus depends on irrigation to avoid hindering growth and production (National Department of Agriculture, 2000). It is essential that citrus trees receive sufficient water to avoid harmful water stress at all stages of growth, so drip/precision irrigation systems are often implemented in the orchards. The amount of water required depends on the weather - soils that are saturated may cause root rot which can kill the trees if not detected in time (National Department of Agriculture, 2000), but the optimum range is usually between 1000 – 2300 mm per year for most citrus types. Citrus trees are evergreen and produce their flowers in spring. The flowering phase is especially sensitive to water shortages which may result in excessive flower and fruitless drop, drastically decreasing fruit production. The fruit develop in spring and summer and are ripe for harvest in late autumn and winter, depending on the variety (Table 2). Citrus grows in a variety of soil types on condition that it is well drained. The ideal soil for citrus production is fertile and aerated with a neutral to slightly acidic pH (6 to 6.5) and a clay content of 10 - 40 percent (National Department of Agriculture, 2000).

Table 2: Citrus harvesting seasons

	J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Oranges					■	■	■	■	■			
Lemons		■	■	■	■	■	■	■	■			
Mandarins					■	■	■	■	■	■		
Grapefruit				■	■	■						

Deciduous fruit

Deciduous fruit comprises table grapes, pome fruit (apples and pears) and stone fruit (peaches, nectarines, plums, and apricots). Most deciduous fruit in South Africa is produced in the Western and Eastern Cape in very specific regions which have unique climates most suitable for deciduous fruit production. The mesoclimates of these regions are controlled by mountains and valleys, which can create vastly different climates within close proximity. Deciduous fruit is also produced on a smaller scale in other regions of the country such as the Free State, Northern Cape, Limpopo, and Mpumalanga provinces, with some grape varieties being grown in the Northern Cape. These provinces have climatic conditions which are ideal for certain varieties of deciduous fruit trees and vines.

Deciduous fruit trees (and other woody perennials) go through an annual phase of dormancy in winter, which allows them to survive unfavourable winter temperatures. Growth may occur in all parts of the deciduous fruit tree except the bud, enabling it to resist freezing temperatures. Once bud breaks begin in spring, the tree is no longer resistant to extreme cold.

In order to enter and overcome winter dormancy, deciduous trees require sufficient winter chilling, which is the minimum time period of cold temperatures that permits bud break in fruit-bearing trees (Cooke, et al., 2012). Autumn temperatures decrease as winter approaches and the trees enter dormancy. The trees remain dormant until they have been exposed to a certain amount of winter chilling. The amount required depends on the type of deciduous fruit and the cultivar. Most pome and stone fruit favour cold, wet winters and warm summers in Mediterranean climates, which is why they are predominantly grown in the Western Cape. Although, certain low-chilling pome and stone fruit varieties are successfully grown in subtropical climates such as Limpopo province. Generally, pome fruit have a higher winter chilling requirement than most stone fruit varieties, therefore the microclimate in pome fruit orchards plays a vital role.

Once the chill requirement has been met, the tree remains in a state of eco-dormancy until favourable climatic conditions return, and usual growth and flowering continues. If there is a cold spell after normal growth resumes, the flowers or young fruit may be damaged or killed. Insufficient winter chilling may result in delayed foliation (flowering irregularly in spring), reduced fruit set (fruit may remain small or be malformed as they ripen) and diminished fruit quality (less firm, greener fruit) (Schulze and Maharaj, 2007).

In order to select the best areas for deciduous fruit cultivation and the best cultivar for the area, it is necessary to measure the amount of winter chilling in areas where deciduous fruit is grown. This called for the development of various chill unit models which measure the accumulation of winter chilling in fruit-growing areas. Chill unit models are used to identify potential growing locations with sufficient chilling for the various cultivars, and to predict the timing of dormancy completion and bud break, making them useful tools for farmers and researchers alike (Schulze and Maharaj, 2007). Chill unit models assign chill units for each hour at temperatures in the required range for winter chilling. They use hourly temperature data for a given location over the winter dormancy period, and sum the chill units accumulated over this period, to quantify the location's total winter chilling. If a crop's chill requirement is known, climate suitability can be determined by comparing the chill requirement with available chill units as determined by temperature.

In South Africa, the Daily Positive Utah chill unit model is used (Linsley-Noakes, et al., 1995). It is a modified version of the Utah chill unit model which estimates winter chilling in areas with milder winters more accurately, as it does not incorporate the influence of higher temperatures on previous chilling (Linsley-

Noakes, et al., 1995; Allan, 1999). The model assigns chilling units for each hour at a given temperature, with temperatures between 2.5 and 9.1°C holding the most chilling units (see Table 3). It calculates accumulated chilling units by summing the average temperature for each hour every 24 hours (Linsley-Noakes et al., 1995; Midgley et al., 2016).

Table 3: Positive Utah Model chill unit calculation

Temperature (°C)	**PCU (h^{-1})**
T≤ 1.4	0
1.4 ≤ T ≤ 2.4	0.5
2.4 ≤ T ≤ 9.1	1
9.1 ≤ T ≤ 12.4	0.5
T > 12.4	0

2.1.2. a) Table Grapes

Table grapes (Vitis vinifera) are grapes that are grown for eating rather than for wine production. The distribution of vineyards depends on temperature, radiation, humidity, and water availability. These factors affect the rates of photosynthesis and evapotranspiration, both influencing the phenology, yield, and taste of the grapes. The ideal areas for growing grapevines have climates ranging from temperate to Mediterranean. They have a mild winter, a frost-free spring, and a sunny summer that favours ripening and rainfall occurring mainly in winter (DAFF, 2012). This explains why in South Africa, more than 80 percent of table grapes are grown in the Western Cape in the valleys of the Hex, Berg, and Olifants Rivers. The rest are grown in the Orange River region in the Northern Cape and the Olifants River region in

Limpopo (DAFF, 2012; SATGI, 2020), as depicted in Figure 3. The grape producing season runs from mid-November to mid-April. The early season is dominated by products from the Limpopo Province as its early summer and warm subtropical climate combine to produce early maturing varieties. The Orange River region experiences hot, dry summers and sunny winters, as well as rich desert soils which, together, result in superiorly sweet fruit. Mid- to late-season varieties flourish in the Western Cape regions whose mild Mediterranean climates produce grapes of an excellent quality (SATGI, 2020).

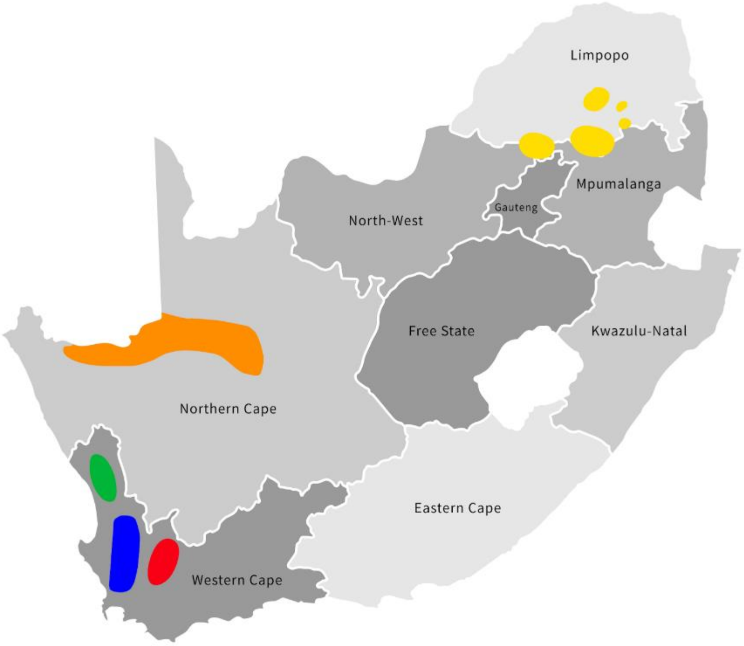


Figure 3: Grape production areas in South Africa (from SATGI, 2020)

Table grapes require dry climates with hot days and cool nights for optimum grape quality (DAFF, 2012). Low winter temperatures (below 0°C) and frost are damaging to the crop and can destroy developing buds, so there should be no late-season frost as this will threaten young buds, leading to a loss of crop for that year (DAFF, 2012; Goldammer, 2018). Low summer temperatures would prevent satisfactory ripening. Warmer temperatures generally produce more consistent harvests. They are best suited for a temperature range of 25°C to 30°C (Hunter and Bonnardot, 2011; Goldammer, 2018) but can be suited to temperatures between 8°C and 38°C. Warm temperatures speed up ripening and increase sugar concentration, producing sweeter, more flavourful grapes (Keller, 2010; Goldammer, 2018). In temperatures exceeding 32°C, photosynthesis decreases, the grape size and weight is reduced, and the skins burn. Temperatures below 25°C reduce photosynthetic activity and slow vegetative growth (Coombe, 1987; Goldammer, 2018), and low temperatures reduce the acid content (Keller, 2010). On the contrary, areas with winters that are not sufficiently cold to reach their chilling requirements raise other physiological problems such as bud break defects and poor fruit quality. This problem is, however, less detrimental to table grapes than wine grapes which require well-balanced sugars, acids and tannins for quality wine production. The number of winter chilling hours varies between grape varieties, but it is substantially lower than other deciduous fruit, roughly 50-400 hours below 7.2°C (Dokoozlian, 1999; Mohamed and El-Sese, 2009; Tharaga, 2014). The use of certain cultural practices has enabled table grape production to be extended to warm tropical climates, such as bi-annual pruning and artificial water stress to induce dormancy (Possingham, 2004).

Vines grow for 160-270 days of the year. The summer season needs to be sufficiently long for the grape berries and the vegetative parts of the plant to mature (DAFF, 2012). Relative humidity of 60-80% is optimal. Grapes are more suited to climates with low rainfall during the growing season as rain causes direct damage to the crop and increases humidity which heightens the risk of disease, especially during the ripening period, although this depends on the variety (de C. Teixeira, 2014; DAFF, 2012). Grape vines require between 400 and 1200 mm of rainfall per year, with an optimal range of 700-850 mm per year (FAO, 2000).

Soil quality determines vine health and thus grape quality and yield (DAFF, 2012). Table grapes grow in a variety of soil types but prefer well-drained sandy loam of at least 75 cm depth which allows the roots to spread and grow. Grapevines are tolerant to a wide range of pH, but 5.5 to 6.0 is the optimal pH range (DAFF, 2012).

2.1.2. b) Pome fruit

Pome fruit are fruits of the *Rosaceae* family that have a core of small seeds surrounded by an edible fleshy membrane.

Apples

Apples (*Malus domestica)* grow in Mediterranean climates with cold winters, moderate summers and medium to high humidity. They are predominantly grown in the Western and Eastern Cape, with Ceres, Groenland, Villiersdorp, and Langkloof being the largest producing regions. Recently, apple orchards have developed in the Free State, Limpopo and Mpumalanga. Apple production was not feasible in these areas due to the frequency of hail, but the introduction of hail nets has made apple farming here viable. These more northern regions produce early-season fruit, beginning in late December, whereas other cultivars come into season from late January to late May. The most common apples varieties grown in South Africa are Golden Delicious, Fuji, Royal Gala, Pink Lady, Granny Smith and Topred (DAFF, 2018b), all of which are highly sought-after in Europe and the UK.

Apples are best suited to areas where the average summer temperature is around 21°C - 24°C during the active growth period, and winters are cold (Griesbach, 2007; Karami and Asadi, 2017). Apple flowers and young fruit can withstand temperatures of -2°C. Spring frost can kill the apple flowers and severely reduce production (Kamas, Nisbett and Stein, 2015a). Apples require around 800-1200 DPCUs (see Table 4) to break dormancy for flowering and fruit production (Kamas, Nisbett and Stein, 2015a), so warmer climates often result in poor fruit yields. They are most suited to areas where they receive uninterrupted rest in winter, as well as plenty of sunshine for colour development. Apple trees thrive in dry highlands (altitudes 1500-2700 m above sea level) and require well-distributed rainfall of between 1000 and 1250 mm throughout the growing season for optimal growth and fruit production. Soil should be well-drained loamy soils with 10-35% clay and a neutral pH of about 6.0-7.0 (Kamas, Nisbett and Stein, 2015a). The soil should also be porous and free of hard substrates to avoid water logging.

Pears

Pears (*Pyrus communis*) also grow best in temperate regions which have cold winters and moderate summers (Griesbach, 2007). The Western Cape, therefore, produces more than half of South Africa's pears. Elgin, Ceres, Wolseley and Langkloof are particularly well known for their pear production. Pears are a summer fruit, whose harvesting time depends on the cultivar and climatic conditions. South Africa's common pear cultivars are Packham's Triumph, Bon Chretien, Abate Fetel, and Forelle. Harvest times vary among the cultivars, but they are generally harvested in late summer.

The dormant plant can endure temperatures as low as -26°C and, during the growing period, the plant can sustain highs of 45°C (Williams, 1978; Verma, 2014), although most popular varieties thrive in regions whose temperature does not exceed 32°C. Abundant sunlight is necessary for good colour development. Most pear crops require 450-1200 DPCUs (see Table 4) to complete their dormancy period for successful flower and fruit production, so they need to be grown in regions with cold winter (Williams, 1978; Verma, 2014; Kamas, Nisbett and Stein, 2015b; Ogundeji and Jordaan, 2017). Some low-chilling varieties require fewer chilling hours, needing roughly 200-800 hours below 7°C (Kamas, Nisbett and Stein, 2015b). Once the pear tree has bloomed, temperatures below -3.3°C and spring or late-season frosts are damaging to the crop. Areas where hail is prevalent are also unsuitable as both fruit and trees can be damaged by hail (Williams, 1978). Most pear farms depend on irrigation for their moisture requirements, however, in areas where the crops rely on rainfall, an average of between 600 and 900 mm per year is required for sufficient soil moisture (Williams, 1978; FAO, 2000).

The optimum soil for pear trees is well-drained, fertile, medium-textured, and sandy loamy soil (Verma, 2014; Kamas, Nisbett and Stein, 2015b). Pear trees are more tolerant of wet soils than apple trees but are less tolerant of drought conditions. The plant requires deep soil (180 cm) for decent root growth, to which higher fruit yields can be attributed (Verma, 2014). The optimal pH range is 6.0-7.0, avoiding alkaline soils which may result in iron deficiency. Pears can be grown from foothills to high altitude (600-2700 m above sea level) (Griesbach, 2007).

2.1.2. c) Stone fruit

Stone fruit production in South Africa is primarily centered around peaches, nectarines, plums, and apricots, with about 350 000 tons of these fruits produced each year. Peaches and nectarines represent more than half of stone fruit production.

Peaches and Nectarines

Peaches and nectarines are the same species (*Prunus persica*) but are regarded as a different fruit commercially. The nectarine is a mutation of a peach and has no fuzz due to a recessive gene (Stein, Kamas and Nisbett, 2015). South Africa's commercial peach production is separated into cling peaches (cling stones) and dessert peaches (freestones), depending on whether or not the flesh sticks to the stone. Because the flesh of cling peaches tends to hold on to the stone, making it difficult to remove from the stone without damaging the flesh, these types are more often processed and used for canning, drying, or pureeing. Dessert peaches are generally firmer, larger, juicier, and have a loose stone, making them ideal for fresh consumption.

The South African peach production season depends on climatic conditions, peach variety, and production area. It runs from October to March, with a small amount being produced in April. Most of the peach production in South Africa occurs in the Western Cape region. The main dessert peach varieties grown in South Africa are Transvalia, Summersun, Temptation, Ambercrest, Witzenberg, Fairtime, Cederberg and Sunsweet. The main cling peach varieties are Kiesie, Kakamas, Sandvliet, Oom Sarel, Cascade, Western Sun and Supreme (DAFF, 2017a).

Peaches and nectarines are best suited to temperate climates which experience warm summers for good colour development and ripening; and cool winters to achieve sufficient chilling to enter winter dormancy (Griesbach, 2007). The dormancy phase enables the trees to survive unfavourable winter temperatures. Different peach cultivars have different chilling requirements (see Table 4), generally between 450 - 800 DPCUs (Tharaga, 2014). Dormancy ends once the plants have received sufficient winter chilling. Insufficient chilling during milder winters results in dormancy not being fully achieved, causing delayed foliation in which the trees flower and sprout irregularly. Peach trees flower in late winter or early spring once they have been exposed to warmer temperatures. Flowers can tolerate temperatures of -3°C. The plant requires a cool and frost-free spring, since small peach fruit can only tolerate a minimum of -1°C and frost will damage the fruit, resulting in poor yields. The optimum annual rainfall for peach trees is between 900 and 1100 mm (FAO, 2000; Frecon, 2002). The amount of rainfall received determines the volume of irrigation required. Rainy and windy conditions are undesirable during the flowering phase as pollinators cannot operate in these conditions, leading to poor fruit set (Kamas, Stein and Nisbett, 2010). At maturity, peaches and nectarines are sensitive to heavy rains which may result in the fruit cracking.

Peach trees are suited to a variety of soil types, but thrive in deep, well-drained loamy soils with 10-35% clay content and an effective depth of at least 60 cm (Kamas, Stein and Nisbett, 2010). They prefer a neutral to slightly acidic soil pH between 5.5 and 6.5. Peaches tolerate heavy or waterlogged soils better than most other stone fruit.

Plums

Plums (*Prunus domestica*) are another popular stone fruit grown in South Africa. Like peaches, plums are best suited to temperate climates. The optimum temperature range for plums is 18-33°C. (FAO, 2000). Temperatures below -2° will kill the tree. They require between 650 and 1000 DPCUs in winter, depending on the cultivar. The plum tree will remain dormant until favourable temperatures return in spring. Should a cold spell or late frost occur after dormancy is broken, the flowers or fruit may be harmed, resulting in poor production. If sufficient winter chilling is not achieved, the trees will experience delayed foliation, a phenomenon whereby the trees flower and sprout irregularly during the spring. Higher chilling plum varieties are therefore more susceptible to delayed foliation. Aside from temperature considerations, plum trees require 900-1500 mm of rainfall for optimum production. They do not tolerate windy and rainy conditions during flowering as this leads to poor fruit set due to the pollinators being inoperative. The trees prefer deep, well-drained soils, ranging from sandy loam to sandy clay loam, with an effective depth of at least 600 mm and a slightly acidic pH of 5.5 to 6.5 (DAFF, 2010).

Table 4: Chilling requirements of various deciduous fruit (adapted from Tharaga, 2014, Rai, et al., 2015; and Ogundeji and Jordaan, 2017)

Type of deciduous fruit	Chilling requirement	DCPUs
Pome fruit	High	> 1000
	Medium	600 – 1000
	Low	< 600
Stone fruit	High	> 400
	Medium	250 – 400
	Low	< 250
Apples		
- Royal Gala	High	800 – 1000+
- Golden Delicious	High	800 – 1000+
- Granny Smith	Medium	600
- Braeburn	Medium	800
- Fuji	Medium – high	800 – 1000
- Pink Lady	Medium – low	450 – 800
- Star king	High	800 – 1000+
Pears		
- Packham’s Triumph	Medium – low	450 – 800
- Bon Chretien	High	800 – 1000+
- Forelle	Low	450 – 600
- Rosemarie	Medium – low	< 800
- Ceres	Medium	450 – 800
Peaches		
- Transvalia	Low	450 – 600
- San Pedro	Low	450 – 600
- Bonnigold	Low	450 – 600
- Talana	Medium	450 – 800
- Bokkeveld	Low	450 – 600
Plums		
- European	High	1000 – 1200
- Japanese	High	700 - 1000
Table grapes	Low	200 – 400

2.2. Climate change scenarios and projections

Future emissions of greenhouse gases are determined by complex driving forces such as socio-economic development and technological changes, which have highly uncertain evolutionary futures. Climate change projections are mostly given as a range of plausible scenarios that capture the nexus between human actions, emissions, atmospheric gas concentrations and changes in global temperature. The International Panel on Climate Change (IPCC) develops standard sets of scenarios as inputs for model simulations of climate change projections used by the modelling community. These scenarios provide the basis for projections presented in the IPCC assessment reports. The IPCC's long-term emission scenarios have been widely used since 1990 in the analysis of potential climate change, and the assessment of its impacts, adaptation and mitigation, and associated uncertainties.

Some scenarios describe futures in which humans continue to rely on fossil fuels, while others can only be achieved by deliberate actions to reduce emissions. The range of scenarios that results reveals the characteristic uncertainty in quantifying human activities and their impact on climate.

The integration and comprehensiveness of climate change scenarios have improved with each IPCC Assessment Report. New scenarios need to be developed regularly to provide coherent, internally consistent time-paths for climate modelers for model development; impact, adaptation and vulnerability modelers to assess consequences of climate change and contextualize adaptive strategies; and for the integrated assessment community to assess the cost of emissions mitigation.

A brief history of the IPCC's emission scenarios

In the IPCC's first Assessment Report (FAR) of 1990, three different types of scenarios were deliberated. Firstly, scenarios in which carbon dioxide concentration was fixed (equilibrium scenarios). Secondly, those in which carbon dioxide concentrations increased by a fixed percentage each year (transient scenarios). Thirdly, four scenarios based on projections of population growth by the World Bank (Scientific Assessment scenarios, or SA90). This original portfolio of scenarios has developed and expanded over the years to include a collection of time-dependent scenarios that project population changes, technology advancements, emissions, changes in energy sources, atmospheric concentrations, radiative forcing, and global temperature over time (Hayhoe, et al., 2017).

Six scenarios (IS92 a-f) were published by the IPCC in 1992, and were used in the Second and Third Assessment Reports (SAR and TAR). IS92 emission scenarios project anthropogenic emissions of greenhouse gases based on assumptions about future trends of population, economic growth, technological change, land use and emission control policies (IPCC, 1994). The six scenarios provided estimates for the full suite of both direct and indirect greenhouse gases by source for four regions over the period 1990-2100 (IPCC, 1994). These IS92 scenarios do not assume any climate policies to reduce greenhouse gas emissions and are mostly non-mitigation scenarios. Evaluation of these scenarios recommended that more detailed work needed to be done to compare the driving forces, particularly economic assumptions, behind the IS92 scenarios. This evaluation led to the development of a new set of scenarios to be used in the Fourth Assessment Report (AR4) in 2000.

In AR4, projections were based on Special Report on Emissions Scenarios (SRES). SRES, like SA90 and IS92, are emission-based scenarios, but are more complex. The scenarios are based on extensive literature about driving forces of future emissions, and were developed using six alternative modelling approaches and an 'open process' which implored participation and feedback from a wide community and made results widely available (IPCC, 2000). SRES are built upon four narrative storylines of projections of population growth and lays out the future's demographic, social, economic, technological and environmental developments (IPCC, 2000). For each storyline, several scenarios were developed using various Integrated Assessment Models (IAMs) which output multiple emission scenarios for each storyline. Each storyline assumes a distinctly different direction for future developments. The multi-model approach resulted in 40 scenarios which describe the divergent futures encompassing the range of uncertainties of future greenhouse gas emissions that arise from the differences between the models, and the driving forces for each storyline (IPCC, 2000). One scenario for each storyline was chosen as the representative scenario which would be used in GCMs to calculate atmospheric concentrations, radiative forcing and climate change for each scenario. Marker scenarios were A1 (fossil-intensive), A2 (mid-high), B1 (mid-low) and B2 (low emission). The SRES scenarios include emission ranges of all relevant greenhouse gases and sulphur, as well as their driving forces**.** The carbon dioxide emissions of the marker scenarios are illustrated in Figure 4.

Although SRES scenarios are more comprehensive than their predecessors, they do not include scenarios which implement climate policy such as the UNFCCC and the Kyoto Protocol, and are therefore not fully representative of the range of possible emission developments (IPCC, 2000; van Vuuren, et al., 2011).

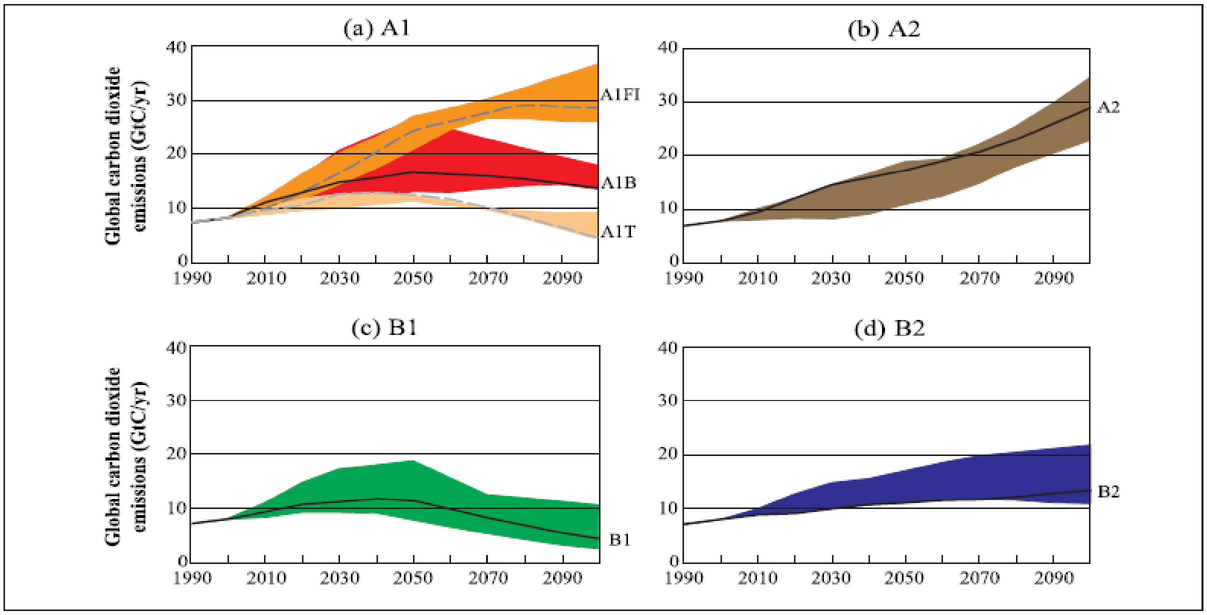


Figure 4: Global CO_2 emissions for SRES scenario groups (IPCC, 2000)

Representative Concentration Pathways

IPCC Assessment Report 5 (AR5) involved the development of Representative Concentration Pathways (RCPs) in 2010. The IPCC requested that RCPs include information on factors beyond greenhouse gas emissions and concentrations, such as emissions of other radiatively active gases and aerosols, their precursors, land use, and socio-economic conditions (IPCC, 2007). Following this, RCPs, unlike SRES, are not emission-based scenarios, but rather radiative forcing scenarios. There are four RCPs which are numbered conferring to the change in radiative forcing at the tropopause by 2100 relative to pre-industrial levels. They are +2.6, +4.5, +6.0 and +8.5 watts per meter squared (W/m^2). Integrated assessment models (IAMs) work backward to derive a range of emission paths and corresponding policies and strategies from each radiative forcing value which will result in the same impact on radiative forcing. The multiple emission pathways are used to derive associated anthropogenic greenhouse gas emissions, aerosols, air pollutants and other species, as well as gridded trajectories of land use and land cover, for each RCP to be used in future climate model simulations. The annual anthropogenic CO_2 emissions and associated warming is summarized in Figure 5.

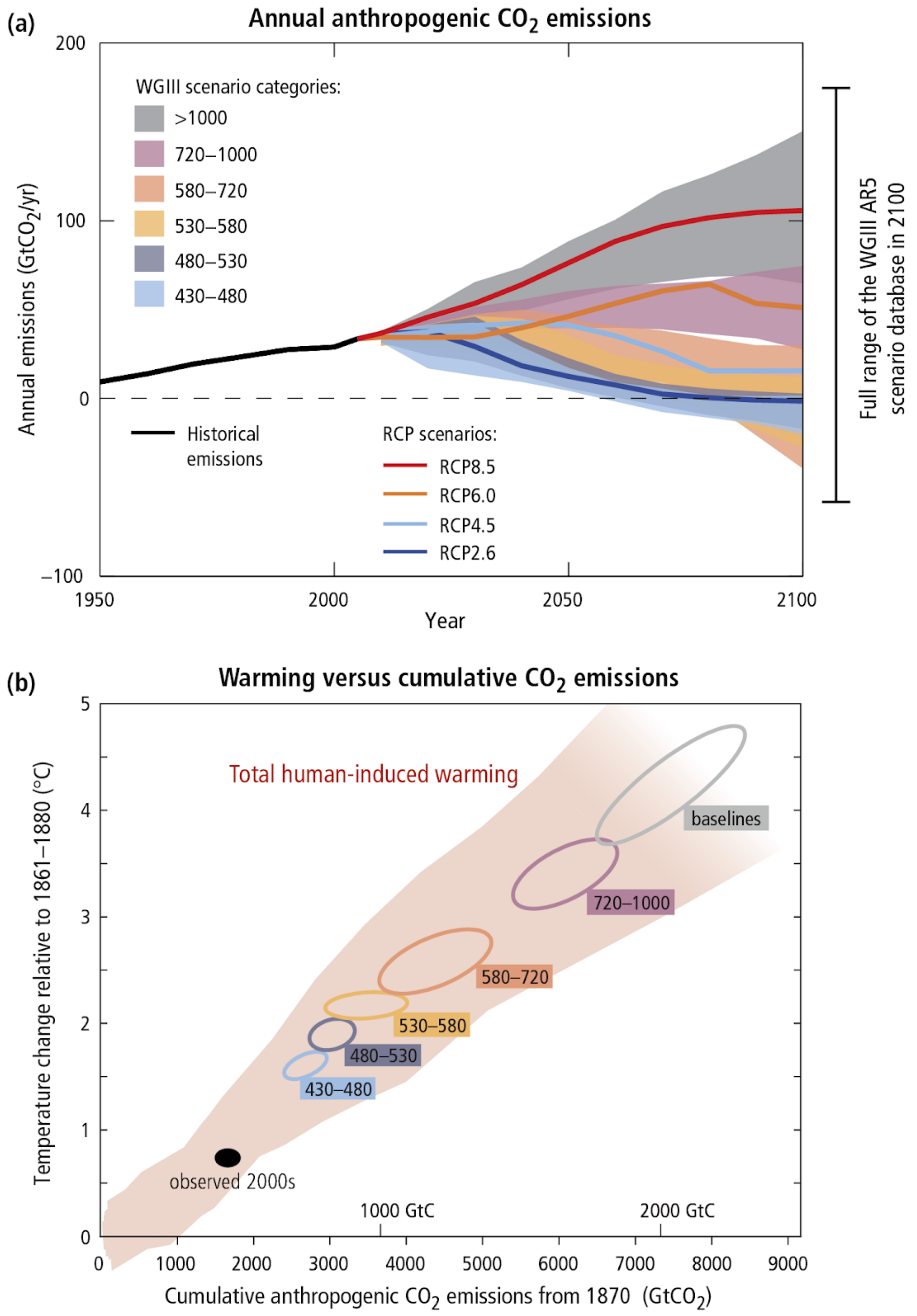


Figure 5: (a) Annual anthropogenic CO$_2$ emissions and (b) warming versus cumulative CO$_2$ emissions (IPCC, 2014)

RCPs are more comprehensive than the emission-based scenarios in that the three lower RCP scenarios (+2.6, +4.5 and +6.0) take into account climate policies and measures that limit radiative forcing. RCP8.5, the highest radiative forcing scenario, represents a future where emissions of greenhouse gases like CO_2 and methane continue to increase by burning fossil fuels, although it does consider a decrease in the growth rate of fossil fuel use in the latter half of the century, substantial reductions in atmospheric aerosols, and more energy-efficient technology.

RCP2.6 was developed by the IMAGE 2.4 modelling framework by the modelling team of the PBL Netherlands Environmental Assessment Agency. IMAGE 2.4 is an integrated assessment model which describes important elements in the long-term dynamics of global environmental change, including climate change, air pollution and land-use change (van Vuuren, et al., 2011). The emission pathway of RCP2.6 is representative of scenarios in the literature that lead to very low greenhouse gas concentration levels, and aims to limit global temperature increase to 2°C. It is a “peak-and-decline” scenario; the radiative forcing level peaks at around 3.1 W/m^2 in the mid-century and decreases to 2.6 W/m^2 by 2100. Atmospheric carbon dioxide levels stay below 450 ppm, and other anthropogenic emissions reach 425 ppm by 2100. This scenario is substantially lower than any SRES scenario because it achieves net negative CO_2 emissions before the end of the century through incorporating the use of policies, whereas SRES scenarios do not (Hayhoe et al., 2017). Towards attaining such radiative forcing levels, greenhouse gas emissions need to be reduced by 70 percent from the baseline scenario, which will entail substantial changes in energy use and emissions of non-CO_2 gases (van Vuuren et al., 2007a; van Vuuren et al., 2011).

RCP4.5 is a scenario that stabilizes radiative forcing at 4.5 W/m^2 by 2100, without ever overshooting that target (Thomson et al., 2011). It was developed by the GCAM modelling team at the Pacific Northwest National Laboratory’s Joint Global Change Research Institute (JGCRI) in the United States. GCAM is a global IAM that tracks long-term global emissions and concentrations of greenhouse gases and short-lived species, as well as land-use-land-cover (Thomson et al., 2011). Under RCP4.5, CO_2 concentrations remain below 550 ppm and other anthropogenic emissions reach 425 ppm by the end of the century (Hayhoe et al., 2017). Reaching this target requires the implementation of climate policies, such as introducing greenhouse gas emission prices, to ensure that emissions and radiative forcing is limited (Thomson et al., 2011).

RCP6.0 is another climate policy intervention scenario, developed by the Asia-Pacific Integrated Model (AIM) modelling team at the National Institute for Environmental Studies (NIES) in Japan. It is a stabilization scenario in which radiative forcing peaks at 6.0 W/m^2 around 2060, and then declines throughout the rest of the century, stabilizing shortly after 2100. Emissions are limited by applying a range of technologies and strategies, including a global market for emissions permits (Masui et al., 2011). The scenario's global mean equilibrium temperature is expected to rise by 3.0°C, and its CO_2 equivalent concentration is 850 ppm in 2100, similar to SRES B2 (Masui et al., 2011; Rogelj et al., 2012).

RCP8.5, developed using the MESSAGE model and the IIASA Integrated Assessment Framework by the International Institute for Applied Systems Analysis, does not include any climate mitigation strategies. Global greenhouse gas emissions and concentrations in this scenario increase substantially over time, resulting in a radiative forcing of 8.5 W/m^2 by 2100. It assumes a future of high population growth and relatively slow income growth, with modest improvements in technology and energy efficiency, leading to high energy demand met by high fossil-intensity and greenhouse gas emissions in the absence of climate change policies (Riahi et al., 2011; Hayhoe et al., 2017). RCP8.5 atmospheric carbon dioxide levels increase from 400 ppm to 936 ppm at the end of the century, and other greenhouse gases and aerosols exceed 1200 ppm by 2100 (IPCC, 2013a; Hayhoe et al., 2017). Under this scenario, global temperature is expected to increase by 4.9°C from the 1986-2005 average by 2100 (Rogelj et al., 2012). Although the emission profile of RCP8.5 reflects the high greenhouse gas emissions scenarios in the scientific literature, it is not intended to describe an upper limit on possible emissions nor as a business-as-usual scenario (Hayhoe et al., 2017).

There is no likelihood assigned to each RCP – higher numbered scenarios correspond to higher emissions and faster global temperature change. Table 5 summarizes the RCPs' radiative forcing level, atmospheric concentrations, and associated temperature increases. Model outputs using scenarios vary considerably from actual outcomes, and confidence in these results decreases as the time horizon increases due to uncertainties surrounding the evolution of human activities, technological advancements, and human responses to potential environmental, economic and institutional constraints. Because each scenario constrains the magnitude of future changes, it is essential for climate impact studies to assess future changes under a range of scenarios in order to consider the uncertainty of anthropogenic forcing in the twenty-first century.

Table 5: RCP overview (Adapted from Moss et al., 2010 and Rogelj et al., 2012)

	Radiative forcing	**Atmospheric concentration**	**Temperature increase**	**Trajectory**	**IAM**
RCP8.5	8.5 W/m^2 by 2100	1370 ppm CO_2 equivalent in 2100	4.9°C	Rising	MESSAGE
RCP6.0	6.0 W/m^2 at stabilization after 2100	850 ppm CO_2 equivalent at stabilization after 2100	3.0°C	Stabilization without overshoot	AIM
RCP4.5	4.5 W/m^2 at stabilization after 2100	650 ppm CO_2 equivalent at stabilization after 2100	2.4°C	Stabilization without overshoot	GCAM
RCP2.6	Peak in RF at 3.1 W/m^2 around 2050, followed by decline to 2.6 W/m^2 by 2100	490 ppm CO_2 equivalent peak around 2050, followed by a decline to ~400 ppm in 2100	1.5°C	Peak and decline	IMAGE

2.3. Changes in Global and South African Climate

Temperature change

Observed changes in temperature

According to the IPCC AR5, mean annual temperatures have increased over the past century over most parts of the African continent, including South Africa. There is strong evidence that anthropogenic forcing contributed to this 20th century continent-wide warming (Niang et al., 2014). South Africa's average yearly temperatures have increased by 0.13°C per decade between 1960 and 2003 (Kruger and Shongwe, 2004). Multiple studies have found that near-surface temperatures have increased by 0.5°C or more over most of the continent in the last 50 – 100 years. Most of southern Africa has undergone increases in annual mean, maximum and minimum temperatures in recent decades, most significantly during the last two decades. The South African Department of Environmental Affairs' Long Term Adaptation Scenarios states that mean annual temperatures in South Africa have increased by at least 1.5 times the observed global average for the past five decades, and maximum and minimum temperatures have shown significant increases annually, in almost all seasons (Department of Environmental Affairs, 2013). A study by New et al. (2006) affirms that minimum temperatures have increased faster than maximum temperatures over southern Africa's interior. The frequencies of occurrences of high temperature extremes have significantly increased, while occurrences of low temperatures have significantly decreased across South Africa, especially in the western and northern interior of the country (Kruger and Shongwe, 2004; Department of Environmental Affairs, 2013).

Future projections of temperature change

A study by Mora et al. (2013) projected the global mean near-surface temperature to exceed 20th century (1860-2005) simulated variability by 2047 (±14 years s.d.) under the highest Representative Concentration Pathway (RCP8.5) and by 2069 (±18 years s.d.) under RCP4.5, an emissions stabilization scenario. They found that unprecedented climates will occur first in tropical regions and low-income countries, stressing the vulnerability of African countries to climate change and the limited capacity to respond to potential impacts.

The IPCC 2013 Summary for Policymakers states that global surface temperature change is likely to exceed 1.5°C by the end of the century for all RCP scenarios except 2.6, relative to pre-industrial times. An excess of 2°C of warming is likely under RCP6.0 and RCP8.5, and probable for RCP4.5. Furthermore, global temperatures will continue to rise beyond 2100 for all pathways except RCP2.6, and warming will not be consistent across the region and will continue to show interannual or interdecadal variability (IPCC, 2013a).

The Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble projected that annual mean temperature increases over all land regions in Africa are very likely in the mid- and end-century periods under both RCP2.6 and RCP8.5 (the lowest and highest RCPs) (Niang et al., 2014). The changes in mean annual temperature projected by the CMIP5 ensemble are greater than 2°C and 4°C above the 20th century baseline in the mid-21st century and end-of-century, respectively, under RCP8.5.

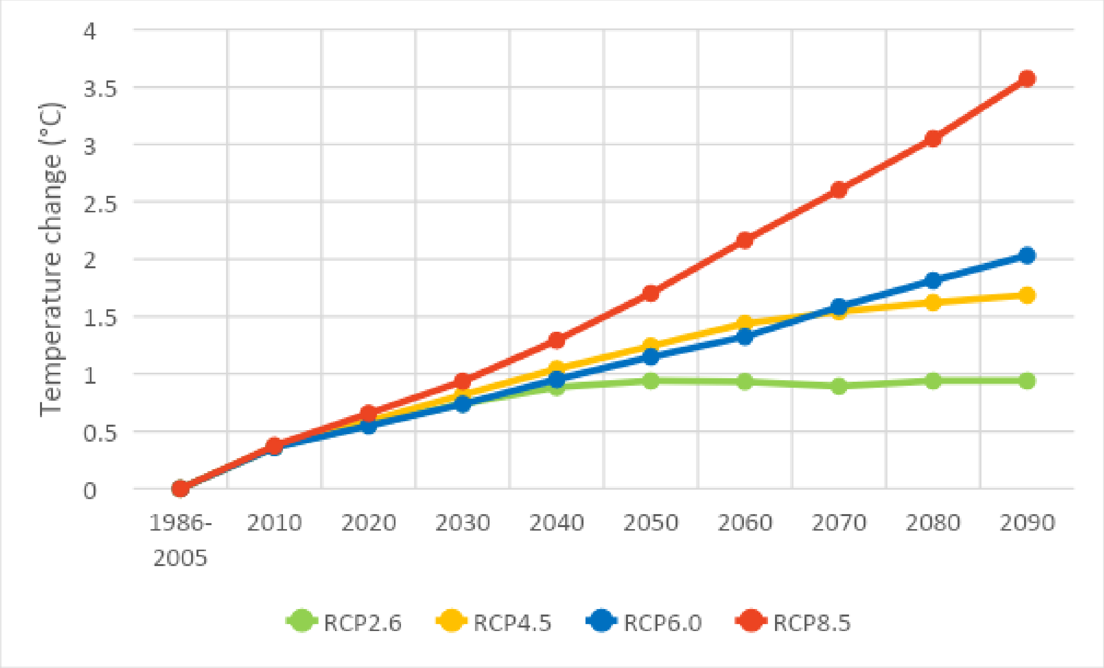


Figure 6: CMIP5 projected global mean temperature change relative to 1986-2005 reference period under Representative Concentration Pathways (RCPs). Data obtained from IPCC, 2013b Table AII.7.5

Climate model projections indicate that temperatures in Africa will rise faster than the global average during the 21st century (Christensen et al., 2007; Sanderson et al., 2011; James and Washington, 2013). Temperature changes are expected to be larger in southern and northern Africa, with less extreme changes expected in central Africa (IPCC, 2014). Southern Africa is particularly sensitive to temperature change, as it will likely experience enhanced warming and the largest temperature increases, as well as relatively faster regional warming in the 21st century (Sillmann and Roeckner, 2008; Sanderson et al., 2011; Orlowsky and Seneviratne, 2012; James and Washington, 2013). Figure 7 illustrates the projected temperature and precipitation for the SADC until 2100.

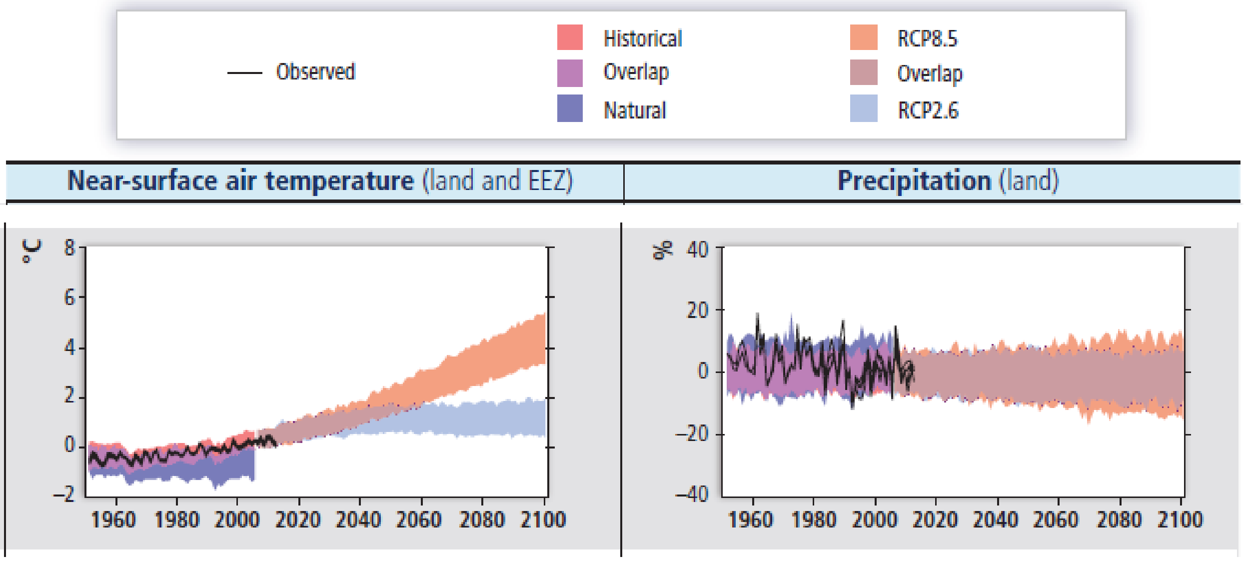


Figure 7: Projected near-surface air temperature and precipitation over the Southern African Development Community (SADC) in the 21st century (Source: Niang et al., 2014)

CMIP5 GCM ensemble projections, CSAG statistical downscalings and CSIR dynamical downscalings described in The South African Third National Communication under the UNFCCC (2018), show patterns of warming (mean, minimum and maximum temperature increases) across southern Africa, with the highest warming anticipated for the western and central interior, while the coast shows weaker warming. Warming in the near-future (2015–2035) under RCP4.5 is projected to be 0.5-1.0°C over most locations and up to 2.0°C over the western and central interior (relative to the baseline period of 1971-2000). In the mid-future (2040-2060) under RCP4.5, warming is highest over the western interior, with temperature increases ranging from 2.0-3.0°C in most projections. Temperatures are expected to continue to rise throughout the 21st century, with increases of 3.0-4.0°C projected for 2080-2099. Projections under the low-mitigation scenario RCP8.5 correspond with those of RCP4.5 for the near-future period, but much stronger warming is projected for the mid-future period, ranging from 3.0-4.0 °C over the interior, and even hotter over some of the western parts. Temperature increases greater than 4°C are likely over the entire South African interior for the far-future period under RCP8.5, while parts of the western, central and northern interior may increase by more than 6°C (Department of Environmental Affairs, 2018).

Increasing mean temperatures are associated with consequences such as a higher occurrence of very hot days (days where the maximum temperature is above 35°C). Orlowsky and Seneviratne (2012) suggest that southern Africa is a hot spot for increasing temperature extremes. The region is anticipated to experience an increase in the number of hot days and very hot days under both high- and low-mitigation scenarios RCP4.5 and RCP8.5 (Orlowsky and Seneviratne, 2012; Department of Environmental Affairs, 2018; Kruger, 2019). Under both RCP 4.5 and 8.5, near-future projections of very hot days are mostly insignificant for the coastal areas and eastern interior, compared to the baseline period of 1971-2000. However, projections indicate that the Northern Cape, North West and Limpopo will see an increase of 20-40 very hot days per year. The western interior is expected to experience an increase of 40-80 very hot days by the mid-future. Far-future projections under RCP8.5 suggest increases of 80 very hot days over most of the southern African interior, and potentially 120 days over the western interior (Department of Environmental Affairs, 2018). These increases in temperature extremes will have devastating effects on agriculture, water security, biodiversity, and human health (Department of Environmental Affairs, 2018).

Rainfall change

Average rainfall in South Africa is very low – around 450mm per year, substantially lower than the global average of 860 mm – and evaporation rates are relatively high (DWAF, 2004; Benhin, 2006). Additionally, surface and groundwater resources are very limited.

Observed changes in precipitation

Modest downward trends in precipitation have been observed over South Africa in the 21st century (Niang et al., 2014). Other observations in Southern Africa include changes in the onset and duration of seasonal rainfall, dry spell frequencies and rainfall intensity (Usman and Reason, 2004; Tadross et al., 2005; Kniveton et al., 2009).

Future projections of precipitation change

A study by Dosio et al., 2019 employed a large ensemble of Regional Climate Models (RCMs) to explore future rainfall characteristics over Africa. They found that southern African region shows the most widespread and consistent trend toward a drier future, with about 40 percent of land area expected to experience a robust reduction in mean precipitation in winter and spring, and nearly 80 percent projected to have a lower frequency of rain (up to 5 days per season in summer and spring) and longer dry spells in winter and spring. The region is also projected to face shorter wet spells. However, some areas (about 12 percent of land area) are projected to experience an increase in precipitation intensity of about 1mm per day.

Orlowsky and Seneviratne (2012) also project precipitation decreases for the region and suggest that southern Africa is one of the main regions where atmospheric water input (precipitation minus evapotranspiration) decreases throughout the year, correspondingly displaying consistent soil moisture depletion in all seasons. Mariotti et al. (2011) and Sanderson et al. (2011) suggest that the areas of maximum drying align with the areas of maximum warming, likely because of a soil moisture-precipitation feedback.

CGCMs of CMIP5, Climate System Analysis Group (CSAG) statistically downscaled projections, and CSIR dynamically downscaled projections of seasonal rainfall change in South Africa under RCP4.5 and 8.5 for the near future (2016–2035), mid-future (2040–2060), and far-future (2080–2099) periods, relative to 1971–2005, are discussed in The South African Third National Communication under the UNFCCC (2018). Near-future projections indicate largely mixed and statistically insignificant signals of wetter and drier conditions for summer and autumn over the summer rainfall regions, with decreases of 20 mm per month projected for these regions by some GCM downscaled projections and increases of the same magnitude projected by others. For the mid-future period, most GCM projections and dynamically downscaled projections are indicative of a significant decrease in rainfall, under both RCPs but particularly under RCP8.5, whereas statistical downscalings continue to show a mixed signal. Rainfall projections become better established for the far-future, with most of the ensemble indicating increased rainfall in summer and decreased rainfall in autumn over the summer rainfall region. Most ensemble members indicate slight to significant increases in winter rainfall over the south-western Cape, although drying is also plausible. Far-future increases in winter rainfall are also projected by most ensemble members over the east coast and the eastern escarpment. Spring rainfall projections are largely mixed, ranging from significant increases to significant decreases. Autumn projections mostly indicate drying in the far-future. The projections largely indicate that southern Africa will not only be drastically warmer, but also generally drier, under low mitigation in the far-future period (Department of Environmental Affairs, 2018).

Future changes in atmospheric CO_2

Carbon dioxide (CO_2) represents between 80 and 90 percent of the total anthropogenic forcing in all RCP scenarios through the 21st century (IPCC, 2014). Atmospheric carbon dioxide concentration is very likely to rise in the 21st century due to anthropogenic CO_2 emissions persisting, even if the emission rate stabilizes or decreases (Collins et al., 2013). The radiative forcing response to greenhouse gas emissions would only decrease long after the cessation of emissions at a rate determined by the lifetime of the gas. It is difficult to determine the lifetime of atmospheric CO_2 as it is sequestered through various physical and biogeochemical processes which operate at timescales ranging from days to thousands of years, in the ocean and on land. The long lifetimes of greenhouse gases such as CO_2cause persistent increasing concentrations long after emissions have ceased (Matthews and Caldeira, 2008; Solomon et al., 2009).

Projected CO_2 concentrations differ under each RCP scenario, as depicted in Figure 8. Under RCP2.6, CO_2 concentration peaks around 2050 at 442.7 ppm, thereafter, slowly decreasing and reaching 420.9 ppm at the end of the century. Under the RCP4.5 scenario, CO_2 concentration rises to 486.5 ppm in 2050 and begins to stabilize thereafter, reaching 538.4 ppm in 2100. RCP6.0 sees the concentration rise steadily throughout the century with concentrations of 477.7 ppm in 2050 and 669.7 in 2100. Under RCP8.5, the highest-emission scenario, CO_2 concentration reaches 540.5 ppm in 2050 and increases more rapidly thereafter, reaching 935.9 ppm in 2100.

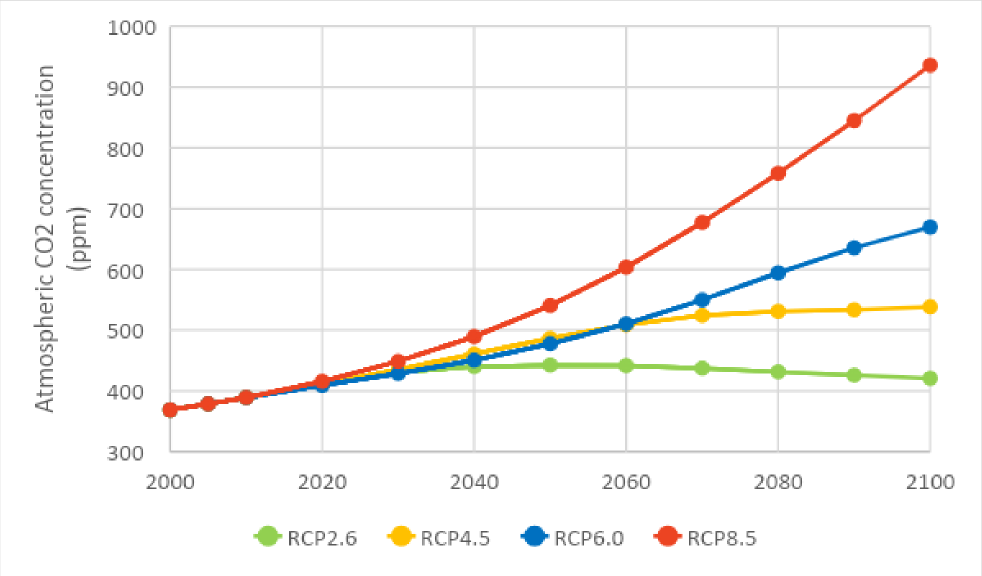


Figure 8: Projected global atmospheric carbon dioxide (CO_2) concentrations under Representative Concentration Pathways (RCPs). Data obtained from IPCC, 2013b Table AII-4-1

Extreme events

Climate change is associated with increased climate variability and climate extremes. In South Africa, more frequent and severe extreme precipitation events are expected (Christenson et al., 2007), giving rise to an increased likelihood of flooding. Drought-prone areas are projected to expand, and droughts are expected to increase in severity and length (Gizaw and Gan, 2016). Shongwe et al. (2009) found that in summer months, the southwestern parts of southern Africa are at high risk of severe dry spells and droughts, as well as a significant decrease in mean precipitation. Christensen et al. (2007) and Hewitson and Crane (2006) projected a drying signal in the southwest, especially in winter. Conversely, the south-eastern region is expected to experience wetter conditions (Hewitson and Crane, 2006; Engelbrecht et al., 2009; Shongwe et al., 2009). Most of the region is also expected to experience an appreciable delay in the onset of the rainy season and early cessation of rains, inferring a significantly shortened rainy season (Shongwe et al., 2009).

Climate change scenarios for South Africa

South Africa's Third National Communication to the UNFCCC describes projected climate change scenarios and their implications for the country's six climatic zones (Department of Environmental Affairs, 2018). A map of the climate zones is shown in figure 9 and the principal climate change impacts are summarized in table 5.

Figure 9 : Map of the six hydrological zones described by LTAS (Department of Environmental Affairs, 2018)

Table 6: Likely climate change impacts for each of the hydrological zones (extracted from Department of Environmental Affairs, 2018)

Zone	Impact
Zone 1 - Northern Interior Irrigated agriculture, power and mining, urban and forestry, with dryland on the Highveld	● Rainfall decreases, particularly in summer ● Significant temperature increases and consequently evaporation ● Agricultural water demand increase ● Increased demand for power generation
Zone 2 – East Coast Rain-fed agriculture and subsistence farming	● Summer rainfall increase and increased storms ● Moderate temperature increases due to proximity to ocean
Zone 3 – Central Interior Mining, industrial, and domestic demand	● Highly uncertain future rainfall, with possible wetting or drying during the summer months ● Increase in storms ● Significant increase in temperatures ● Agricultural water demand increase ● Increased demand for power generation

Zone 4 – West Coast and North-western Interior Intensive irrigation and groundwater use	● Uncertainty of rainfall patterns in the eastern parts, but with likely increased storm activity ● Likely drying in the arid western and coastal areas ● Significant increase in temperature ● Agricultural water demand increase ● Existing water scarce zone in the west is projected to become drier.
Zone 5 – Southern Cape Large rural population with a high level of subsistence farming.	● Uncertain rainfall impacts in year-round rainfall zone, although likely drying in the west ● Likely increases in summer rainfall in the west ● Moderate temperature increases ● Extreme events such as flooding might have an impact on the large rural population.
Zone 6 – South Western Cape Large urban population and strong commercial agriculture	● Uncertain climate impacts on winter rainfall, but likely increase in orographic activity ● Possible spread of rainfall beyond the historical winter rainfall period ● Moderate temperature increases ● Increase in extreme events will affect vulnerable communities ● Agricultural and domestic water demand increases

2.4. Climate change impacts on crop production/suitability in South Africa

South Africa’s agricultural sector is one of the most vulnerable economic sectors to potential climate change impacts. Projected changes in climate in South Africa, such as those discussed in Changes in Global and South African Climate (section 2.3) are expected to affect crop productivity and suitability because crops are strongly dependent on variables such as temperature and precipitation. Agriculture is directly impacted by precipitation, temperature, and evaporation changes and secondarily through disaster risk and health impacts. The extent of these effects depends on the crops’ sensitivities to environmental conditions.

Dry conditions

Water availability is the most yield-limiting factor for South Africa's agriculture (Johnston, et al., 2016). South Africa experiences a high frequency of droughts, which are expected to increase in the 21st century. The nation will be subjected to increased water scarcity which will be worsened by high spatial variability of rainfall (Benhin, 2006). Only 10 percent of the country receives in excess of 750mm annually and an excess of 60 percent of surface water resources and a significant fraction of groundwater are used for agricultural purposes (Department of Environmental Affairs, 2018), although most of the crop farming in South Africa is rain-fed field crops such as maize, wheat and sugarcane. The extensive nature of farming these crops means that they are particularly sensitive to climate change due to the country's aridity. Marginal lands are increasingly being used for farming. Rain-fed crop yields are likely to be most harshly affected by precipitation decreases, however, irrigation demands for horticulture are also projected to increase due to warming (UNFCCC, 2017; Department of Environmental Affairs, 2018), putting more pressure on the threatened water resources.

Variable water availability is expected across the different climatic zones and agricultural systems in South Africa (Benhin, 2006). Although there is lower confidence in rainfall projections than temperature projections, the projections of rainfall decreases over the winter rainfall region of the southwestern Cape, a major fruit-growing region in South Africa, are particularly robust (Department of Environmental Affairs, 2018).

Warming will also result in increased evapotranspiration, but the mixed signals of projected precipitation, with some regions anticipating increased rainfall and others drought, make it difficult to predict how this will impact the water table. Despite these uncertainties, water deficits are expected in the major fruit-growing regions, which will limit the crops' vegetative and reproductive development. Water stress may result in a reduced yield due to decreased fruit size and bud fertility, and a decline in fruit quality due to modified fruit composition (Ripoll et al., 2014).

Heat stress

Hot temperatures put significant heat stress on crops as well as farm labourers. Heat stress is considered to be amongst the most threatening abiotic factors that limits fruit quality and production, and results in huge economic losses (Sharma and Manjeet, 2020). A review by Sharma and Majeet (2020) found that many fruit crops experience negative impacts due to high temperatures. Including changes in their morphology, anatomy and physiology. Apples experience a negative chilling effect, and have been found to change in taste and texture over the past few decades in response to climate change, such as decreased acidity and firmness which result from earlier blooming and high temperatures during the maturation phase. High temperatures affect table grapes by delaying bud sprouting and hindering fruit set. High temperatures also advance harvest time of grapes and change the fruit quality in terms of sugar and acidity levels and alterations in aroma compounds. Peaches experience shortening of early developmental phases which can result in decreased fruit size and yield (Sharma and Majeet, 2020).

Increasing temperatures due to climate change are expected to lead to an increase in work-related heat stress, especially in the agricultural sector, which impairs productivity and will result in job and economic losses. A 2019 report entitled “Working On A Warmer Planet: The Impact Of Heat Stress On Labour Productivity And Decent Work” by the International Labour Organization warns that heat stress, which usually occurs at temperatures exceeding 35°C and high humidity, is an occupational health risk which affects productivity and may result in heat stroke and death in extreme cases. South Africa is projected to experience an increase in the number of hot days and very hot days under high- and low- mitigation scenarios (Orlowsky and Seneviratne, 2012; Department of Environmental Affairs, 2018; Kruger, 2019) putting workers under heat stress. Heat stress is more prevalent in countries with fewer resources to adapt to extreme heat, exacerbating economic disadvantages in these countries which face high rates of poverty, unemployment, and informal employment, and lack effective social protection (International Labour Organization, 2019). The physical nature of agricultural labour and the fact that it takes place outdoors in direct heat, coupled with the informal structure of the sector with labourers less likely to have access to social protection makes heat stress a concern in a warming South Africa. The horticultural industry may face significant job losses as working hours may be reduced due to heat stress. High temperatures may also render some farming regions unproductive and cause many farm workers to be displaced to cities or other countries in search of employment. Exposure to extreme heat will pose a serious risk in the future, impacting food production and resulting in greater poverty and food insecurity, even under modest-high mitigation.

Phenology

Phenology (the date at which bud break, flowering, and the onset of ripening occur) is driven by temperature. Higher temperatures trigger advanced phenology, meaning that flowering and, thereafter, ripening will be earlier. For grapes, this shifts the ripening phase to warmer periods in the summer, which will affect grape composition, particularly with respect to aroma compounds. Higher temperatures will result in increased sugar levels in grapes. This is because increased temperatures and their indirect effect of earlier ripening times mean that the grapes will ripen in warmer conditions (van Leeuwen and Darriet, 2016).

Climate change can also influence the timing of winter dormancy release in deciduous fruit trees. Rising temperature in autumn through spring can result in a later fulfilment of chilling requirement, resulting in shifts in timing of bud burst, leaf unfolding and blossom (Chmielewski, Blümel and Pálešová, 2012). Furthermore, inadequate winter chill accumulation may result in delayed foliation, flower bud abscission, poor fruit set, reduced fruit quality with respect to size and shape, and uneven ripening (Schulze and Maharaj, 2007; Atkinson, Brennan and Jones, 2013).

Pests and diseases

Climatic parameters have a great effect on crops' susceptibility to pests and diseases, as well as the longevity of pests. Plant diseases may be fungal (such as apple, pear, citrus, and stone fruit scab, powdery mildew, and downy mildew mostly affecting grapes) or bacterial (such as fire blight infecting pome fruit, and canker on citrus, pome and stone fruit). The disease triangle consists of a pathogen, a host (the plant) and suitable environmental conditions for infection, such as relative humidity, temperature, rainfall, soil moisture, aeration, and sunlight intensity.

Climate change affects environmental conditions and will therefore impact crop disease susceptibility and crop health. Changing climate conditions can affect both the host and the pathogen, for example, certain (usually warmer) temperatures favour pathogen growth, and certain temperatures can make the host more resistant to infection. If temperatures rise above the plant's optimal temperature requirement, an infestation of pathogens might occur. Many bacteria and fungi thrive under warmer, wetter conditions, and higher carbon dioxide concentrations, which are to be expected in the 21st century.

Common pests include weevils, grape berry moths, aphids, mites, and mealybugs. Although different pests respond differently to their environments, climate change impacts on pest populations generally include changes in phenology, geographic and temporal distribution, population size and community composition (Walther, et al., 2002). Increasing temperatures and a longer growing season could allow certain pests to undergo multiple additional life cycles per season which increases the ability of the pests to overcome plant resistance and causes more damage to the crops. Warmer temperatures also reduce stress from cold temperatures and improve winter survival rates of pests. Global warming has resulted in a poleward expansion of pest populations as they become increasingly suited to temperate climates, and less tolerant of the hot tropics (Bebber, Ramotowski and Gurr, 2013). Warming temperatures and increased precipitation generally favour the growth and distribution of many pest species by providing a warm and moist environment to grow in, however, when temperatures get too hot, growth and reproduction rates can slow, and excessive rain can wash away the eggs and larvae of some pests (Skendžić et al., 2021).

Extreme weather events

The frequency of severe storms is expected to increase. These storms will damage fruit crops if they occur during the growing or fruit bearing season as they are often accompanied by strong winds, heavy rain and hail. Hail can damage the leaves, stems, flowers, branches, and fruit, especially those of sensitive stone fruit and grapes. Wounds caused by hail damage are also entry sites for infectious bacteria, such as fire blight in pome fruit and brown rot in stone fruit (Longstroth, 2016). These damages and diseases will reduce fruit quality and yield, which is particularly problematic for high value export fruit as they are expected to be in perfect condition. The prevalence of these extreme weather conditions can also interrupt the supply chain and cause increases in food prices due to low supply due to damages.

Increased risk of flooding may impact fruit crops due to changes in oxygen availability and chemically and physically altered soil occurring after flooding. Flooding negatively affects plant processes such as water and nutrient uptake, decreased carbon dioxide assimilation, reduced root and shoot growth, decreased stomatal conductance, affects flowering, reduces fruit set, yield and quality. Apples, peaches, and citrus are particularly sensitive to flooding and waterlogging. On the other hand, a beneficial attribute of flooding is its ability to control certain soil borne pathogens such as nematodes, parasitic plants, and fungi by means of oxygen deprivation (Schaffer et al., 1992).

2.5. Modelling climate change impacts on crops

Crop models are mathematical algorithms that offer a simplified representation of crop systems in a way that can explain and predict crop behaviour. They can simulate many seasons, locations, treatments, and scenarios in a few minutes. Crop models contribute to agriculture in many ways and have a wide range of applications including exploring the dynamics between a crop's physiology, its surrounding atmosphere, and the soil, assisting in crop agronomy, pest management, breeding, and management of natural resources, and assessing the impact of climate change (Asseng, et al., 2014).

To better understand the potential impacts of climate change on crop behaviour, two main modelling approaches have been studied, namely empirical modelling and process-based modelling. Depending on the purpose of the study and the data available, either approach may be more appropriate for a given study.

Empirical modelling

Empirical or statistical models are mathematically relating output to input, independently of internal processes. For example, weather can be used as a mathematical variable toward resolving a function modelling a crop response (Lobell and Asseng, 2016; Das and Sharma, 2020). The approach involves examining the data, selecting appropriate equation(s), and fitting them to the data. Empirical models give no descriptions of the mechanisms that produce the crop's response (Das and Sharma, 2020) and the models rely only on observed correlative relationships in line with implicit mechanistic understanding. Historical crop production and weather data are used to calibrate the relatively simple regression equations, which are applied to future climate projections to predict the impact on crop variables such as growth and suitability.

Lobell and Burke (2010) describe three main types of empirical approaches. First, time series approaches which are based solely on time series data from a single point. Second, panel approaches which are based on variations in both time and space, and third, cross-sectional approaches which are based solely on variations in space. Time series models have the advantage of capturing the behaviour particular to the given area, while panel and cross-sectional models assume common parameter values for all locations in the study. Cross section methods are particularly prone to errors from omitted variables that are spatially variable, such as soil types or fertilizer application. The strength of cross-sectional and panel modelling approaches is the ability to aggregate data from multiple sites, whereas time series models are often limited by data (Lobell and Burke, 2010).

While empirical models are typically simpler than process-based models, and are thus limited in applications where extensive knowledge is required about how a particular system works, they are ideally suited to analysis at large temporal and spatial scales (multi-seasonal or inter-annual studies at the regional level) (Fischer et al., 2005; Hertel and Rosch, 2010). A critical strength of empirical modelling approaches to climate change impacts are the much lighter data requirements, and the ability to apply the models to national or global spatial resolutions (Hertel and Rosch, 2010)

Another advantage of empirical crop models is their limited use and reliance on field calibrated data, as they can make use of observational data. Observational data can be taken from farmer surveys, official government statistics, or some combination of these and other sources (Lobell and Asseng, 2017). The benefit here is that using observational data takes into consideration a farmer's management practices even when it is not explicitly observed (Roberts et al., 2017). Another key strength of empirical models is their transparent assessment of model uncertainties (Hertel and Rosch, 2010; Lobell and Burke, 2010). For example, if a model does a poor job of representing crop yield responses to climate, this will be reflected in a low coefficient of determination between modelled and observed quantities, as well as a large confidence interval around model coefficients and predictions (Hertel and Rosch, 2010).

A common concern in empirical crop modelling is the co-linearity of predictor variables, relating to the difficulty involved in distinguishing the effects of highly correlated weather variables, such as temperature and rainfall in many locations (Sheehy et al., 2006, Lobell, 2007; Lobell and Burke, 2010). Lobell and Asseng (2017) argue that this criticism can be overcome with the growing amount of data available. Fischer et al. (2005) acknowledge that empirical models may be prone to larger errors and problematic validation, due to lack of both crop and management detail. Another shortfall of empirical modelling is its reliance on past conditions for predicting future responses, rather than cause and effect (White, et al., 2011). Empirical models assume that past correlations will remain stationary in the future despite evolving management practices. Furthermore, empirical models do not consider plant biophysiological processes that highlight the relationship between climate, soil, pests, diseases, and agricultural practices. The presence of noise on yield or weather data can also obscure the relationship between the two (Lobell and Burke, 2010).

Examples of climate change impact studies that use empirical models to assess changes in fruit crop suitability include modelling the suitability of strawberry and apple (Lane and Jarvis, 2007), banana (Van den Bergh, et al., 2010; Ramirez-Villegas and Thornton, 2015), Sago palm (Makinano-Santillan and Santillan, 2015), balanites (Cherif, et al., 2022), and date palm (Shabani, Kumar and Taylor, 2012). Commonly used empirical models for crop suitability include Ecocrop (Lane and Jarvis, 2007; Van den Bergh, et al., 2010; Jarvis et al., 2012; Ramirez-Villegas, et al., 2013; Makinano-Santillan and Santillan, 2015; Ramirez-Villegas and Thornton, 2015; Egbebiyi, et al., 2019; Hunter and Crespo, 2019), MaxEnt (Cherif et al., 2022; Kogo, et al., 2019), and CLIMEX (Shabani, Kumar and Taylor, 2012; Ramirez-Cabral, Kumar, and Shabani, 2017).

Process-based modelling

Contrary to empirical crop models, process-based models explicitly describe a system's behaviour by incorporating system physiological mechanisms in their simulations to dynamically determine crop outcomes using deterministic equations of underlying processes. They enable further understanding of crop growth cycles and the interaction of crops with the soil, climate, and management practices to provide for agronomic adaptation techniques (Fischer et al., 2005). They can be more comprehensive than empirical models and typically operate at shorter time scales of minutes to days (Lobell and Asseng, 2017). The development on this approach to crop modelling began in the 1960s, mostly for applications in field-level crop system decision support. Since then, they have increasingly been used to evaluate climate change impacts in crops (Lobell and Asseng, 2017). As process-based models were not originally intended for this use, key processes related to extreme climate conditions may be missing, which is a cause for concern in using this approach for climate change studies (White, et al, 2011).

Process-based models are designed with high resolution data demands for calibration and validation, and while this makes them very useful for studies at the local to national scale (provided that sufficiently detailed 'representative sites' can be found to cover the study area), and allow for simulation of more realistic field management activities, they are less effective for application at large spatial scales (Fischer et al., 2005; Challinor, et al., 2009; Adams et al., 2013). At larger spatial scales, process-based models do not capture sufficient detail or adequate information on climate impacts. Often, process-based models are validated at experimental sites (point-based), but such generalized validation does not consider the spatial heterogeneity in climate, soil and management practices of a larger region (Challinor, et al., 2009). Additionally, process-based models often have high data input requirements in terms of farm management, meteorological, and crop phenological data. These data are often not available at large scales or are unreliable or incomplete (Adams, et al., 2013; Kephe, 2021). However, there is ongoing effort by model intercomparison projects (such as the Agricultural Model Intercomparison and Improvement Project - AgMIP) to improve process-based crop models' ability to simulate global-scale impacts (Rosenzweig, et al., 2013).

Process-based crop models are also constrained by their structure and the biophysical processes considered for their development, based on the purpose for which they were developed. Many process-based models do not include all parameters for crop development, particularly data-poor parameters such as pest and disease damage and agronomic practices. For example, some process-based crop models have been hydrological models that have been adapted for agricultural water management and lack robust crop growth and fertilizer management (Kephe, 2021). However, the strength of process-based models lies in their usage of daily weather data to simulate growth stages, enabling extreme weather impacts to be assessed, as well as the ability to specify crop varieties and agronomic practices such as fertilizer application and irrigation, which are important for climate adaptation strategy formation (Hertel and Rosch, 2010)

Examples of process-based crop models that have been widely used in South Africa include the Decision Support System for Agro-Technology Transfer (DSSAT) (e.g. Estes et al., 2013; Zinyengere, et al., 2015), Agricultural Production Systems Simulator (APSIM) (e.g. Dimes, et al., 2011), AquaCrop (e.g. Hadebe, et al., 2020), and Environmental Policy Integrated Model (EPIC) (Kephe, et al., 2011).

Our chosen approach

The large spatial and temporal scale of this study, together with the limited availability of data relating to the fruit crop sector, pointed us directly toward using an empirical approach. This decision is further supported by the challenges faced by process-based models in modelling perennial and tree crops where some variables affect the system well beyond the hourly/daily/seasonal dynamic scale of the modelled process. This decision comes at a cost, as it is well known that biophysical accuracy cannot be the focus of this study, and the chosen approach likely will not describe the absolute crop production rates at specific locations or under specific climate conditions. Nevertheless, as we are studying large spatial scales where climate spatial variability becomes and major driver of crop suitability, and doing so over large time scales where climate change becomes a major driver of crop suitability, an empirical approach offers the capacity to satisfactorily observe expected relative changes over space and time, which are meaningful for this study.

3. Data and Methods

3.1. Study site

South Africa is located at latitude 22°–35°S and longitude 16°–33°E, covering an area of 1 219 602 km^2. It is bordered by two oceans: the Atlantic Ocean on the west coast and the Indian Ocean on the east coast, both playing important roles in the country's climate. The coastline extends 2 850 kilometres. There are 9 provinces in South Africa, namely the Western Cape, Eastern Cape, Northern Cape, Gauteng, KwaZulu Natal, Limpopo, Mpumalanga, Free State and North West. The country comprises three major physio geographic regions; a large central plateau (highveld; 1220-1830 meters above sea level), an escarpment on the western, southern, and eastern sides of the plateau (peaks above 3000 m), and low-lying land along the coast. The country experiences highly varied climates, ranging from arid desert in the northwest, to humid subtropical on the east coast. Although South Africa's climate is highly varied, the temperature is moderated by the surrounding ocean to the west, south and east, as well as the altitude of the interior plateau, to which its warm temperate conditions is owed. The four main climatic zones are desert (northwest), arid (interior), subtropical wet (KZN and Eastern Cape coasts), and Mediterranean winter rainfall region (Western Cape coast). Figure 10 illustrates these climatic zones in more detail. These diverse climatic zones allow for a multitude of farming opportunities and provide ideal conditions for a variety of fruit to be grown.

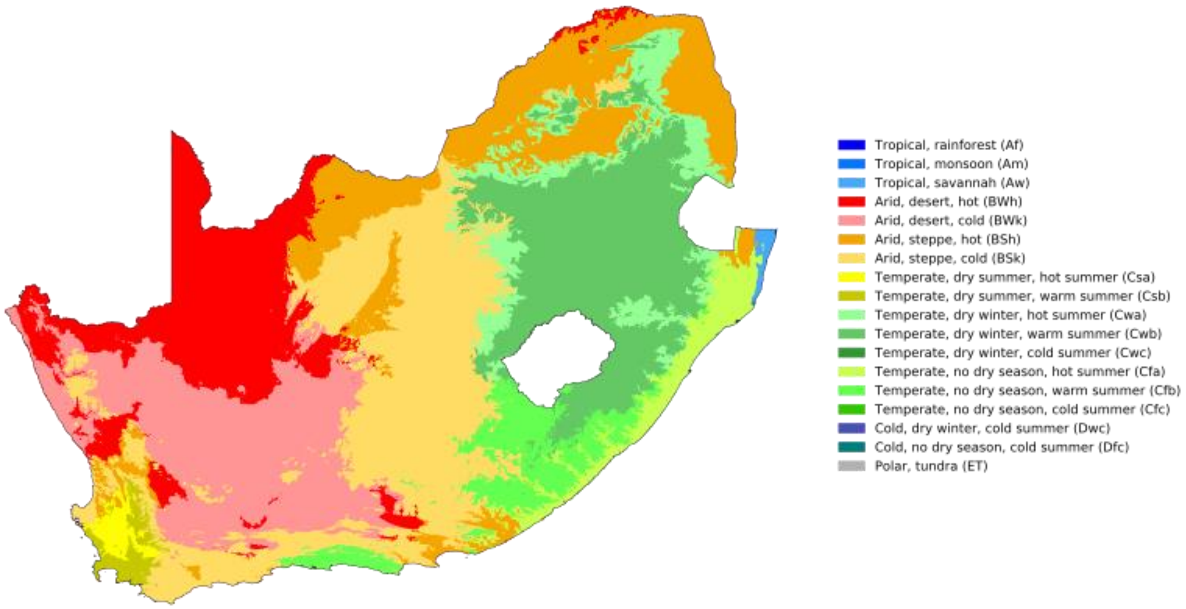


Figure 10: Köppen–Geiger climate classification map for South Africa (Beck et al., 2018)

The topography of South Africa is shown in Figure 11. The high altitude of the plateau makes it cooler than other regions at the same latitude. The altitude in the interior keeps the average summer temperatures below 30°C, however, in winter, temperatures drop below freezing. The low-lying coastal regions are moderated by the surrounding oceans and are therefore relatively warm in winter. South Africa is a relatively dry country, receiving an average annual rainfall of 464 mm. While the Western Cape gets most of its rainfall in winter, the rest of the country generally receives summer rainfall.

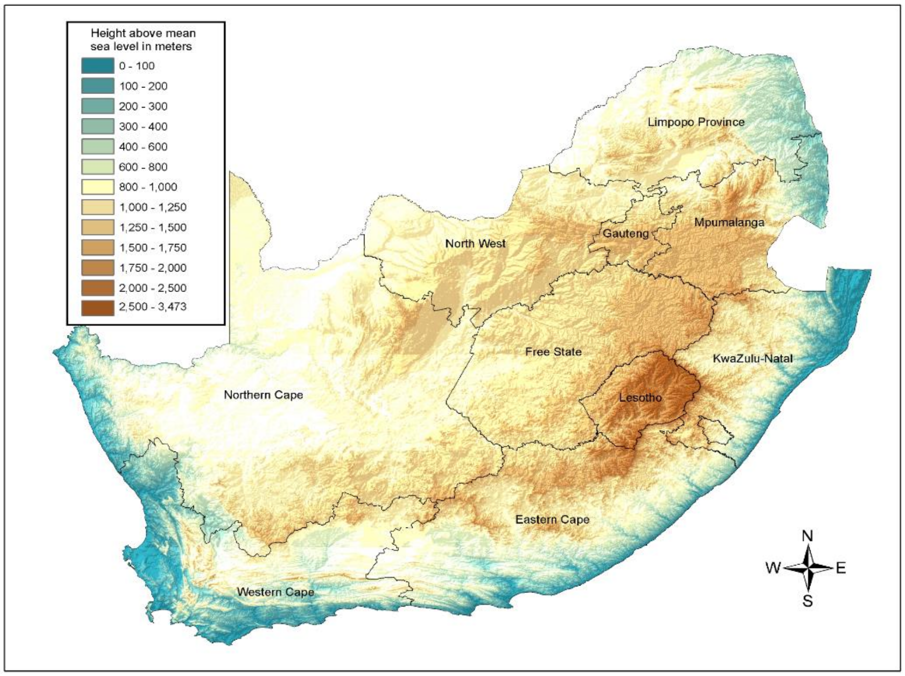


Figure 11: Elevation map of South Africa with provincial borders (Riter, 2021)

3.2. Current crop production areas

To assess the crop suitability model's capacity to represent crop suitability, data on current production areas of the fruit crops must be obtained. The number of trees and area under cultivation per region was obtained from Hortgro, 2019 for apples, pears, peaches, and plums. Citrus production regions were obtained from the Citrus Growers association, 2020. Maps of growing areas for each fruit type were obtained from Post-Harvest Innovation Programme (2022). The historical suitability plots produced by the model for each fruit crop were compared to the known presence locations to validate the model.

3.3. Approach: modelling climate change impacts on crop suitability

Climate data

This study made use of two sources of climate data, namely Climate Research Unit (CRU) and Coordinated Regional Climate Downscaling Experiment (CORDEX).

Climate Research Unit (CRU) observational climate data

The CRU dataset (CRU TS 4.05) is a gridded observational monthly climate data series from the Climatic Research Unit (University of East Anglia) and the Met Office, provided at 0.5° latitude x 0.5° longitude grid resolution and spanning the period of 1901-2018 (Harris et al., 2020). The dataset contains monthly climate data for 10 variables, including mean and minimum temperatures, and precipitation variables over all land domains except Antarctica. Several studies have employed the CRU observation data as reference data for various climate impact assessment studies (Craig et al., 2004; Tabor and Williams, 2010; Egbebiyi et al., 2019)

CORDEX model simulated climate data

Global Climate Models (GCMs) used for climate projections typically run at spatial resolutions of hundreds of kilometres, potentially covering variable landscapes with varying possibilities of extreme events such as flooding or droughts. Regional Climate Models (RCMs) used for the dynamical downscaling of GCMs provide higher resolution information on much smaller scales, enabling far more detailed representation of localized weather. This is necessary because climate change impacts are felt at a regional and national scales and impact assessment and adaptation planning needs to be appropriate for the region, particularly for vulnerable areas.

CORDEX (Coordinated Regional Climate Downscaling Experiment) is a CMIP5 diagnostic model intercomparison project (MIP) developed by the World Climate Research Programme (WCRP) for greater coordination of downscaling activities. Its goal is to advance and coordinate the science and application of downscaled regional climate data through global partnerships (Cordex, 2020). CORDEX provides a global framework with common protocols for the development and intercomparison of high-resolution projections and makes the datasets readily available by publishing the data on the Earth System Grid

Federation (ESGF) and other online portals (Tuma, 2018). CORDEX data is available for the period 1951-2099.

Climate models are the primary tool for investigating the climate systems' response to various forcings. It is, therefore, crucial to evaluate the models' performance and to carefully consider the interpretation of future climates based on GCM outputs. One way to evaluate model performance is the use of multi-model ensembles (MMEs). The most common approach to characterize MME results is to calculate the arithmetic mean of the individual model results, giving equal weight to each model. Although multi-model mean results are used in this study, climate models make use of different parameterization schemes and simulate future climate in different ways, providing a range of potential futures. The projections provided by climate models are equally plausible, so it is important to consider the results from individual models as well as the ensemble mean.

Climate change includes not only the increase in global mean temperatures, but the regional changes in features such as daily extremes, inter-annual variability, timing and magnitude of precipitation, and solar radiation, all of which play a role in crop suitability alongside temperature change. These features occur on relatively smaller scales than mean temperature change. To account for this, the study makes use of downscaled GCMs from the CORDEX CMIP5 ensemble which provide information on much smaller scales to support more detailed impact and adaptation assessment and planning. The GCMs are downscaled with RCA4, a regional atmospheric model, to a resolution of 0.44°, making it appropriate for capturing smaller processes.

5 models from the CORDEX CMIP5 ensemble were used in this study, namely NOAA's GFDL-ESM2M, MOHC's HadGem2-ES, CSIRO-QCCCE's CSIRO-Mk3-6-0, CCCma's CanESM2 and MIROC's MIROC5. The resolutions of these GCMs are described in Table 6. The GCMs were downscaled by the Rossby Centre regional atmospheric model, RCA4, after which their resolution is 0.44° x 0.44°, which equates to a grid size of approximately 50 km^2.

Table 7: List of the dynamically downscaled CMIP5 GCMs used in this study

Modelling Centre	Abbreviation	Model name	Resolution
NOAA geophysical fluid dynamics laboratory	NOAA-GFDL	GFDL-ESM2M	2.5° x 2.0°
UK Met Office Hadley center	MOHC	HadGem2-ES	1.875° x 1.25°
Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO-Mk3-6-0	1.875° x 1.875°
Canadian Centre for climate modelling and analysis	CCCMA	CanESM2	2.8° x 2.8°
Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and Centre for Climate System Research / National Institute for Environmental Studies, Japan.	MIROC	MIROC5	1.4° x 1.4°

Selection of past and future time periods

The historical period of 1971-2000 was chosen as the baseline for this study. The baseline period was used to compare CORDEX simulated data with historical observed data to establish confidence in applying CORDEX data for future climate suitability projections, and to be used as reference for changes in future climatic suitability. Two thirty-year future climate periods were selected for analysis; the mid-century period (2031-2060) and the end-of-century period (2071-2100).

Monthly data for minimum and mean temperature (T_{min} and T_{mean}) and precipitation (Pre) were extracted from CRU observations and each of the CORDEX GCMs for the thirty-year period. The same monthly climate variables (T_{min}, T_{mean} and Pre) were extracted from the CORDEX GCMs for these future periods under two Representative Concentration Pathways, RCP4.5 and RCP 8.5, giving four cases of future climate for analysis.

Table 8: Four future cases

	RCP 4.5	RCP8.5
Mid-century (2031-2060)	**MID-45**	**MID-85**
End-of-century (2071-2100)	**END-45**	**END-85**

Mean monthly temperature and precipitation were plotted over South Africa for each of these periods to compare future and historical climates. The historical and future temperature and precipitation plots produced showed very little variation between GCMs, so a median temperature and precipitation was calculated for each case, to improve robustness and conciseness of projections.

Calculation of winter chilling

To calculate winter chill unit accumulation, daily Tmin and Tmax were extracted from the CORDEX models' mean for the historical and future time periods. Hourly temperature was derived by determining an empirical daily temperature curve from Tmin and Tmax using a combination of the following equations described by Linvill (1990); a sine curve to describe daytime warming (Eq 1), and a logarithmic decay function for night-time cooling (Eq 2).

$$T(t) = (Tmax - Tmin)\ x\ \sin[(\pi \times t)/(DL + 4)] + Tmin \qquad [1]$$

where T(t) is temperature at time t after sunrise; Tmax is maximum temperature; Tmin is the morning minimum temperature, and DL is daylength (in hours)

$$T(t) = Ts - [(Ts - Tmin) / \ln(24 - DL)] \times \ln(t) \qquad [2]$$

where T(t) is temperature at time t > 1 hr after sunset and Ts is the sunset temperature obtained from Eq 1.

These daily dynamics are integrated in the stack_hourly_temps() function in chillR package in R (Leudeling, 2022). This function takes as input a dataset of daily minimum and maximum temperatures and latitude of the place of interest and applies the above equations to calculate hourly temperatures.

Analysis of winter chill requires hourly temperatures. Mean annual downscaled hourly temperatures were used to construct a complete dataset for three sites (Ceres, Klein Karoo, and Groblersdal) for the climatic historical period and for the future periods. Ceres, Klein Karoo, and Groblersdal were chosen for analysis as they are major production areas for deciduous fruit that require winter chilling. The pcu_model function in ChillR was used to calculate daily positive chill units (DPCUs) at each site for each period, according to the Daily positive Utah chill unit model. The DPCUs were subsequently accumulated between May and August to determine the chill unit accumulation totals for each site.

Figure 12: Locations of Ceres (1), Klein Karoo (2), and Groblersdal (3)

Crop suitability

In modelling crop interactions with climate, it is crucial to have a thorough understanding of the interactions between plants and their environment. Crop models have been resorted to for fast and inexpensive experimentation, but for their outputs to be robust, they require thorough research question formulation, sufficient methodology and input data. Most crop models make use of quantitative parameterizations of plant biophysical processes and crop management practices to predict their effects on crop production or suitability. A constant challenge to crop model simulations, especially for future crop performance projection studies such as this, is the unavailability of reliable historical observational data for model calibration. Input data deficiencies hamper effective crop modelling as they may not be of the required quality or quantity to drive the crop model.

The impact of future climate on crop suitability was assessed using an empirical approach with the Ecocrop suitability model. Ecocrop was developed by Hijmans et al. (2001) and improved by Ramirez-Villegas et al., (2013). It uses crop expert-derived knowledge from the Food and Agriculture Organization's (FAO) Ecocrop database, which identifies 2568 plant species for given environments (temperature, precipitation, soil characteristics, light intensity, climate types, latitude, altitude, etc.) and uses (plant's main use, part of plant that is used (FAO, 2000). The Ecocrop database also offers information and data on the crop species, including descriptions, yields and growth requirements. The EcoCop model used this data to calculate climatic suitability for specific crops, based on their marginal and optimal ranges of monthly temperature and precipitation (Makinano-Santillan and Santillan, 2015). Ecocrop requires few crop-specific parameters and can therefore be applied to a wide range of crops, including those which have less detailed data available.

Using monthly gridded temperature (T_{min} and T_{mean}) and rainfall (Pre) data, the model's algorithm determines the conditions over the growing season at a particular place, producing suitability scores ranging from 0 (unsuitable) to 1 (optimal suitability) for temperature and precipitation, as in Figure 13 (Ramirez-Villegas, et al., 2013). The total suitability score is calculated as the product of the temperature and precipitation scores, unless the crop is irrigated, in which case the suitability score is calculated from temperature variables only. The model can be adjusted either by using the known presences of a crop or using expert knowledge, or by directly drawing data from the FAO-Ecocrop database (Ramirez-Villegas et al., 2013). Ecocrop is a widely used crop model and past studies show that it produces results comparable to those of more complex models. For this reason, Ecocrop has been deemed an appropriate tool to develop a coarse understanding of future climate change impacts on fruit crop suitability in South Africa. However, Ecocrop uses monthly temperature and precipitation data, which has the advantage of simplicity, but consideration needs to be given to the fact that ecologically stressful conditions may occur at shorter timescales.

Model description

The Ecocrop model defines two ecological ranges for a given crop, each defined by a pair of parameters for temperature and rainfall variables. Firstly, the absolute range, defined by the minimum and maximum absolute temperatures (T_{MIN-C} and T_{MAX-C}, respectively) for the temperature variables, and by the minimum and maximum absolute rainfall at which the crop grows (R_{MIN-C} and R_{MAX-C}, respectively) for precipitation. The second ecological range is the optimum range, defined by minimum optimum and maximum optimum temperatures and rainfall, ($T_{OPMIN-C}$ and $T_{OPMAX-C}$, and $R_{OPMIN-C}$ and $R_{OPMAX-C}$) at which the plant grows (Ramirez-Villegas et al., 2013).

When temperatures and rainfall over the growing season are beyond the crop's absolute thresholds, the area is not suitable for the crop (depicted by the white area in figure 13A). When temperatures and rainfall are between the absolute and optimum thresholds, the area has a suitability between 0.01 and 0.99 (dark grey area in figure 13A). When temperatures and rainfall are within the crops' optimum ranges, the area is highly suitable and has a suitability score of 1 (light grey area in figure 13A). Ecocrop calculates temperature suitability (T_{SUIT}) and precipitation suitability (R_{SUIT}) separately and then calculates the interaction by multiplying them together (figure 13B) (Ramirez-Villegas et al., 2013).

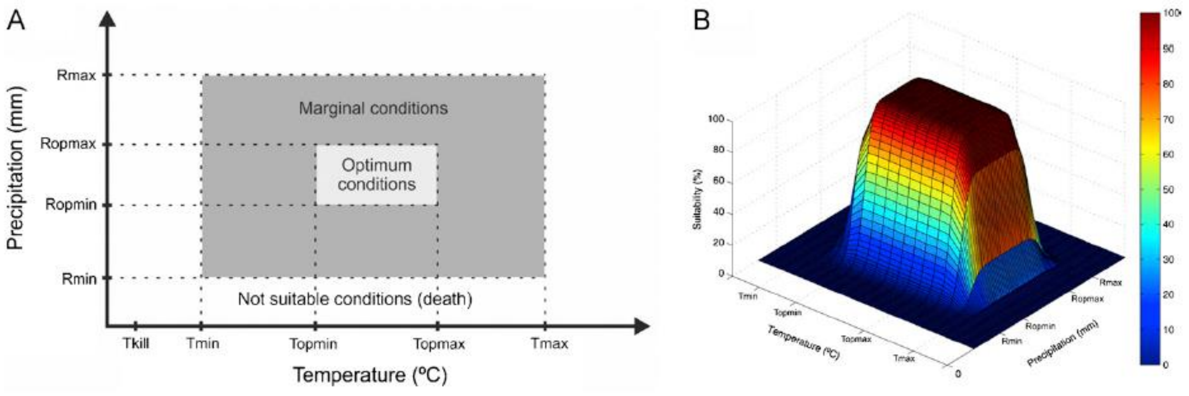


Figure 13: 2-dimensional (A) and 3-dimensional (B) diagram of the Ecocrop model (Ramirez-Villegas, et al., 2013)

The temperature suitability (T_{SUIT}) is calculated by comparing the different crop parameters with the climate data for each month (i) of a crop's growing season (G_{AVG}) at a given site (P), as in Equation 3.

$$T_{SUITi} = \begin{cases} 0 & T_{MIN-Pi} < T_{KILL-M} \\ 0 & T_{MEAN-Pi} < T_{MIN-C} \\ a_{T1} + m_{T1} * T_{MEAN-Pi} & T_{MIN-C} \leq T_{MEAN-Pi} < T_{OPMIN-C} \\ 100 & T_{OPMIN-C} \leq T_{MEAN-Pi} < T_{OPMAX-C} \\ a_{T2} + m_{T2} * T_{MEAN-Pi} & T_{OPMAX-C} \leq T_{MEAN-Pi} < T_{MAX-C} \\ 0 & T_{MEAN-Pi} \geq T_{MAX-C} \end{cases} \quad [3]$$

Where;

- T_{SUITi} is the temperature suitability index for the month i,
- $T_{MIN\text{-}C}$, $T_{OPMIN\text{-}C}$, $T_{OPMAX\text{-}C}$ and $T_{MAX\text{-}C}$ are temperature parameters defined for each crop,
- a_{T1} is the intercept, and m_{T1} is the slope of the regression curve between [$T_{MIN\text{-}C}$, 0] and [$T_{OPMIN\text{-}C}$, 100],
- a_{T2} is the intercept, and m_{T2} is the slope of the regression curve between [$T_{OPMAX\text{-}C}$, 100] and [$T_{MAX\text{-}C}$, 0].
- $T_{MIN\text{-}Pi}$ is the minimum temperature of the month i at the site P,
- $T_{MEAN\text{-}Pi}$ is the mean temperature of the month i,
- $T_{KILL\text{-}M}$ is the crop's killing temperature plus 4°C. The model assumes that if the month's minimum temperature in a particular place is below [T_{KILL} + 4°C], then the minimum absolute killing temperature will be reached in at least one day of the month, and the crop will freeze and fail.

The final temperature suitability (T_{SUIT}) is the minimum value of all 12 potential growing seasons.

The precipitation suitability (R_{SUIT}) is calculated only once using the total rainfall over the crop's growing season, and the minimum and maximum absolute and optimum rainfall requirements, as in Equation 4.

$$R_{SUIT} = \begin{cases} 0 & R_{TOTAL-P} < R_{MIN-C} \\ a_{R1} + m_{R1} * R_{TOTAL-P} & R_{MIN-C} \leq R_{TOTAL-P} < R_{OPMIN-C} \\ 100 & R_{OPMIN-C} \leq R_{TOTAL-P} < R_{OPMAX-C} \\ a_{R2} + m_{R2} * R_{TOTAL-P} & R_{OPMAX-C} \leq R_{TOTAL-P} < R_{MAX-C} \\ 0 & R_{TOTAL-P} \geq R_{MAX-C} \end{cases} \qquad [4]$$

Where

- R_{SUIT} is the rainfall suitability score,
- $R_{TOTAL\text{-}P}$ is the total rainfall of the crop's growing season at site P,
- $R_{MIN\text{-}C}$, $R_{OPMIN\text{-}C}$, $R_{OPMAX\text{-}C}$ and $R_{MAX\text{-}C}$ are rainfall parameters defined for each crop,
- a_{R1} and m_{R1} are the intercept and the slope of the regression curve between [$R_{MIN\text{-}C}$, 0] and [$R_{OPMIN\text{-}C}$, 100], and

- ○ a_{R2} and m_{R2} are the intercept and the slope of the regression curve between [$R_{OPMAX\text{-}C}$, 100] and [$R_{MAX\text{-}C}$, 0].

Finally, the total suitability score is the product of the temperature and precipitation suitability surfaces calculated separately, i.e. $SUIT = R_{SUIT} * T_{SUIT}$ (Ramirez-Villegas et al., 2013).

Table 9: A description of Ecocrop suitability index value used for the study (Adapted from Egbebiyi, Crespo & Lennard, 2019).

Suitability index value	Description
0	Not suited
0.01 – 0.2	Unsuitable
0.21 – 0.4	Very marginally suitable
0.41 – 0,.6	Marginally suitable
0.61 – 0.8	Suitable
0.81 – 1.0	Highly suitable

Application of Ecocrop model in this study

Ecocrop was used to calculate climatic suitability scores for each of the fruit crops using gridded climate data from each of the 5 GCMs, for the historical period and each of the four future cases. This was done by computing the suitability score over each crop's growing season over the spatial domain of South Africa for each thirty-year period. The Ecocrop model was run using R software using the 'Ecocrop' function from the 'dismo' package for species distribution modelling (Hijmans et al., 2011). The function requires inputs of T_{min} (vector of monthly minimum temperatures in °C), T_{mean} (vector of monthly average temperatures in °C), and R_{total} (vector of total monthly precipitation in mm), and a logical argument 'rainfed' which, if set to 'false', the crop is assumed to be irrigated, and the precipitation variable is ignored. The model calculates the climatic suitability for each crop using FAO-Ecocrop's crop ecological requirements database (Table 1) with the methodology described in Ramirez-Villegas et al. (2013). Gridded climate data (T_{min}, T_{mean}, and R_{total}) for the historical period and each of the four future cases from each of the 5 GCMs was used to run Ecocrop and the parameter 'rainfed' was set to 'false' for all of the fruit crops in the study, since they are all irrigated. It outputs a raster object of suitability scores for that particular crop over the specified time period (Hijmans et al., 2011).

The raster outputs were used to make composite maps of suitability scores for each crop in each case for each GCM. A median plot of suitability scores produced by each GCM was produced for each fruit crop in each case, to improve conciseness of results. The total land area categorized by each suitability index descriptor (Table 8) was calculated for each crop in each case, to assess the spatial changes in suitable land area. To visualize the future spatial change in crop suitability, historical suitability scores for each crop were subtracted from the suitability score in MID-45, MID-85, END-45, and END-85, and the anomalies were plotted in composite maps.

Suitability of Ecocrop's Parameters for application to fruit crops

The fruit crops examined in this study have complex physiological requirements, such as winter chilling, frost free springs, and temperature and moisture requirements at different phases of fruit development, as discussed in Section 2.1. Ecocrop is a simplistic empirical model which does not have the capacity to capture these complex crop climatic requirements, and therefore some suitability modelling inaccuracies are expected. Ecocrop is better suited to simpler annual field crops, such as maize, wheat, millet, etc., which do not have such physiological complexities.

4. Results and Discussion

This chapter is divided into three sections. In 4.1, historical climate patterns over South Africa are explored in terms of temperature and precipitation, and the climate models are validated against CRU observational data. The four cases of future projections of temperature, precipitation, and winter chilling under different Representative Concentration Pathways are compared to the historical climate. In 4.2, the Ecocrop model is validated by comparing historical suitability scores against known fruit presence data. The suitability scores of various fruit crops are examined for each of the four cases. Section 4.3 contains a discussion comparing the results from RCP4.5 and RCP8.5, a comparison of the effects of the different GCMs used, and a discussion of response planning and adaptation to climate change impacts on crop suitability.

4.1. Climate

4.1.1. Historical climate

4.1.1.1. Inter-model agreement on historical climate

Figures 14 and 15 compare the 5 GCMs' historical temperature and precipitation over South Africa, respectively. All 5 GCMs show a very similar pattern of average monthly temperature for the historical period (1971-2000) with very little variation between GCMs. One noticeable difference, although minor, is that CanESM2 presents slightly warmer mean historical temperatures than the other models, with the east coast reaching 22°C while the other 4 models only reach 20°C.

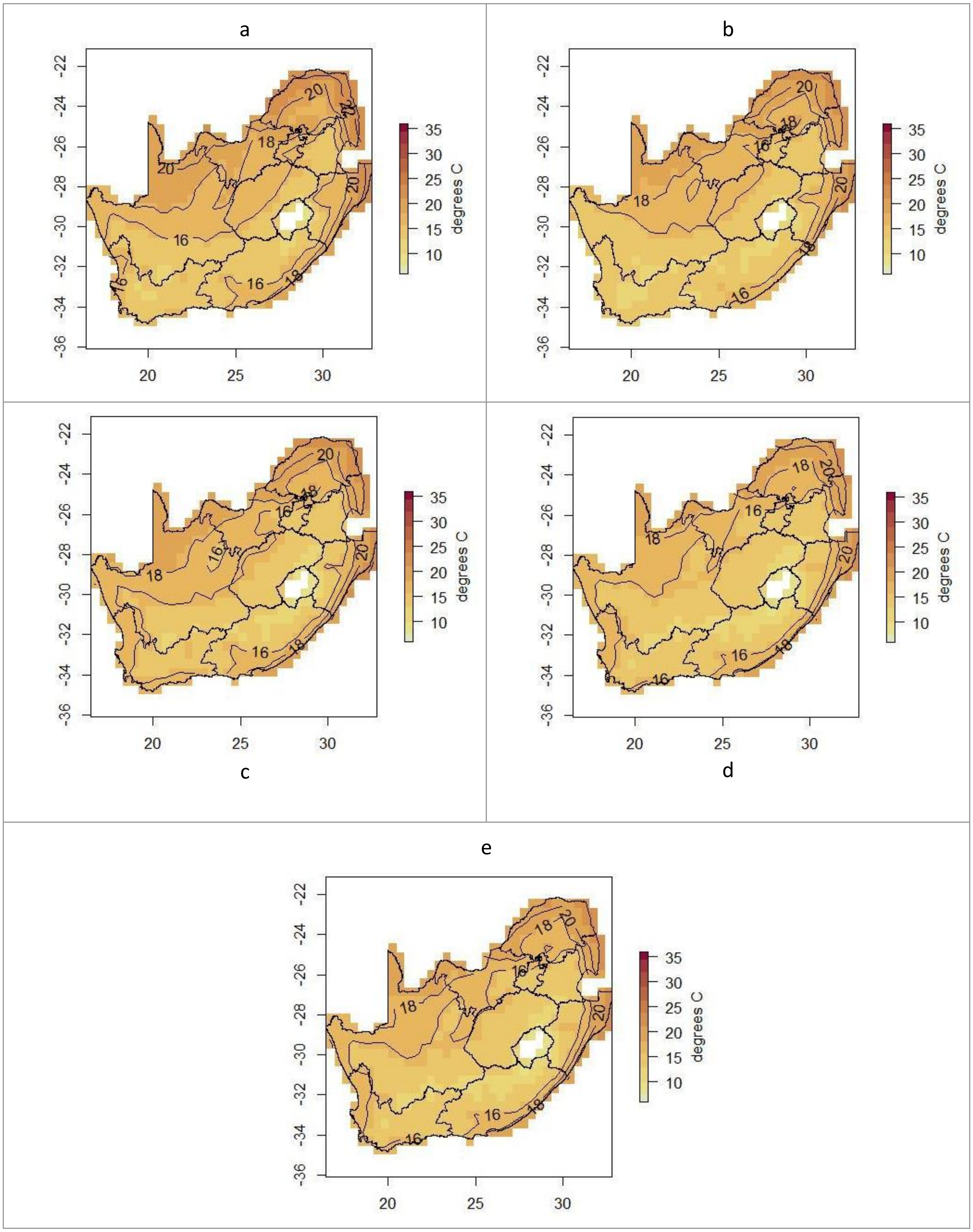
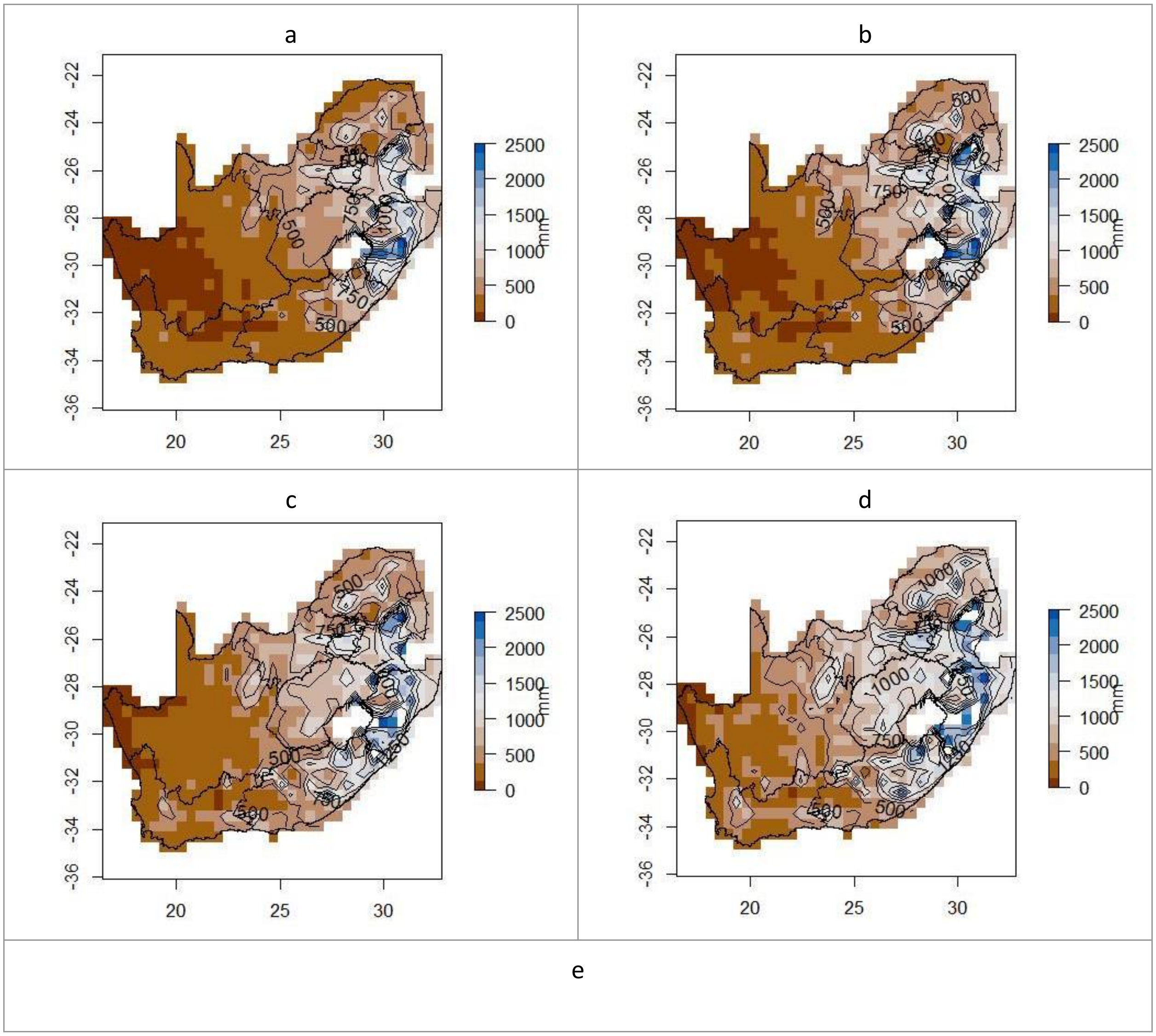


Figure 14: Mean monthly average temperature for the historical period using (a) CanESM2, (b) CSIRO-Mk-3-6-0, (c) HadGem2-ES, (d) MIROC5 and (e) GFDL-ESM2M

The 5 GCMs also agree on historical precipitation patterns across the country. MIROC5 gave a slightly higher mean annual precipitation than the other GCMs, while CanESM2 gave a slightly lower mean annual precipitation. The pattern was the same throughout, showing very low rainfall in the west, illustrating the arid and Mediterranean climates, increasing eastward into moderate climate over the interior and then to the wet subtropical climate over the eastern provinces. These results provide confidence in aggregating the GCMs for suitability analysis.



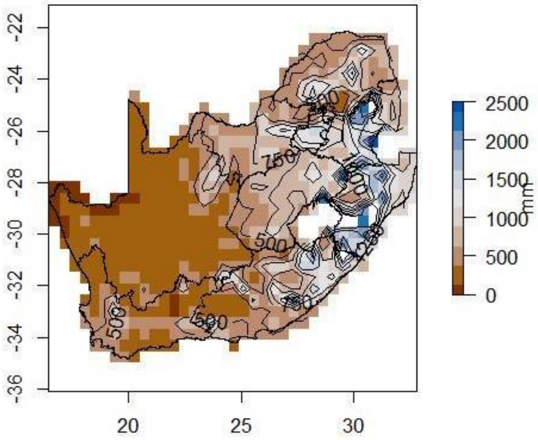


Figure 15: Mean annual precipitation for the historical period using (a) CanESM2, (b) CSIRO-Mk-3-6-0, (c) HadGem2-ES, (d) MIROC5 and (e) GFDL-ESM2M

4.1.1.2. Historical temperature and precipitation – model evaluation

Figure 16 compares plots of average monthly mean temperature for the historical period from (a) the aggregated CORDEX data and (b) CRU observational data. The datasets agree that the interior of the country, the Eastern Cape and the Western Cape had a mean temperature of 14-16°C, while warmer temperatures reaching 18-22°C in the northern parts of the country (Northern Cape, North West, Mpumalanga and Limpopo) and KwaZulu Natal on the east coast. Figure 17 show plots comparing the historical mean monthly minimum temperatures for the historical period using (a) CORDEX data and (b) CRU observational data. Once again, the datasets concur, with both having historical mean minimum temperatures range from 8°C in the interior to 12-14°C along the coast and in the north, and up to 16°C on the KwaZulu Natal coastline.

CORDEX-simulated mean annual precipitation and CRU observed mean annual precipitation for the historical period are compared in Figure 18. Both plots illustrate the western parts of the country (Northern Cape and Western Cape – hydrological zones 4 and 6) receive the least rainfall (0-250mm per year), increasing eastward, with the central provinces (Free State, North West, Gauteng and Eastern Cape - hydrological zones 1,3 and parts of zone 4) receiving around 500-1000 mm and the eastern provinces (KwaZulu Natal, Limpopo and Mpumalanga – hydrological zones 2 and 5) receiving around 1000-2500mm per year on average.

The above results thus show a strong agreement between CORDEX-simulated historical climate and CRU observations, instilling confidence in applying CORDEX climate projections in future crop suitability analysis.

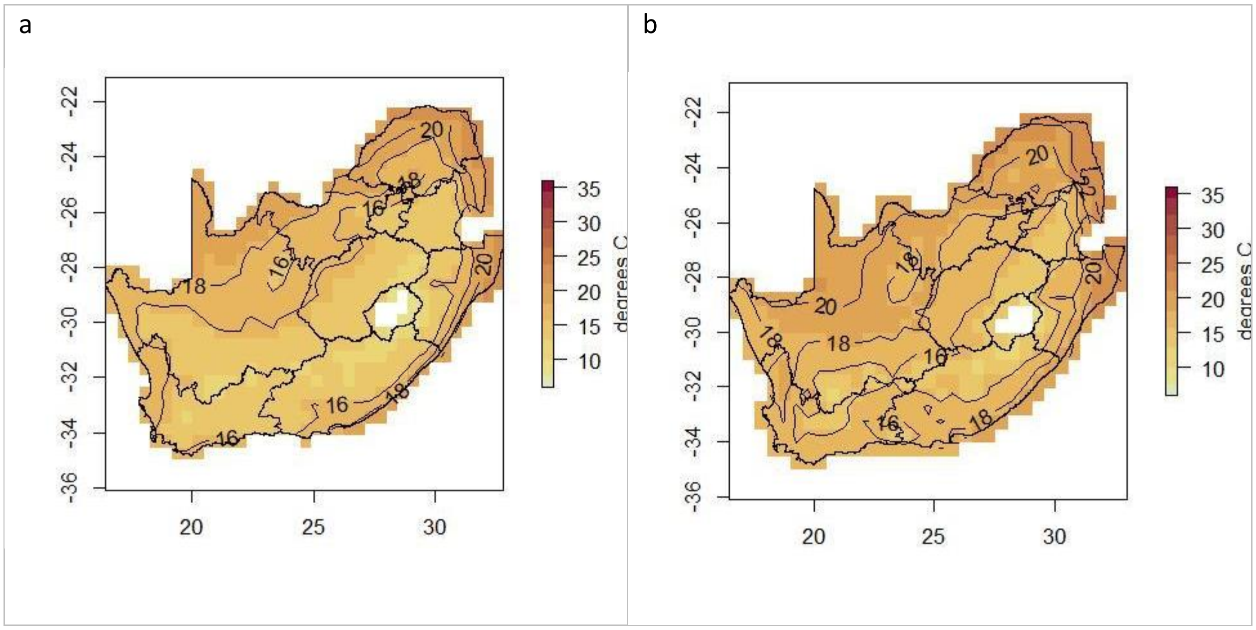


Figure 16: (a) CORDEX historical mean monthly average temperatures, and (b) CRU historical mean monthly average temperatures

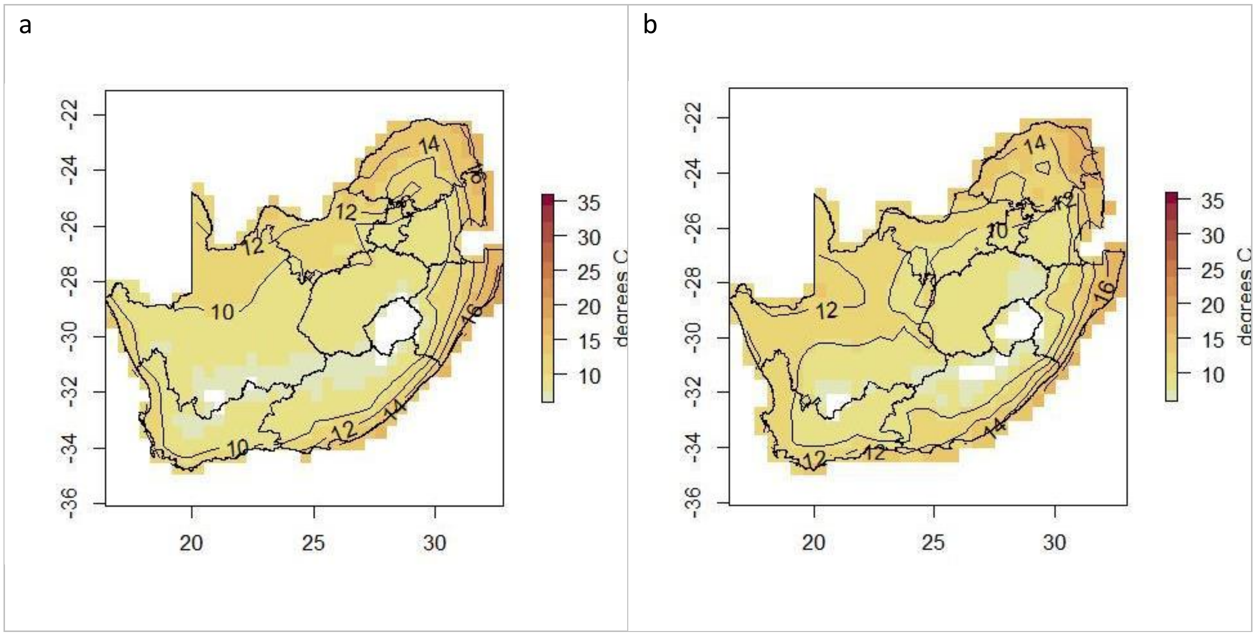


Figure 17: (a) CORDEX historical mean monthly minimum temperatures, and (b) CRU historical mean monthly minimum temperatures

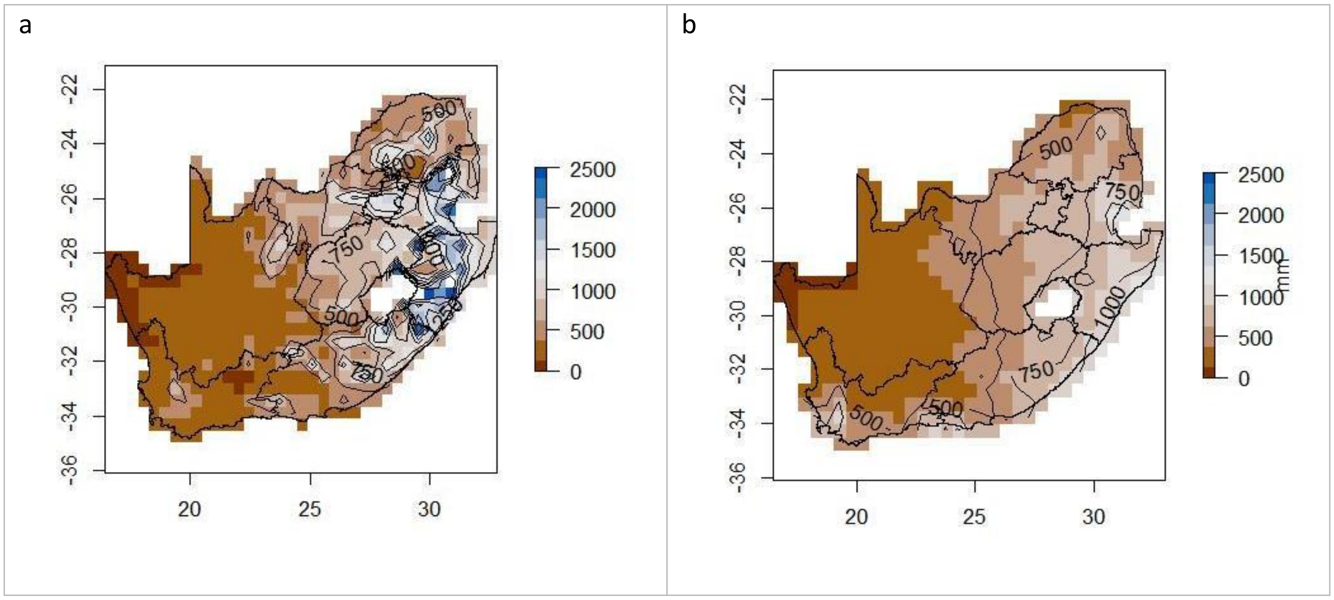


Figure 18: (a) CORDEX historical mean annual precipitation, and (b) CRU historical mean annual precipitation

4.1.2. Future climate projections

Future temperature projections by all 5 GCMs indicate a warmer and drier South African climate in the mid-21st century and the end of the century.

4.1.2.1. Temperature projections

Climate data used in this study (outputs from 5 GCMs in the CORDEX CMIP5 ensemble) agree with projected future temperature change for South Africa in the literature. Patterns of warming are seen across South Africa under all 4 cases, with the strongest warming anticipated for the interior and the weakest warming along the coast. Warming is strongest at the end of the century under RCP8.5.

Figure 19 below illustrates the mean monthly mean temperatures in each future case. Figure 20(a) illustrates the projected mean monthly temperature anomalies for MID-45 from historical values, as a median of the 5 GCMs. The average monthly temperature increases 1°C along the coast of South Africa and 2°C in the interior. In case MID-85 (Figure 20(b)), there is an average increase of 2°C over the whole of South Africa, with some northern parts of Limpopo and North West increasing as much as 3°C on average. In END-45 (Figure 20(c)), the coastal zone sees an average temperature increase of 2°C, whereas the interior is expected to warm as much as 3°C on average. In case END-85 (Figure 20(d)), extreme warming is expected for the end-of-century period. The coastal belt is expected to warm by an average of 3°C. The escarpment sees a 4°C temperature increase, and the interior may warm by an average of 5°C.

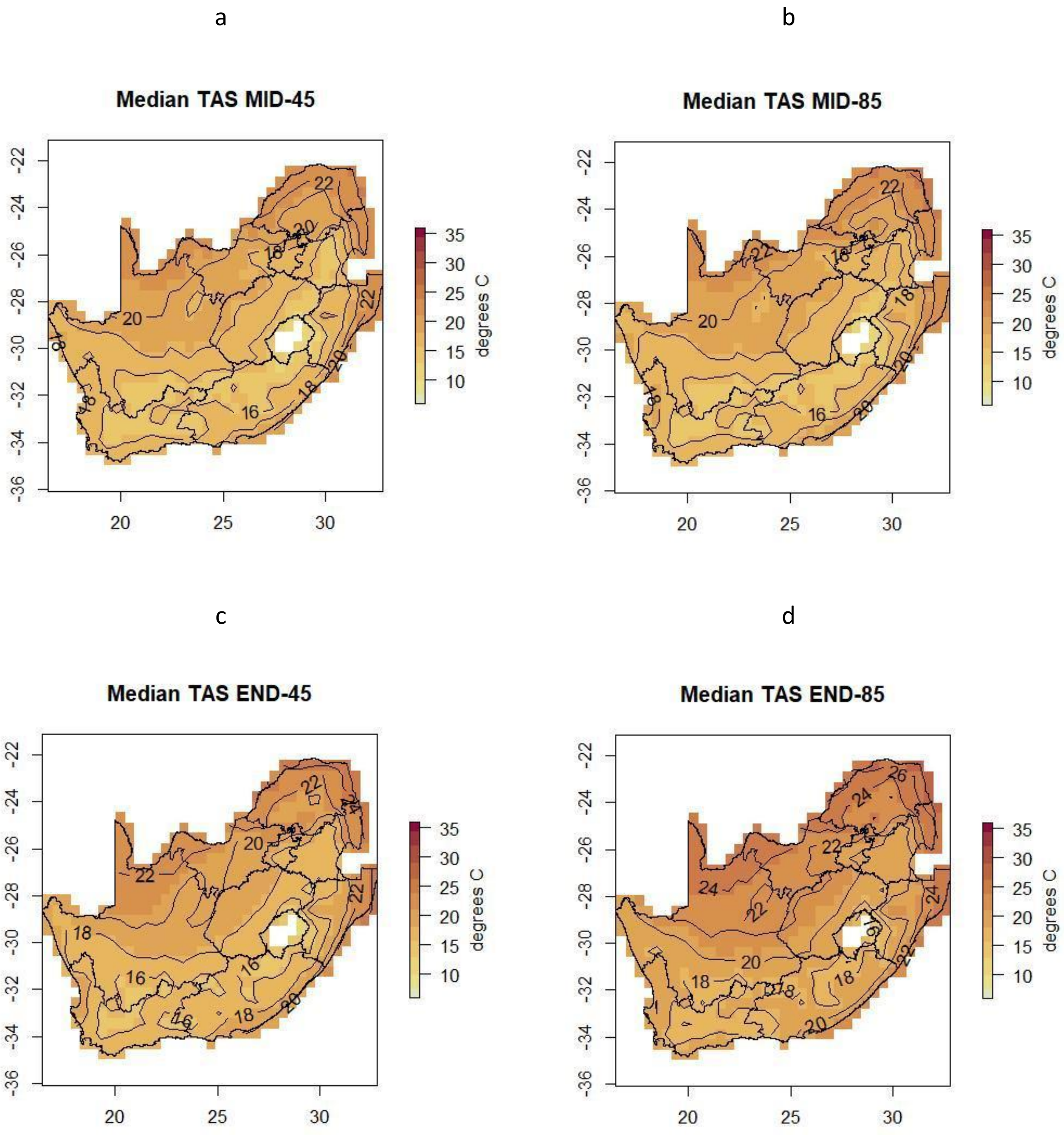


Figure 19: CORDEX projected mean monthly temperatures for (a) MID-45, (b) MID-85, (c) END-45 and (d) END-85

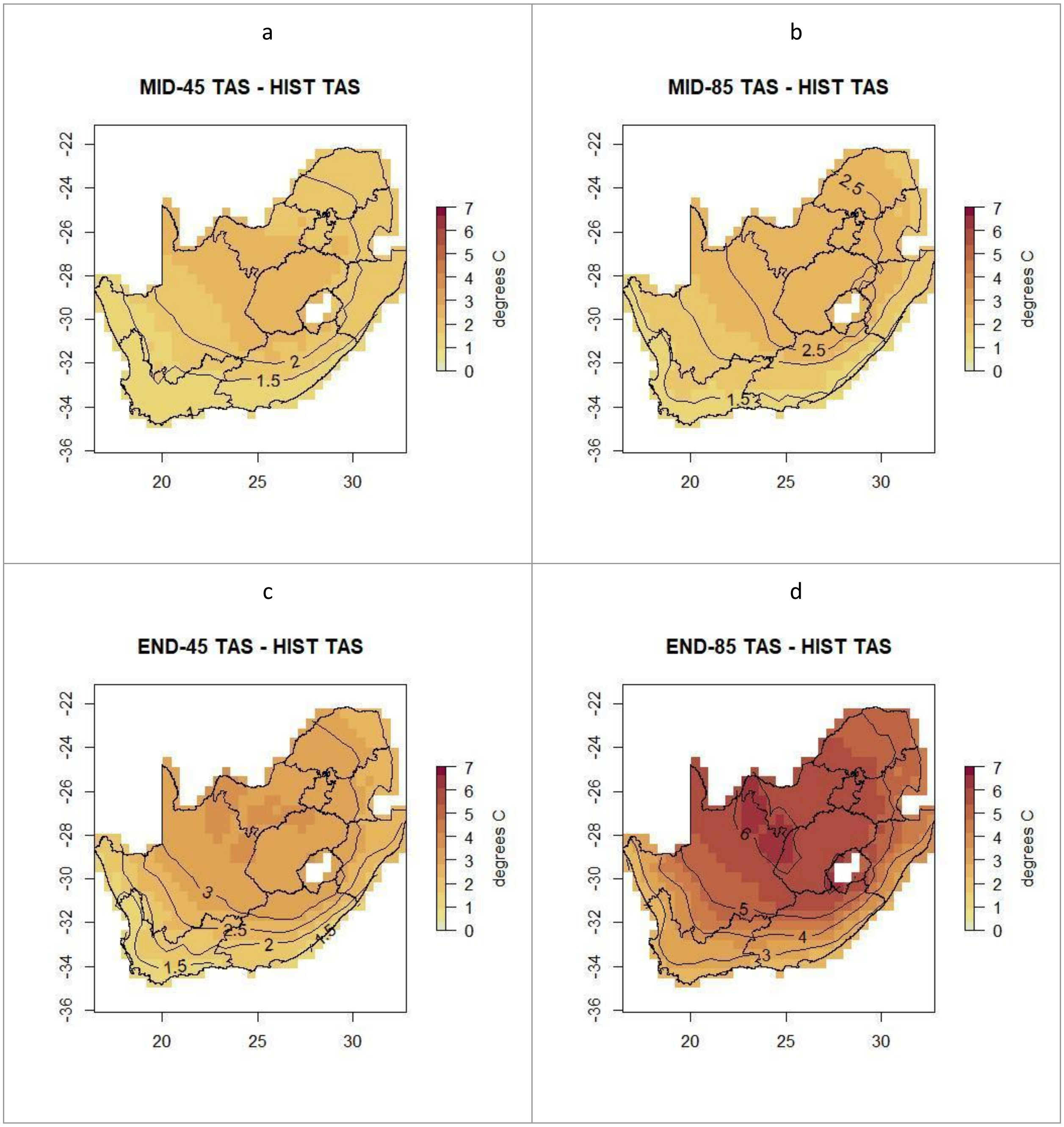


Figure 20: CORDEX projected mean monthly temperature anomalies (future minus historical) for (a) MID-45, (b) MID-85, (c) END-45 and (d) END-85

4.1.2.2. Precipitation projections

Figure 21 shows median of the 5 GCMs' projected mean annual precipitation in each of the future cases, and Figure 22 shows the mean annual precipitation anomalies from the historical period in each of the four cases. Mild drying (50-100mm per year) is projected for the eastern and southern coastal regions of South Africa in MID-45 (Figure 22(a)). There is little to no change in annual precipitation expected for the interior of the country. In MID-85, the drying signal increases slightly and a small region of the highveld (parts of the Free State and North West) is expected to experience a slight annual precipitation increase of up to 100 mm (Figure 22(b)). Precipitation over most of the interior remains unchanged. In END-45 (Figure 22(c)), the mean annual precipitation is expected to further decrease over the eastern escarpment and the coastal low-lying land. This drying signal expands toward the interior, although a large part of the interior is expected to remain unchanged. Under END-85 (Figure 22(d)), the drying over the eastern escarpment becomes more prevalent, with annual precipitation decreases of up to 400 mm projected in the east. A larger proportion of the country is expected to experience a precipitation decrease compared to the mid-century and RCP4.5.

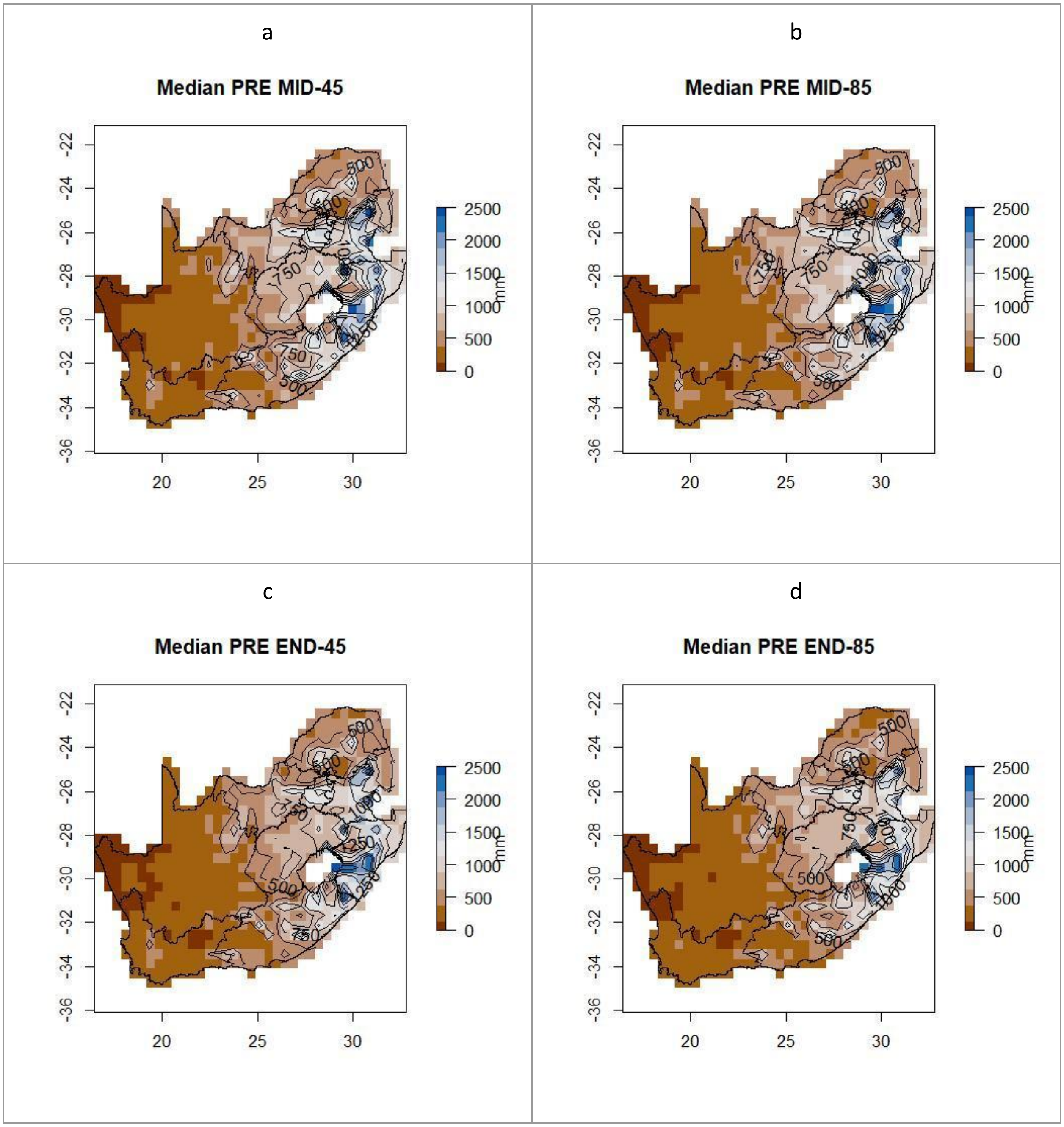


Figure 21: CORDEX projected mean annual precipitation in (a) MID-45, (b) MID-85 2, (c) END-45 and (d) END-85

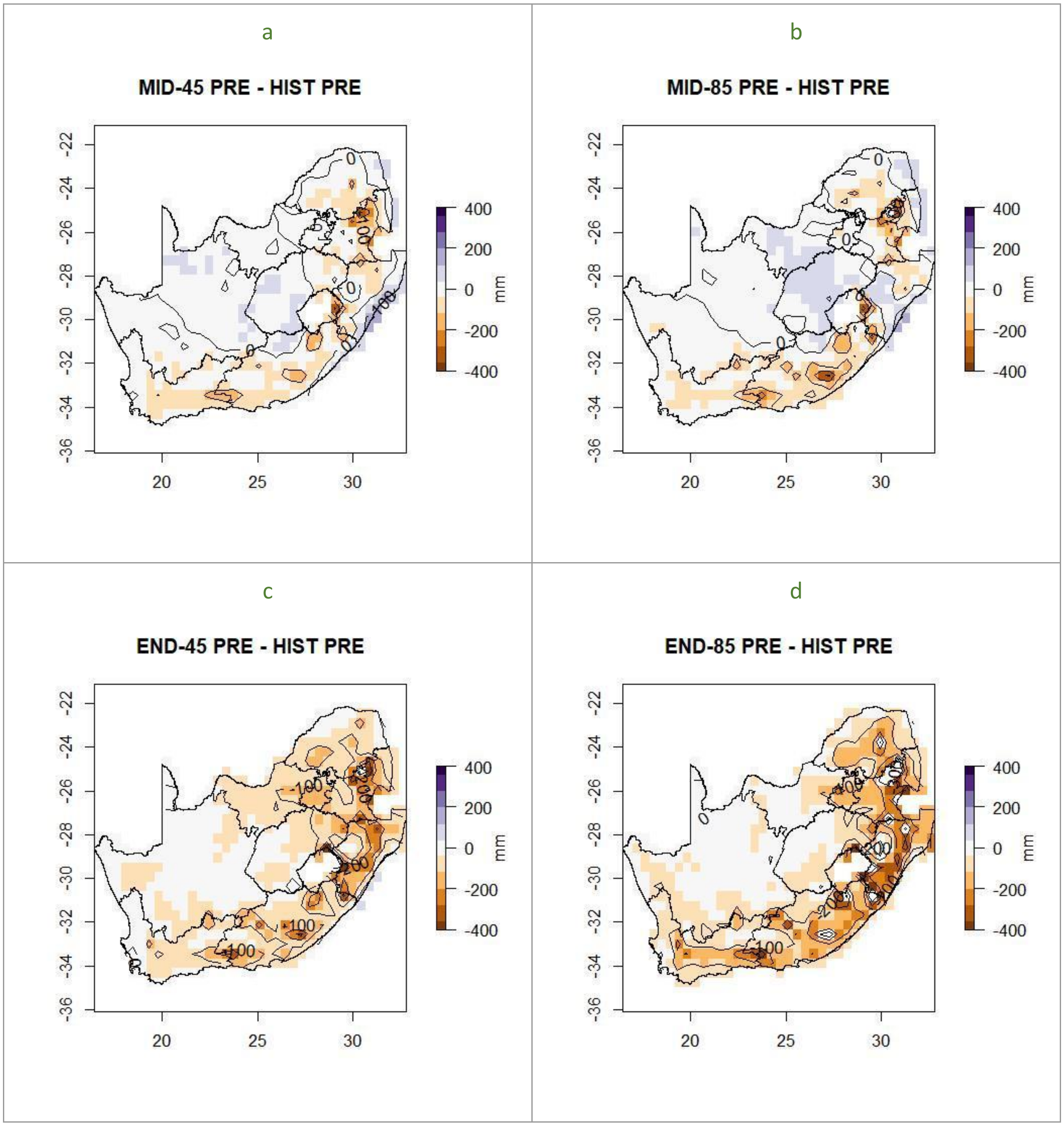


Figure 22: CORDEX projected mean annual precipitation anomalies from historical mean annual precipitation for (a) MID-45, (b) MID-85, (c) END-45 and (d) END-85. Purple represents a positive change (increased precipitation), orange represents a negative change (drying)

4.1.3. Winter chill unit accumulation change

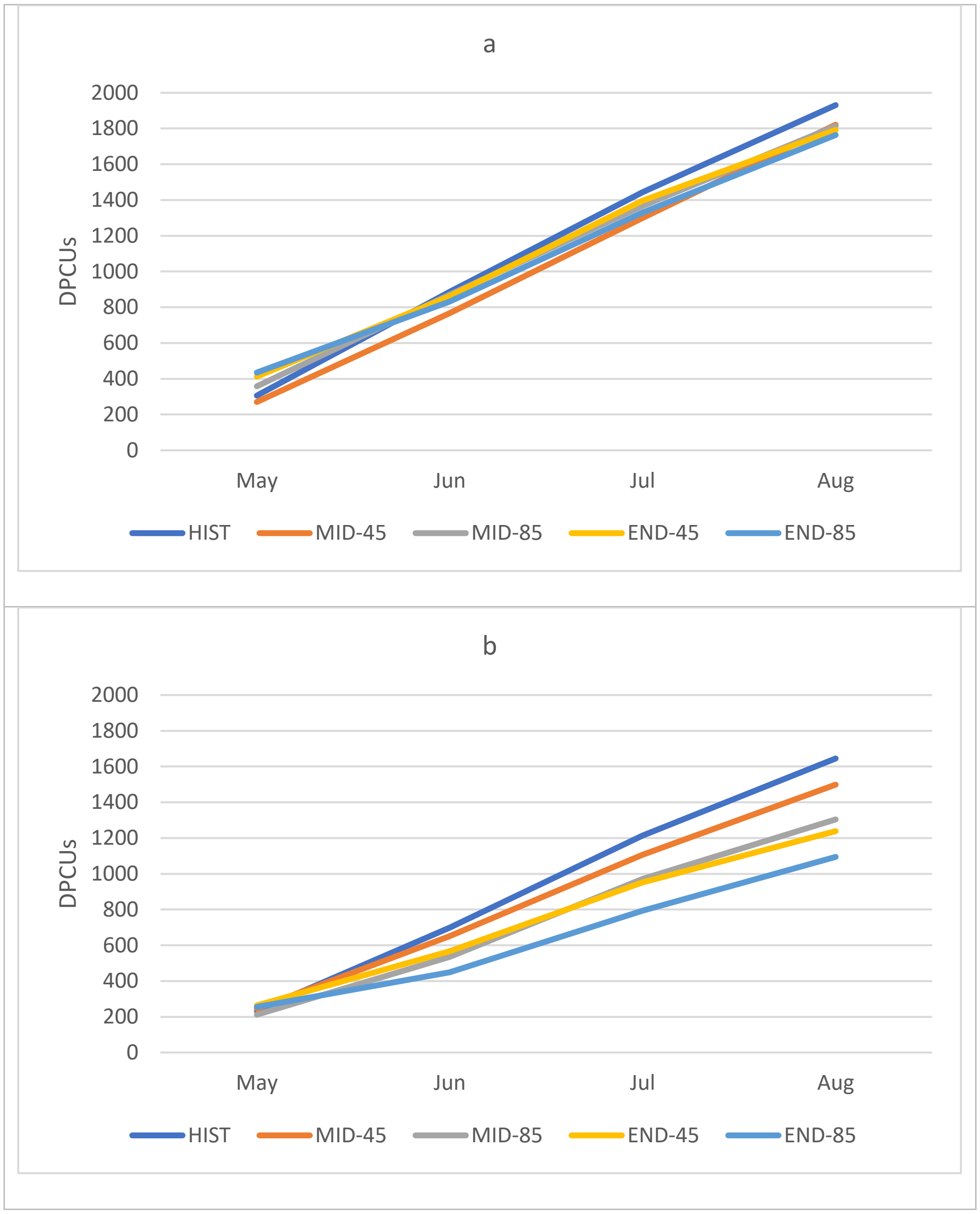
Figure 23 presents the accumulated winter chilling in DPCUs from the Positive Utah Model for the historical (1971–2000), mid-century (2031-2060) and end-of-century (2071-2100) for both RCP4.5 and 8.5 at (a) Ceres, (b) Klein Karoo, and (c) Groblersdal. Chill unit accumulation was calculated from May to August for each year of the study period and the seasonal mean was calculated for each study period.

The results from the PCU model indicate that historically, Ceres provided a mean of 1931 DPCUs between May and August (figure 23(a)). This value decreased in all four future cases. The model calculated 1821 DCPUs in MID-45 and 1814 DPCUs in MID-85. For the 2071-2100 period, 1792 and 1764 DPCUs were calculated for Ceres in END-45 and END-85 respectively. The latter is a reduction of 167 DPCUs.

In the historical period, Klein Karoo accumulated a mean of 1645 DPCUs between May and August (figure 23(b)). Once again, all future cases saw a reduction in chill unit accumulation. MID-45 and MID-85 saw an accumulated 1498 and 1304 DPCUs respectively. END-45 and END-85 saw further decreases in chill units, with 1238 and 1084 DPCUs accumulated, respectively. The largest decrease was in END-85, with a difference of 551 DPCUs.

Groblersdal provided a mean of 1380 DPCUs historically (figure 23(c)). The results indicated a decrease in chill units for all future cases. MID-45 and MID-85's mean total winter chilling for Groblersdal were 1106 and 1076 DPCUs, while END-45 and END-85 had mean winter chilling of 991 and 550 DPCUs, respectively. The greatest change was observed in END-85, with a massive reduction of 830 DPCUs

Figure 23 indicates that, with increase in temperature throughout the 21st century, the accumulated chill units will reduce in three major deciduous fruit-growing regions under both high and low mitigation pathways.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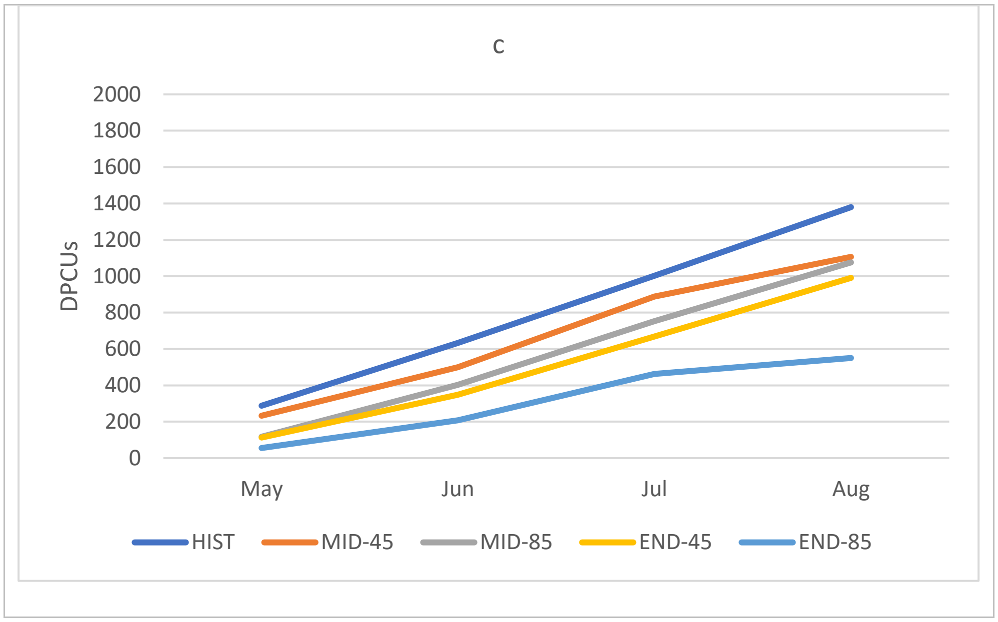

Figure 23: Accumulated DPCUs in each case at (a) Ceres, (b) Klein Karoo, and (c) Groblersdal

Comparing projected accumulated DPCUs with fruit chilling requirements

The fruits with the highest chilling requirements are apples (800 – 1 000 DPCUs) and plums (1 000 – 1 200 DPCUs). These high chill varieties are likely to suffer in areas like Groblersdal and perhaps Klein Karoo which are projected to experience a large decreases in winter chilling, especially under RCP8.5 and towards the end of the century. Medium to low-chill fruit types such as pears (450-800 DPCUs), peaches (450 – 800 DPCUs) and table grapes (200 – 400 DPCUs) are unlikely to be impacted by the reduction in winter chilling in all three studied areas, as are all projected to receive sufficient winter chilling to meet the requirements of the trees to induce bud break, even under the high emission scenario and at the end of the century.

4.2. Effect of climate change on crop suitability distribution

4.2.1. Historical suitability and Ecocrop model evaluation

Citrus

South Africa has a total of around 86 744 hectares under citrus cultivation (Citrus Growers Association, 2020). The main citrus cultivation areas are in Limpopo, Western Cape, Eastern Cape, and Mpumalanga. As shown in the map in figure 24. The cultivation areas differ in climatic conditions, as different varieties are suited to each environment. The temperate Western Cape and Eastern Cape are the cooler citrus growing areas where Navel oranges, lemons, limes, and most of the soft citrus are best suited, while the warmer subtropical climate in Mpumalanga, Limpopo and KwaZulu-Natal is better suited to the cultivation of grapefruit and Valencia oranges (DAFF, 2018a). Figure 25 depicts that Limpopo has the largest area under citrus cultivation with 36 000 hectares, followed by the Eastern Cape with 23 020 hectares and the Western Cape with 16 205 hectares. Smaller amounts of citrus are grown in Mpumalanga, KwaZulu Natal, Northern Cape, North West, and the Free State.

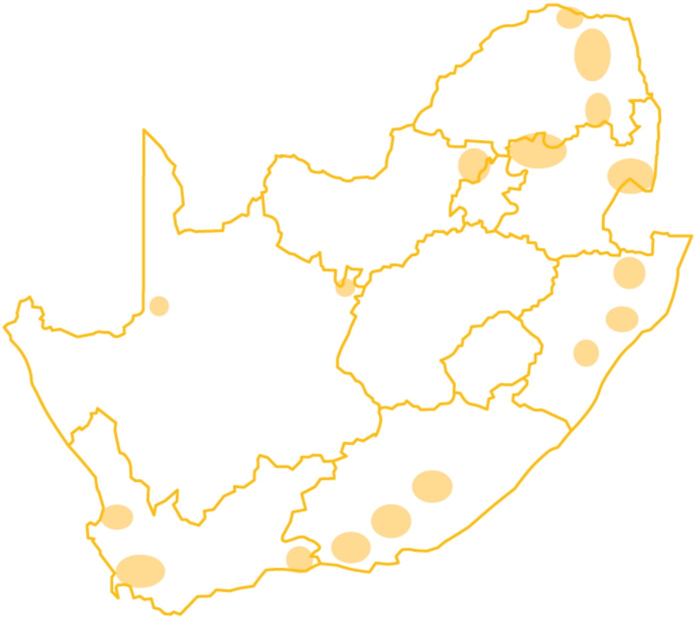

Figure 24: Citrus growing regions of South Africa. Western Cape: Boland, Citrusdal, Ceres; Eastern Cape: Patensie, Eastern Cape Midlands, Sundays River Valley; KwaZulu Natal: Pongola, Nkwalini, KZN Midlands; Northern Cape; Vaalharts, Orange River region; Mpumalanga; Onderberg, Malelane, Nelspruit, Senwes; Limpopo: Hoedspruit, Letsitele, Vhembe (source: Post-Harvest Innovation Programme, 2022)

Oranges

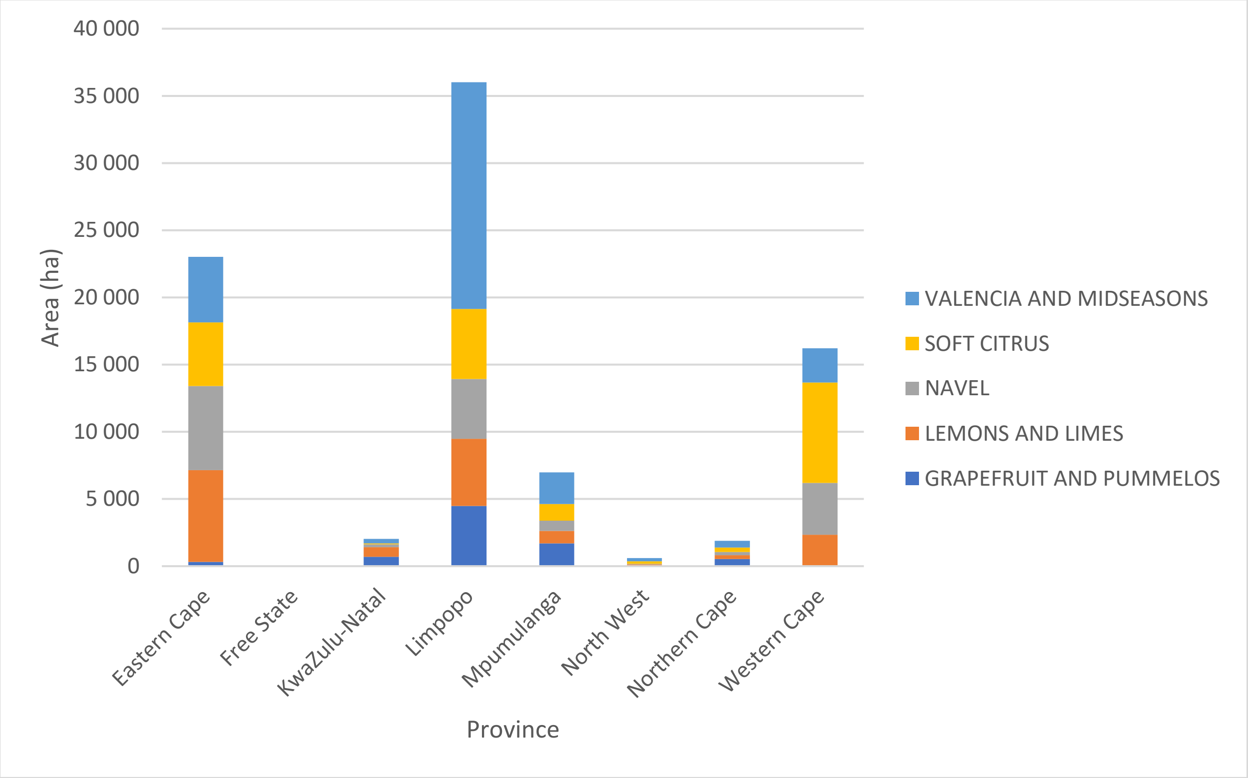

Figure 25: Proportion of citrus type grown in each area

Ecocrop results for the historical period indicate very poor orange suitability over South Africa having a suitability score of 0 over most of the country, and scores of 0.2 in parts of Mpumalanga, and Limpopo (Figure 27). The coast of KwaZulu Natal extending south to the Eastern Cape have the best suitability scores although they are still low (between 0.3 and 0.5). A very low 0.17 percent of South Africa's land area was classified as '*suitable*', i.e., having a suitability score of 0.61-0.8. Valencia oranges and Midseasons are the most common type of citrus and are predominantly grown in Limpopo, Eastern Cape, Western Cape, and Mpumalanga (Citrus Growers association, 2022). Currently, oranges are predominantly grown in Limpopo (27%), The Eastern Cape (41%), Mpumalanga (5%) and the Western Cape (24%) (Citrus Growers Association, 2022). Besides the Western Cape, which is a large producer of oranges, having no suitable land predicted, these growing areas concur with the suitable areas predicted by Ecocrop for the historical period. The failure to capture suitable areas in the Western Cape may be due to the inability of the GCMs to capture small scale processes in this mountainous area, due to low resolution and/or model biases. Additionally, Ecocrop's sole reliance on temperature variables in this study neglects the complex physiology of orange trees, resulting in a poor estimation of their suitable area.

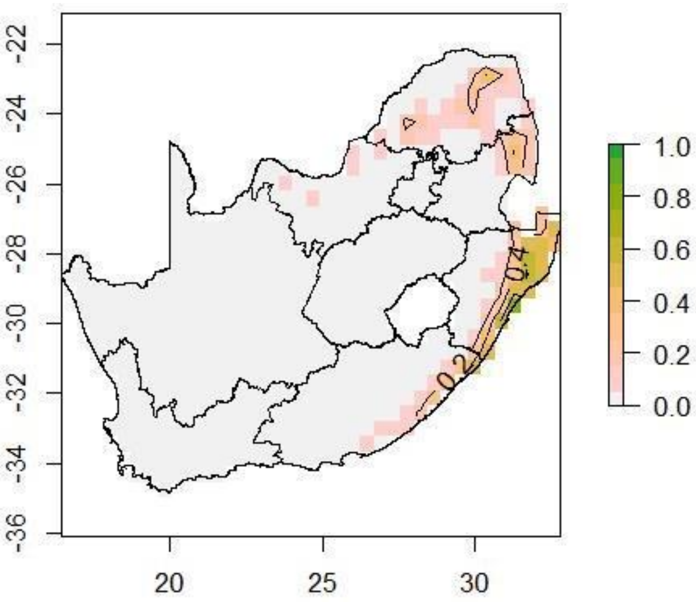

Figure 26: Historical orange suitability (aggregate)

Lemons

Ecocrop results for the historical period show very poor lemon suitability over South Africa, with a suitability score of 0 over most of the country (Figure 27). 2.91% of the land area, found at the KwaZulu Natal coast, was 'highly suitable', having a suitability score of 0.81-1.0, and parts of Limpopo, Mpumalanga and coastal Eastern Cape are also 'marginally suitable' to 'suitable' (0.41-0.8). According to data from the Citrus Growers Association (2022), lemons are grown in the Eastern Cape (42%), Limpopo (31%), Western Cape (14%), Mpumalanga (5%), and KwaZulu Natal (4%). With the exception of the Western Cape, these growing areas are considered suitable by Ecocrop for the historical period. This result indicates confidence in Ecocrop for projecting future lemon suitability. Number of Western Cape citrus growing areas are located nearby mountainous features, which are small features poorly captured by a large-scale statistical approach like Ecocrop.

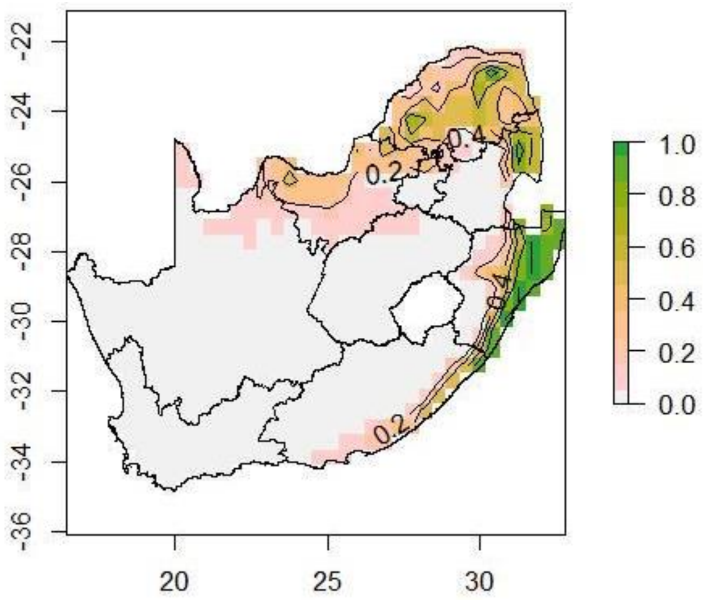

Figure 27: Historical lemon suitability (aggregate)

Mandarins

Historical suitability for the selected soft citrus, mandarin, is very marginal to unsuitable over the whole country except the eastern escarpment where suitability score reaches 0.4. The high lying areas of Limpopo have suitability scores reaching 0.2. Mandarins are grown in the Western Cape (37%), Limpopo (28%), Eastern Cape (25%), and Mpumalanga (7%) (Citrus Growers Association, 2022). This concurs with the mandarin suitability calculations by Ecocrop for the historical period, except the Western Cape is considered unsuitable. The failure to capture suitable areas in the Western Cape may be due to the inability of the GCMs to capture small scale processes in this mountainous area, due to low resolution and/or model biases. Additionally, Ecocrop's sole reliance on temperature variables in this study neglects the complex physiology of mandarin trees, resulting in a poor estimation of their suitable area.

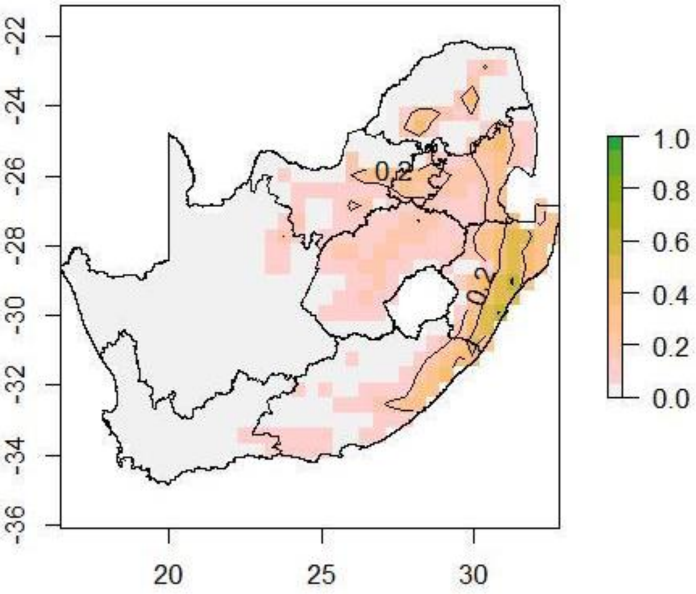

Figure 29: Historical mandarin suitability (aggregate)

Grapefruit

Historical suitability for grapefruit is very marginal to unsuitable over the whole country except the eastern escarpment where suitability score is 0.4 – 0.5, or marginally suitable. The most suitable area for grapefruit is the KwaZulu Natal midlands, reaching a score of 0.8. Grapefruit are grown in Limpopo (56%), Mpumalanga (20%), KwaZulu Natal (10%), and Northern Cape (6%) (Citrus Growers Association, 2022). The known presences concur with the historical suitability calculated by Ecocrop.

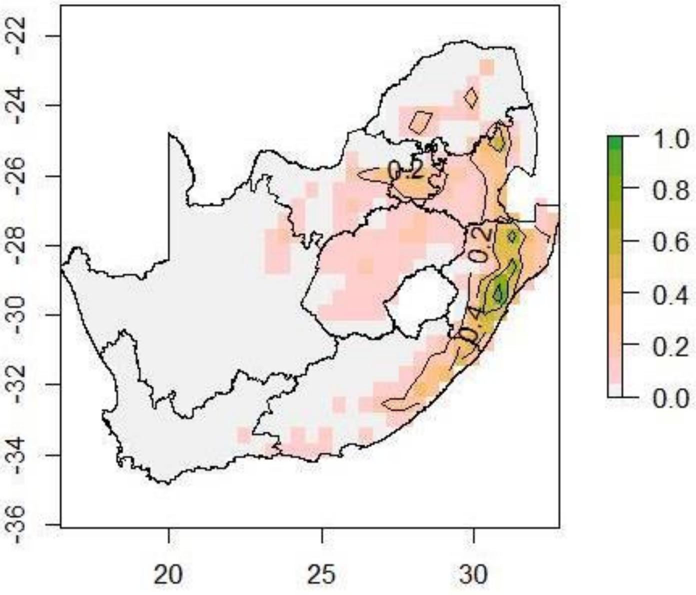

Figure 30: Historical grapefruit suitability (aggregate)

Pome fruit

Apples and pears thrive in a temperate climate, with cold wet winters followed by a cool summer, such as in the Western Cape. Figure 31 shows the pome fruit production areas in South Africa.

Apples

Known presences of apple orchards are in the Western Cape (about 80 percent, predominantly Ceres and Groenland), Free State, and Mpumalanga. Historically, apple suitability is greatest along the east coast of South Africa and the highveld region (figure 32). The lowveld also has areas of marginal apple suitability (0.41-0.6). Most of KwaZulu Natal and Mpumalanga is 'highly suitable' (scores greater than 0.8), covering 10.3% of the land area, while 5.3% is 'suitable'. Suitability decreases westward, and most of South Africa is considered unsuitable, having scores lower than 0.2. The high suitability scores in Mpumalanga, and moderate suitability scores in the Free State instil some confidence in Ecocrop for future apple suitability projections, however, the Western Cape which is the main apple growing region is estimated as unsuitable for apples, which substantially reduces the confidence in our results. The failure to capture suitable areas in the Western Cape may be due to the inability of the GCMs to capture small scale processes in this mountainous area, due to low resolution and/or model biases. Additionally, Ecocrop's sole reliance on temperature variables in this study neglects the complex physiology of apple trees, such as their winter chill requirement, resulting in a poor estimation of their suitable area. .

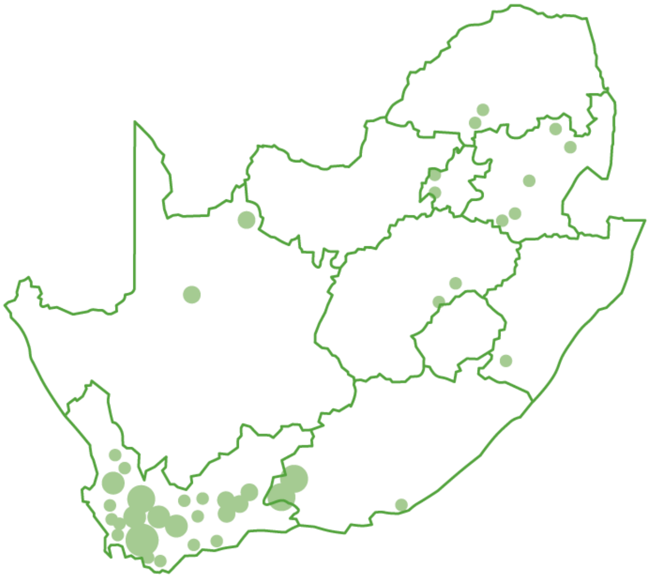

Figure 31: Pome fruit-growing regions of South Africa. Western Cape: Ceres, Groenland, Villiersdorp/Vyeboom, Wolseley/Tulbagh, Klein Karoo, Southern Cape, Langkloof West, Piketberg, Somerset West, Stellenbosch, Worcester, Paarl, Franschhoek; Eastern Cape: Langkloof East; Limpopo, Northern Province, North West, Mpumalanga, Free State (source: Post-Harvest Innovation Programme, 2022)

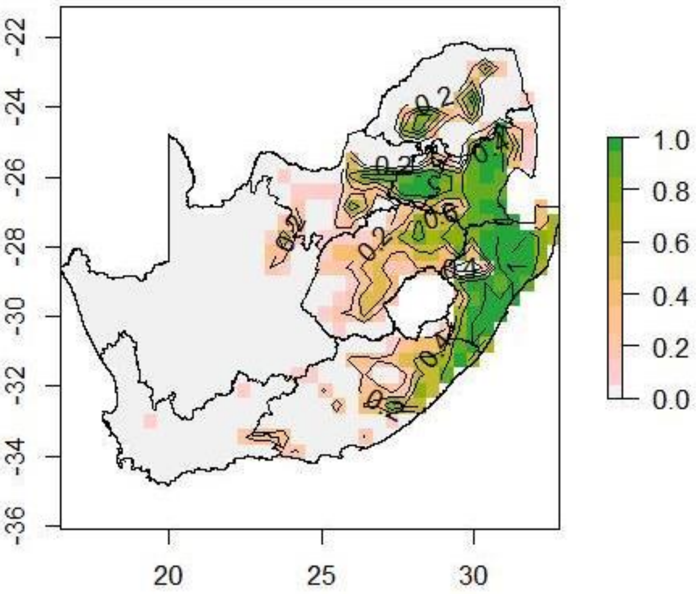

Figure 32: Historical apple suitability (aggregate)

Pears

About 79 percent of South Africa’s pear production occurs in the Western Cape with Ceres dominating the production (37 percent) and 13 percent coming from Groenland (Hortgro, 2019). Ecocrop fails = to capture suitable areas in the Western Cape, which may be due to the inability of the GCMs to capture small scale processes in this mountainous area, due to low resolution and/or model biases. Additionally, Ecocrop’s sole reliance on temperature variables in this study neglects the complex physiology of pear trees, such as winter chill requirements, resulting in a poor estimation of their suitable area. The remainder of South Africa’s pears are grown in the Eastern Cape and Mpumalanga, both of which Ecocrop considers moderately suitable for pears (figure 33). This poor performance by the suitability model gives low confidence in the results for future pear suitability results. Ecocrop predictions indicate that South African climate is largely unsuitable for pear production in the historical period, with most of the country being completely unsuitable to very marginal for pear production. The historical period had good suitability scores along the east coast of KwaZulu Natal, with the highest suitability score being 0.8 in northern KZN. 3.3% of the land area was ‘suitable’ or ‘highly suitable.’ The eastern and central provinces had areas which are marginally suitable (scores of 0.2 - 0.6).

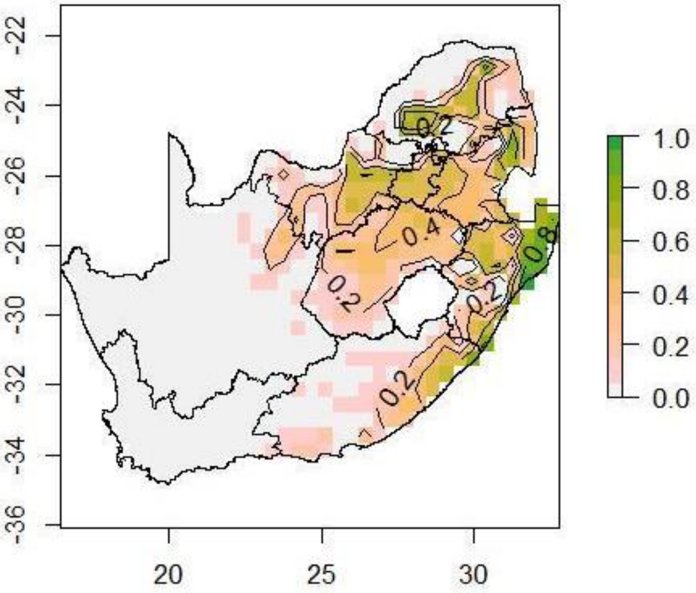

Figure 33: Historical pear suitability (aggregate)

Stone fruit

Peaches and plums are best suited to temperate climates which experience warm summers for good colour development and ripening; and cool winters to achieve sufficient chilling to enter winter dormancy. Dessert peaches are primarily grown in the Western Cape (70 percent) with large proportions coming from Ceres, Klein Karoo, and Citrusdal, Northern Provinces (16.6 percent), Free State (5.7 percent) and Mpumalanga (3.7 percent). 97 percent of cling peaches are grown in the Western Cape with over half (51 percent) coming from the Klein Karoo, followed by Ceres (13 percent), Wolseley/Tulbagh (11 percent) and Worcester (6 percent). Mpumalanga is the second largest cling peach producer, producing 1.3 percent of the country's supply. More than 99 percent of South Africa's plums are grown in the Western Cape, with the Klein Karoo producing 30 percent and Wolseley/Tulbagh producing 12 percent (Hortgro, 2019). A map of stone fruit production areas is shown in figure 34.

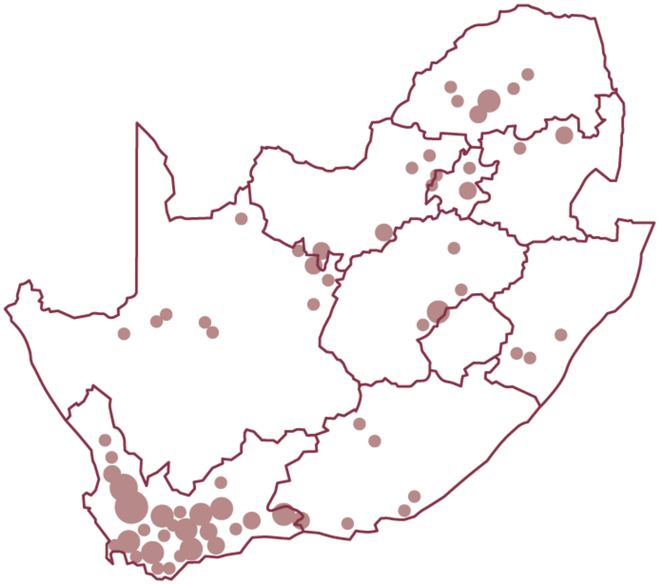

Figure 34: Stone fruit-growing regions of South Africa. Western Cape: Klein Karoo, Villiersdorp/Vyeboom, Wolseley/Tulbagh, Paarl, Worcester, Piketberg, Stellenbosch, Southern Cape, Franschhoek, Groenland, Langkloof West, Somerset West, Cape Town; Eastern Cape: Langkloof East; Northern Province, Limpopo, Mpumalanga, Free State, North West, Gauteng, Northern Cape, KwaZulu Natal (source: Post-Harvest Innovation Programme, 2022)

Peaches

Ecocrop model predictions suggest that the historical climate in South Africa is unsuitable for pear production, apart from the east coast and the highveld which have very marginally suitable areas (0.2 – 0.3). Peaches are primarily grown in the Western Cape, Limpopo, Free State, North West, and Mpumalanga (Hortgro, 2019). While the Western Cape is computed as unsuitable for peaches, the remainder of the known presence points align somewhat with Ecocrop's estimated suitable areas (figure 35). The failure of Ecocrop to capture highly suitable areas over the country is likely due to the model not taking into account physiological factors such as winter chilling and temperature requirements at different growth phases. This inability to accurately capture suitable areas for peaches gives us low confidence in the future suitability projections for peaches.

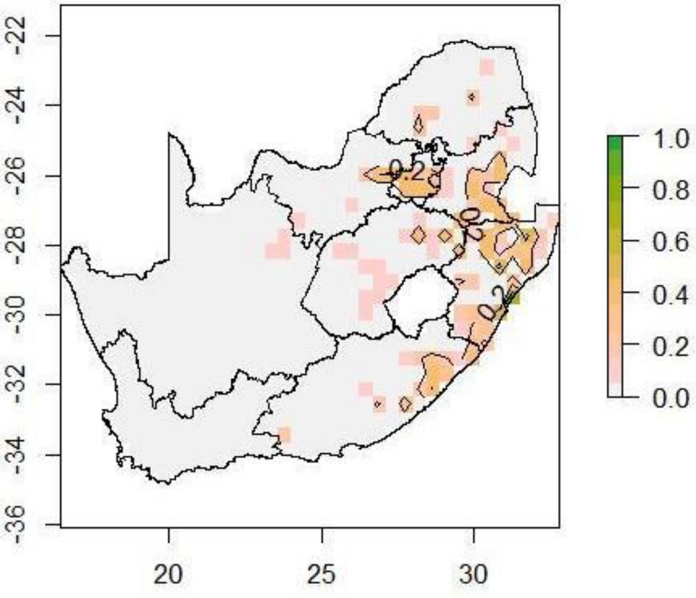

Figure 35: Historical peach suitability (aggregate)

Plums

For the historical period, plums were most suitable on the east coast, with 1.2% land area having a suitability score above 0.6. The highveld had areas of marginal suitability (0.41-0.6), while the lowveld and the rest of the country were very marginally suited or unsuited to plum production (Figure 52). The vast majority (99%) of plums are grown in the Western Cape, followed by Limpopo, North West, Gauteng and the Eastern Cape (Hortgro, 2019). While the Western Cape is computed as unsuitable for plums, the remainder of the known presence points align somewhat with Ecocrop's estimated suitable areas (figure 36). . The failure of Ecocrop to capture highly suitable areas for plum production is likely due to the model not factoring in physiological factors such as winter chilling and temperature requirements at different growth phases. This inability to accurately capture suitable areas for plums gives us low confidence in the future suitability projections for the crop.

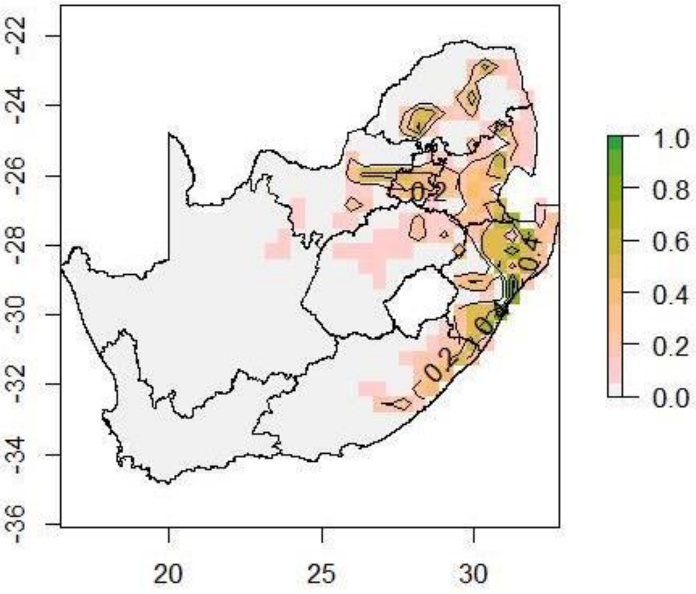

Figure 36: Historical plum suitability (aggregate)

Table grapes

Grapes prefer a temperate and Mediterranean climate with mild winters, a frost-free spring, sunny summer, and rainfall that occurs mainly in winter. This explains why, in South Africa, more than 80 percent of table grapes are grown in the Western Cape in the valleys of the Hex, Berg and Olifants Rivers. The Orange River region in the Northern Cape and the Olifants River region in Limpopo are also high producing regions, as depicted in Figure 37. Other production areas include the Eastern Cape, Free State, and Mpumalanga (DAFF, 2012; SATGI, 2020). Table grapes are 'unsuitable' over the western half of the country in the historical period, whereas parts of the interior and the east coast, making up 8% of the total land area, have 'very marginal' grape suitability (0.21-0.4). While the grape producing regions in the Western Cape and Northern Cape were not captured by Ecocrop (figure 38), some of the known presence locations in Limpopo, Free State and Mpumalanga aligned with suitable regions. The failure of Ecocrop to capture suitable areas over the country is likely due to the model not taking into account the vines' physiological factors such as winter chilling and temperature requirements at different growth phases. This result instils low confidence in Ecocrop's ability to predict future changes in suitable areas for table grape production.

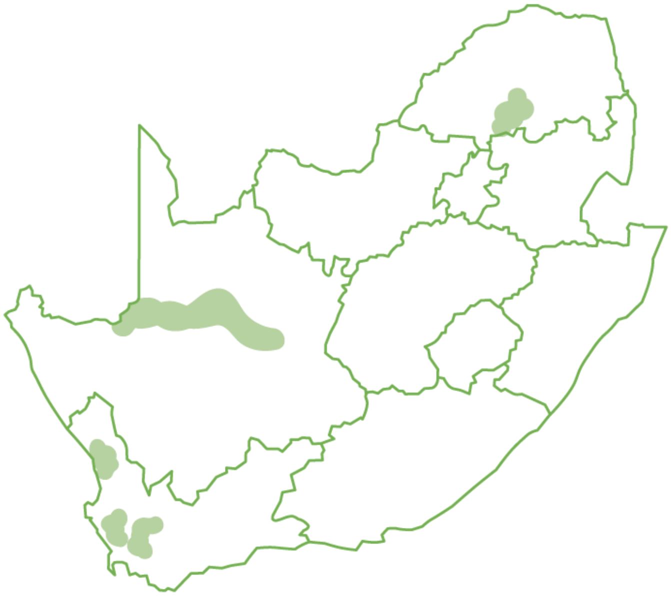

Figure 37: Table grapes growing regions of South Africa. Hex River Valley: from Worcester to De Doorns (includes Brandwag, De Wet, Nonna and Nuy); Berg River Valley: Piketberg, Porterville, Saron, Riebeeck-Kasteel, Paarl; Lower Orange River: from Pofadder to Schmidtsdrift; Nothern Province: Marble Hall, Brits, Laphalale and Mokopane; Olifants River Valley: from Citrusdal to Lutzville (source: Post-Harvest Innovation Programme, 2022)

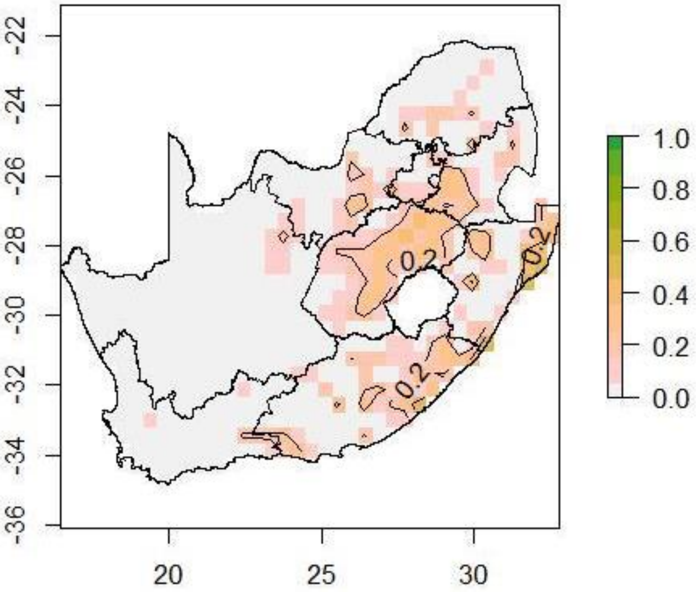

Figure 38: Historical grape suitability (aggregate)

4.2.2. Changes in climatic suitability under climate change

Citrus

Oranges

The bar graph in Figure 39 illustrates the areas of suitability categories for oranges for the different study periods and RCP scenarios. In the historical period, 0.17% of South Africa's land area was classified as 'suitable' and 0% was 'highly suitable'. 'Suitable' land area increased to 0.51% and 0.68% in MID-45 and MID-85 respectively, while both these mid-century cases had 0.17% 'highly suitable' land. 'Suitable' land area increased to 0.68% by the end of the century under RCP8.5, however, 'highly suitable' land decreased to zero. Under END-85, the 'suitable' and 'highly suitable' land areas increase to 1.54% and 0.34% respectively.

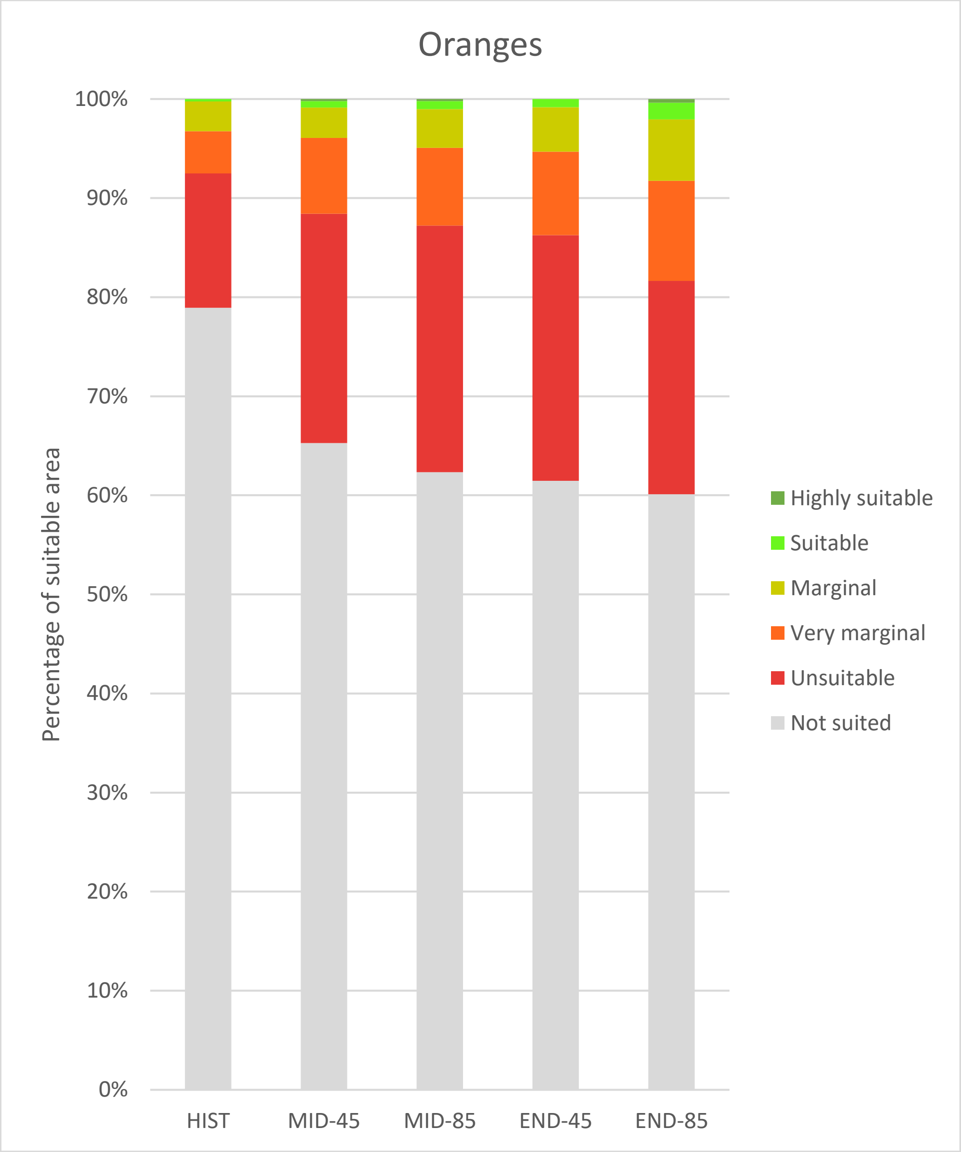

Figure 39: Percentage of land area classified by suitability categories for orange production

Figure 40 shows the spatial change in orange suitability into the 21st century. There is a distinct area of suitability score increase for oranges along the eastern escarpment and the highveld region of Mpumalanga and Limpopo (see Figures 10 and 11 for geographical reference) into the 21st century. This pattern is evident in all cases but strengthens toward the end of the century and under END-85, in which case, suitability score increases as much as 0.6, and orange suitability becomes 'highly suited' with scores reaching 0.8 along the escarpment in KZN. However, decreases in orange suitability along the east coast and the lowveld are seen in END-85, although this signal is weak.

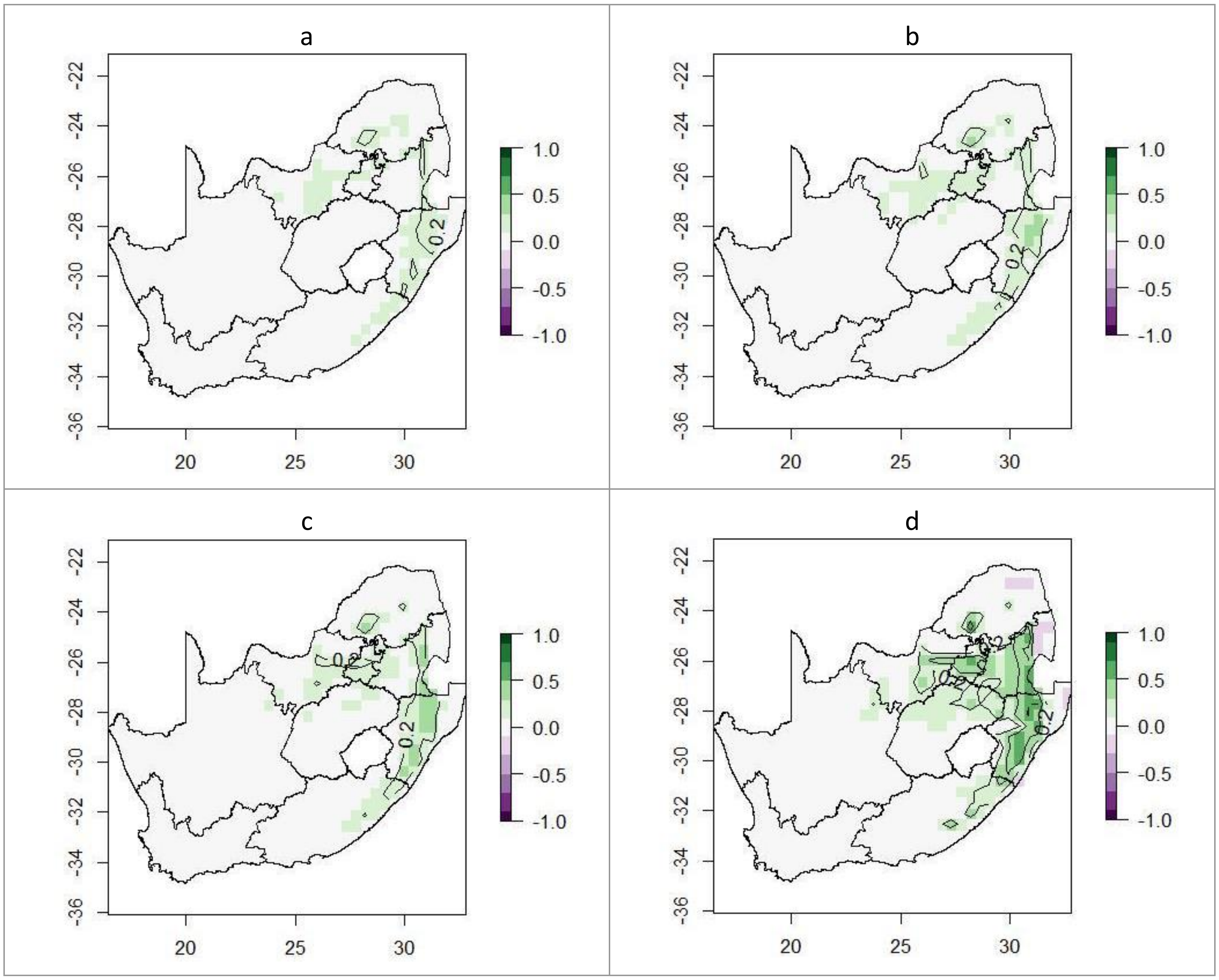

Figure 40: Orange suitability score anomalies historical period to (a) MID-45, (b) MID-85, (c) END-45 and (d) END-85

Lemons

Figure 41 illustrates the percent of land area characterized by each suitability classification. 1.71% of the land area was ‘suitable’ and 2.91% was ’highly suitable’ for lemons in the historical period. Suitable land area increased in all cases, although there was little difference in suitable land area for MID-45, MID-85 and END-45, which had sum total ‘suitable’ and ‘highly suitable’ land area percentages of 10.8%, 12.5% and 12.5% respectively. END-85 saw the largest increase in suitable land for lemons, with 9.1% classified as ‘suitable’ and 11% as ‘highly suitable’.

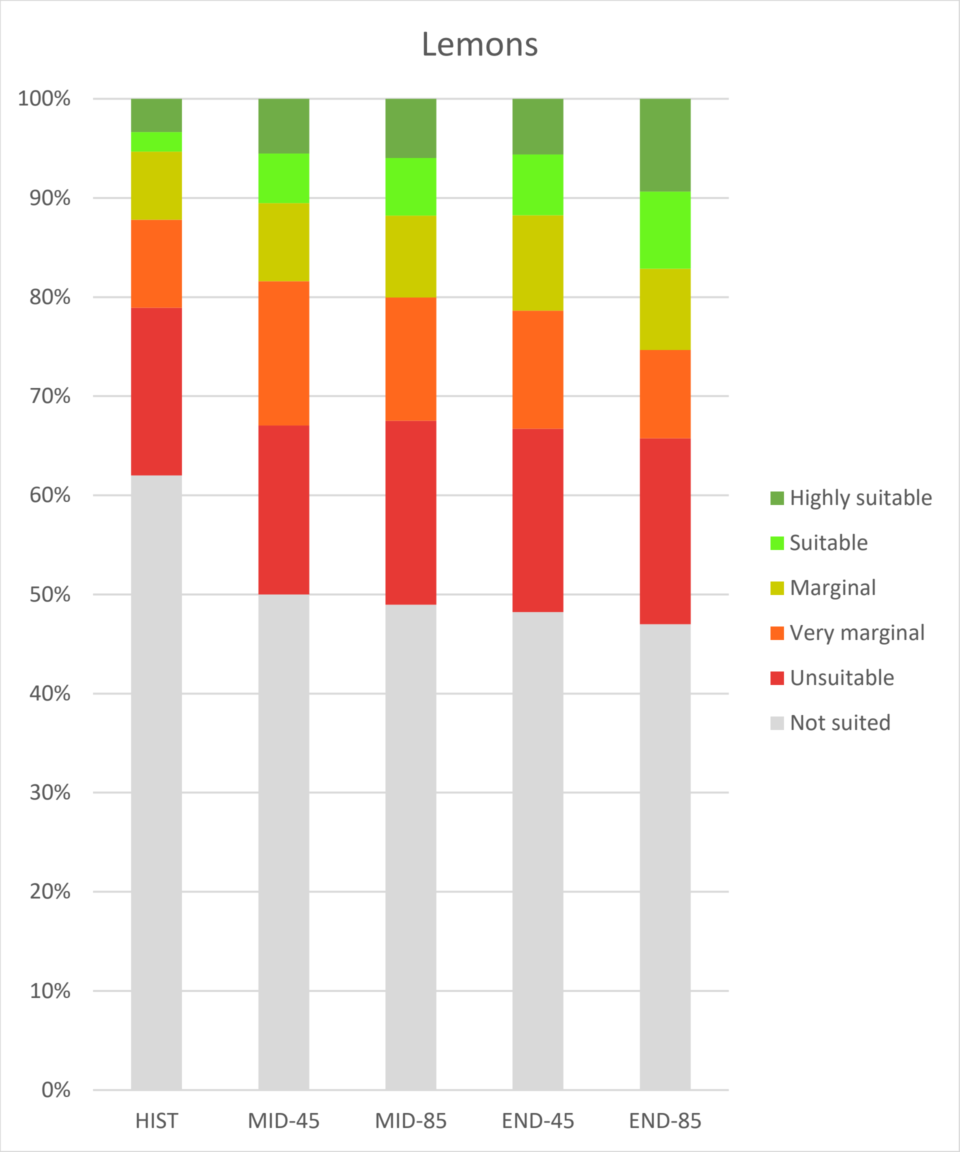

Figure 41: Percentage of land area classified by suitability categories for lemon production i

Once again, the increasing suitability pattern along the eastern escarpment and the highveld can be seen for lemons (Figure 42). The increases in lemon suitability are very large, mostly between 0.4 and 0.7 over the entire eastern escarpment and the highveld extending westward into the arid Northern Cape region.

The lowveld region in Limpopo experiences decreases in lemon suitability, strongest in END-85 which had a decrease of 0.2 – 0.3.

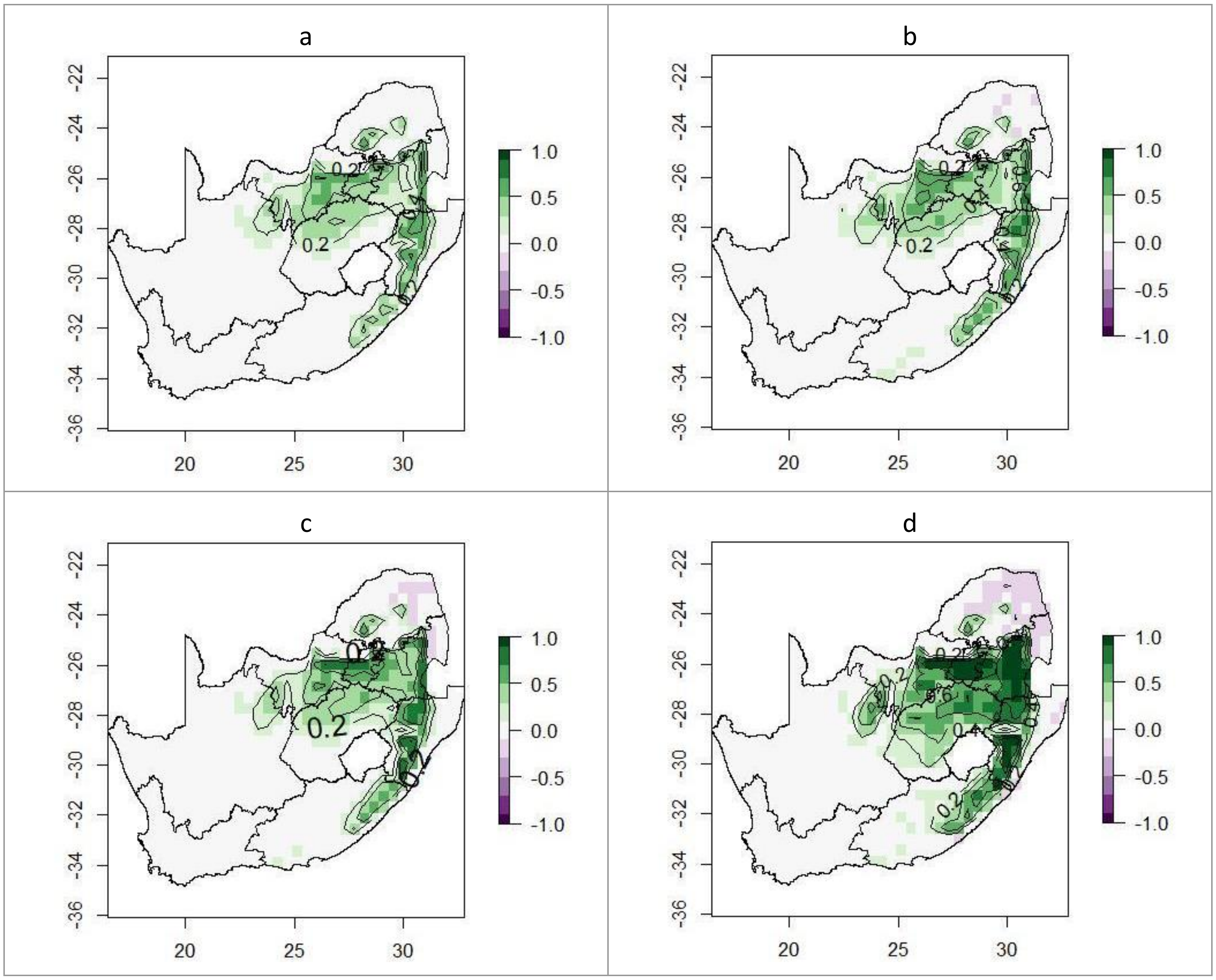

Figure 42: Lemon suitability score anomalies from historical period to (a) MID-45, (b) MID-85, (c) END-45 and (d) END-85

For the mid-century period, lemon suitability scores increased over the areas mentioned above for all models under both MID-45 and MID-85. Suitability remains highest along the east coast, particularly in KwaZulu Natal, reaching a maximum score of 1 in some regions, and decreasing inland. North West and Mpumalanga also have regions which are ‘suitable’ to ‘very suitable’. The results indicate that RCP8.5 is more favourable for lemon suitability than RCP4.5 during the mid-century period. Large improvements in lemon suitability are seen at the end-of-century period, especially in END-85. The high-altitude regions of the Free State, Gauteng and Mpumalanga which were previously unsuitable become marginally to very suitable. However, the east coast and lowveld experience decreased lemon suitability, especially in END-85.

Mandarins

For none of the cases was any land considered 'highly suitable' for mandarins (figure 43). 2.1% of land area was 'marginally suitable' in the historical period. 'Marginally suitable' land increased to between 2.9% and 3.1% in all future cases. Under RCP4.5, 'suitable' land increased from 0% in the historical period to 0.17% in both mid-century and end-of-century periods, and to 0.34% in under RCP8.5 for both future periods.

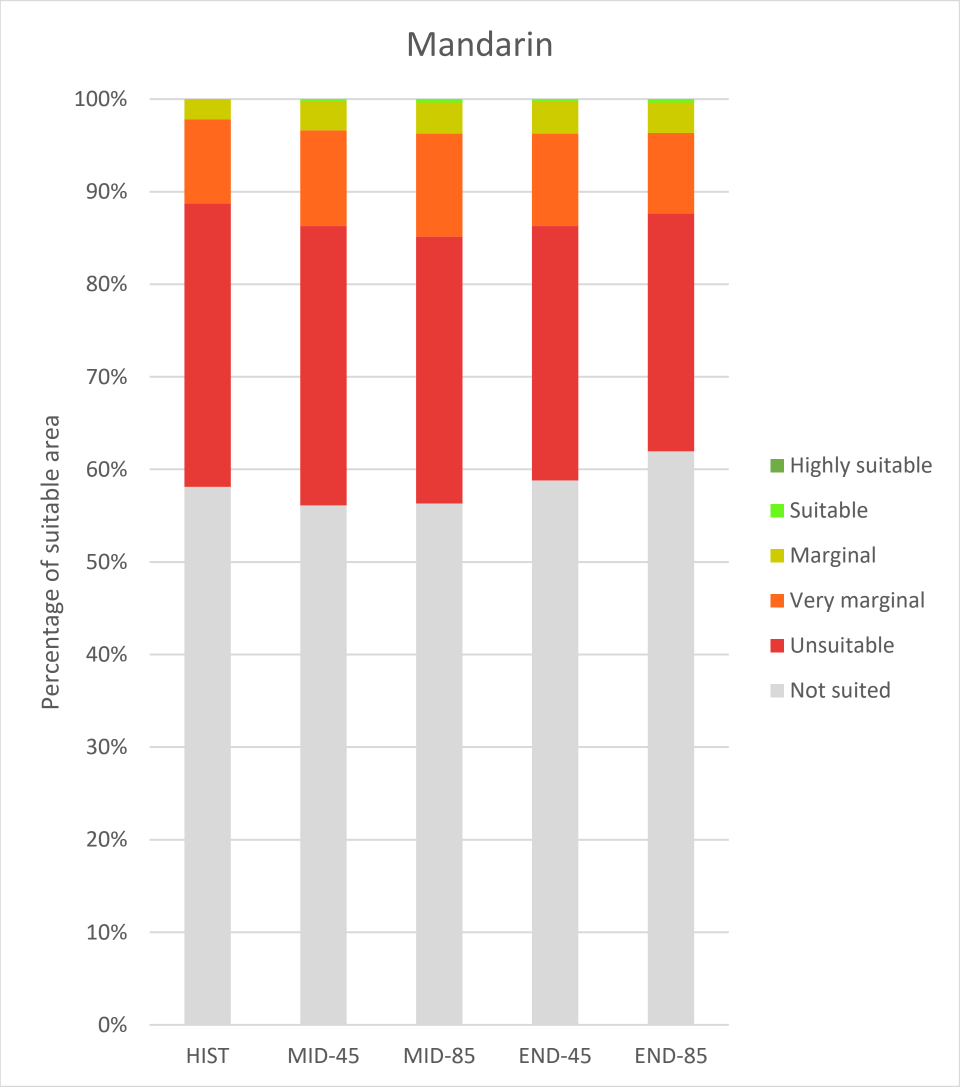

Figure 43: Percentage of land area classified by suitability categories for mandarin production

Suitability score distribution for mandarin remain relatively unchanged for all cases. Slight suitability increases are seen along the eastern escarpment, strengthening by 0.2 in END-85. Suitability scores in the west remain constant (zero) throughout (figure 44).

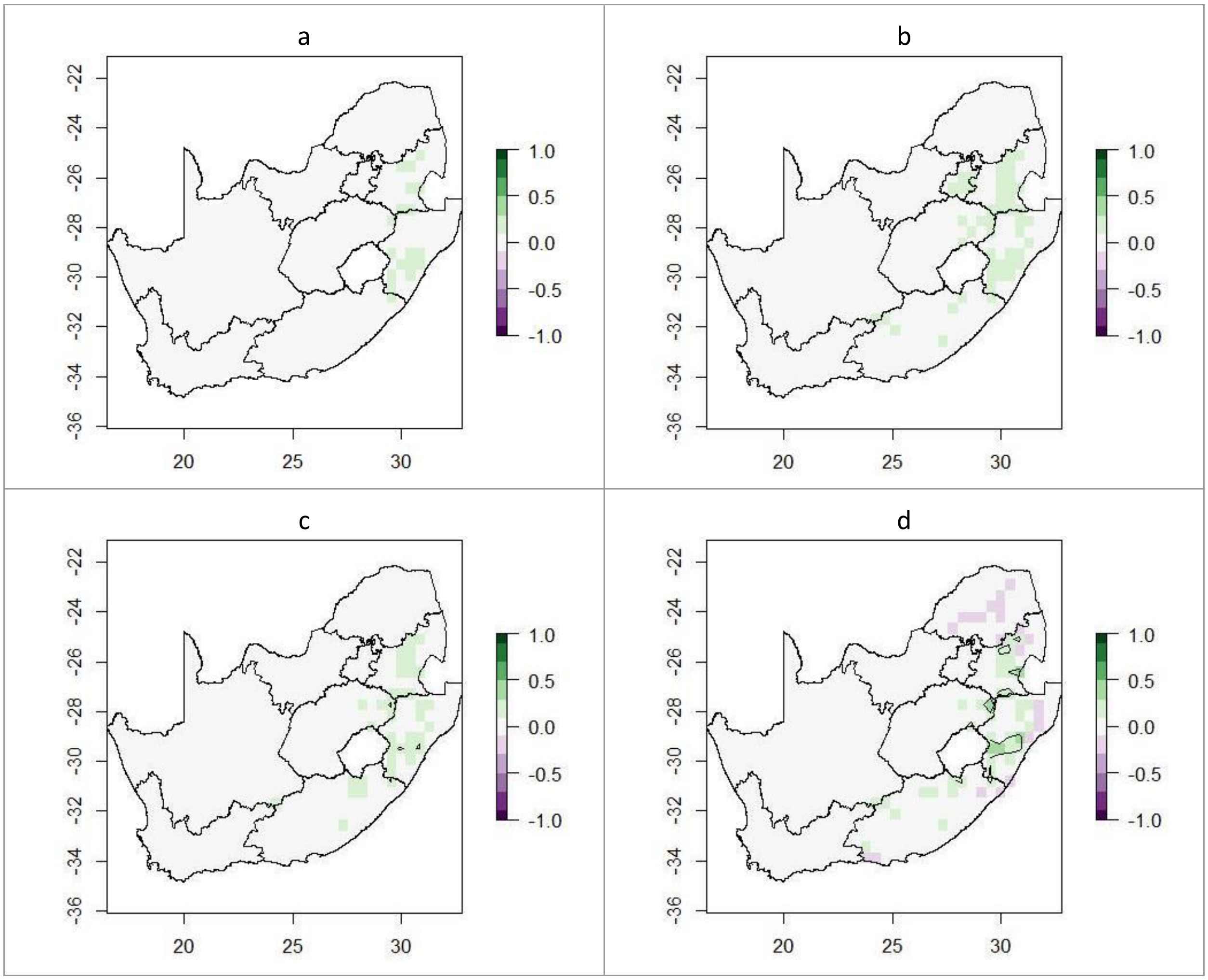

Figure 44: Mandarin suitability score anomalies historical period to (a) MID-45, (b)MID-85, (c) END-45 and (d) END-85

Grapefruit

‘Highly suitable’ land for grapefruit increased from 0.17% in the historical period to 0.34% in the mid-century under both RCPs, and then decreased to zero in the end-of-century period under both RCPs (figure 45). ‘Suitable’ land remained constant at 0.51% from the historical period to the mid-century under both

RCPs, and increased to 0.68% in END-45, while it decreased to 0.34% in END-85. ‘Marginally suitable’ land followed a similar pattern increasing in the mid-century and decreasing in the end-of-century. The changes in suitable land area are negligible in the mid-century, although there is a clear but small decrease in suitable land area in the end of the century.

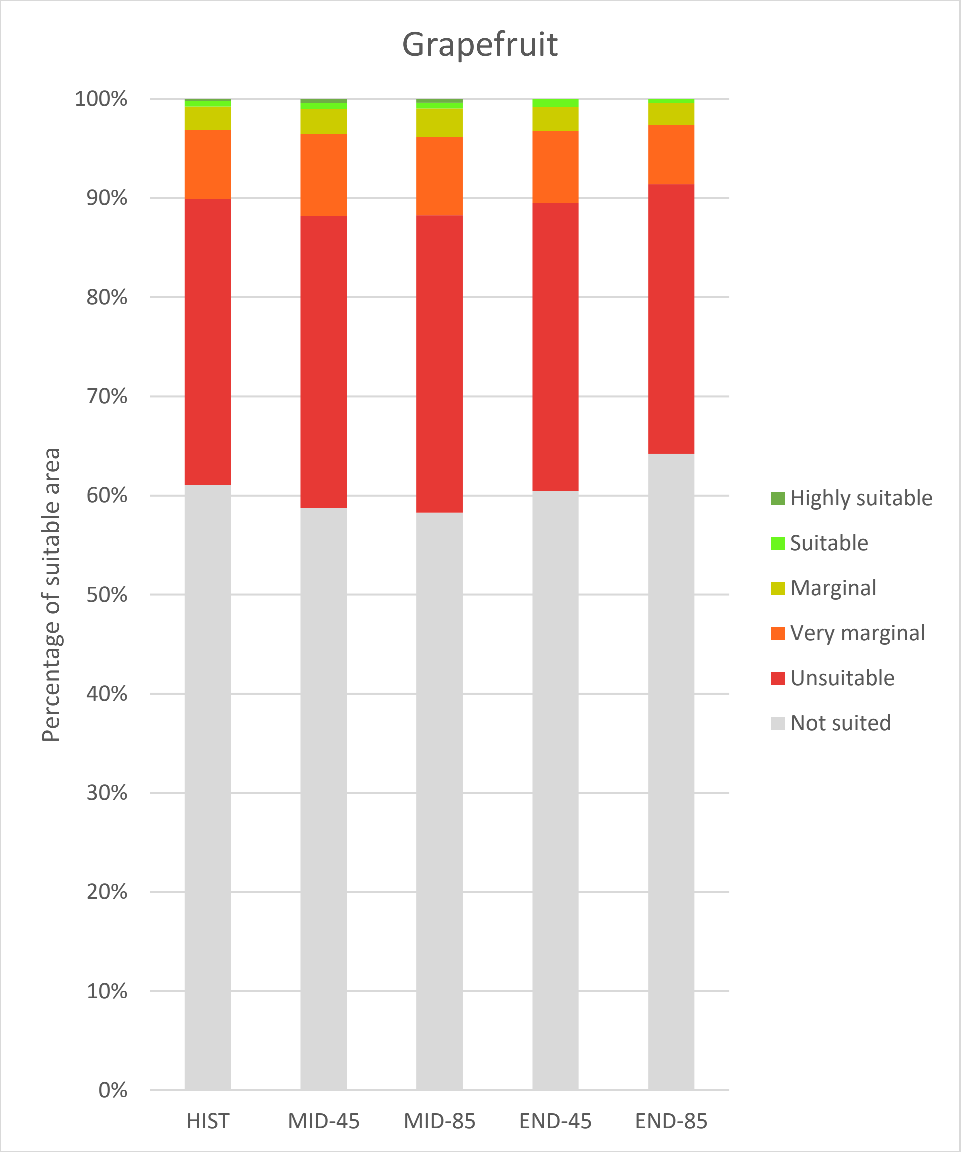

Figure 45: Percentage of land area classified by suitability categories for grapefruit production

The same pattern of increased suitability along the eastern escarpment as seen for mandarin is projected for grapefruit in all cases, although the effect is weak. END-85 also sees spotty decrease in grapefruit suitability along the east coast and the lowveld (figure 46)

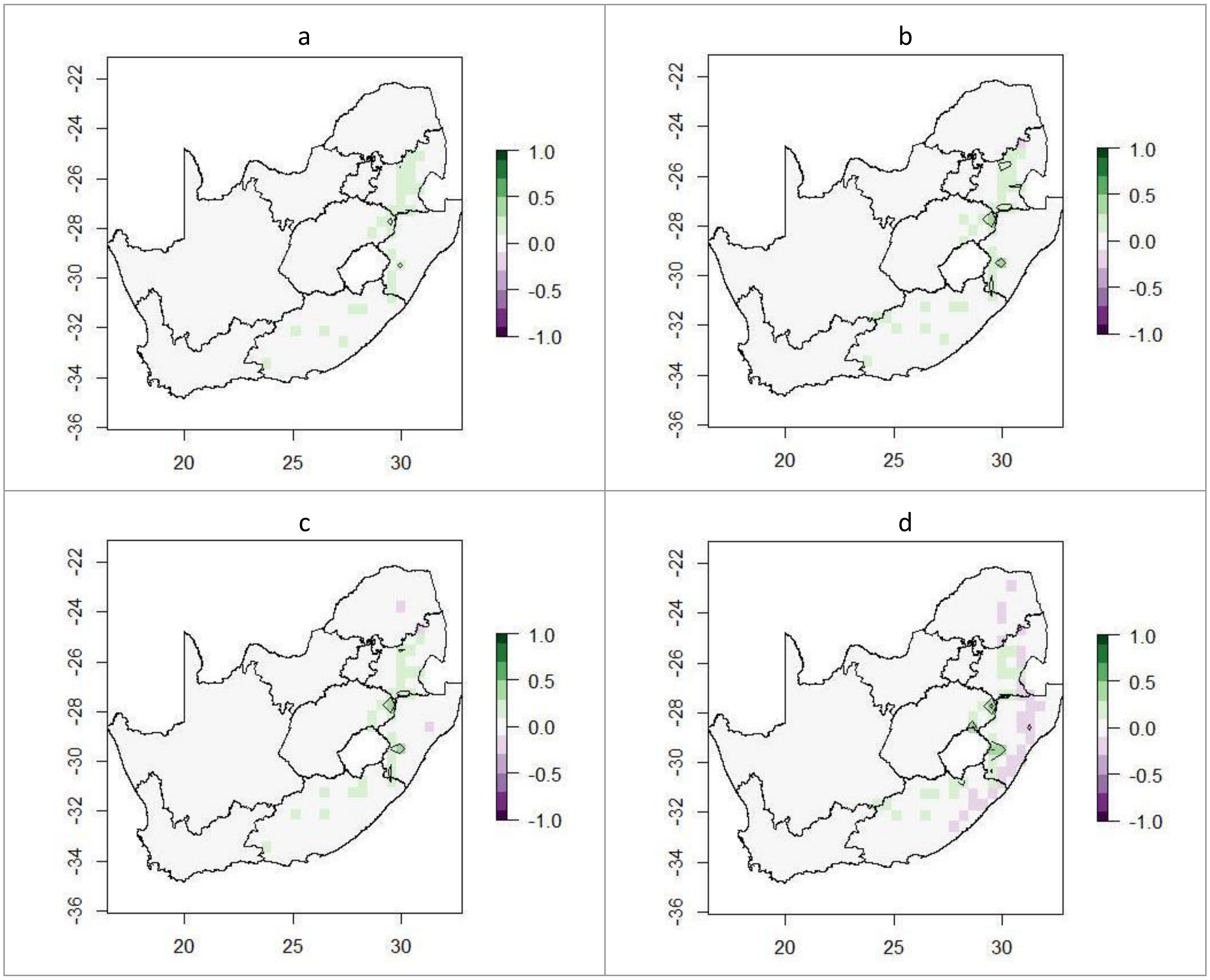

Figure 46: Grapefruit suitability score anomalies from historical period to (a) MID-45, (b) END-45, (c) MID-85 and (d) END-85

Citrus suitability change

Projected changes in suitability for oranges, lemons, mandarins, and grapefruit all have a similar pattern, however, they vary in amplitude. Oranges and lemons have a similar response to climate changes in that they both experience strong, widespread, and consistent increases. This pattern is particularly strong for lemons, for which the largest improvements in suitability scores and suitable land area are projected. On the other hand, mandarins and grapefruit experience weaker spotty changes. Increased suitability is seen along the escarpment and the highveld and central interior, whereas decreased suitability is seen along the east coast and the lowveld. The decreasing trend extends southward to the Eastern Cape in the case of mandarin and grapefruit toward the end of the century. Although some suitability increases are evident in mandarins and grapefruit, there is a net decrease is suitable land area for these fruits.

The strong drying along the east coast and weak drying over the central interior over the course of the 21st century renders the region with an annual rainfall which falls in the optimum range for citrus growth, especially for oranges and lemons which have a greater optimal temperature range. All four citrus fruits decrease in suitability over parts of the lowveld under END-85, even though warming occurs at a similar rate here to the rest of the country. This region was already very hot in the historical period, so increases in temperature of 5-6°C in END-85 will push this region into extreme heat beyond their optimum range. This is especially true for lemons which have a much lower optimum maximum temperature of 28°C, explaining the strong decrease in lemon suitability in this area.

Pome fruit

Apples

'Highly suitable' land area increases from 10.3% in the historical period to 10.8% in the mid-century under both RCPs and decreases to 9.1% and 8.4% in END-45 and END-85 respectively. 'Suitable' land area decreases from 5.3% in the historical period to 4.1% in both mid-century cases, and further decreases to 3.6% in END-45 and 2.7% in END-85 (figure 47).

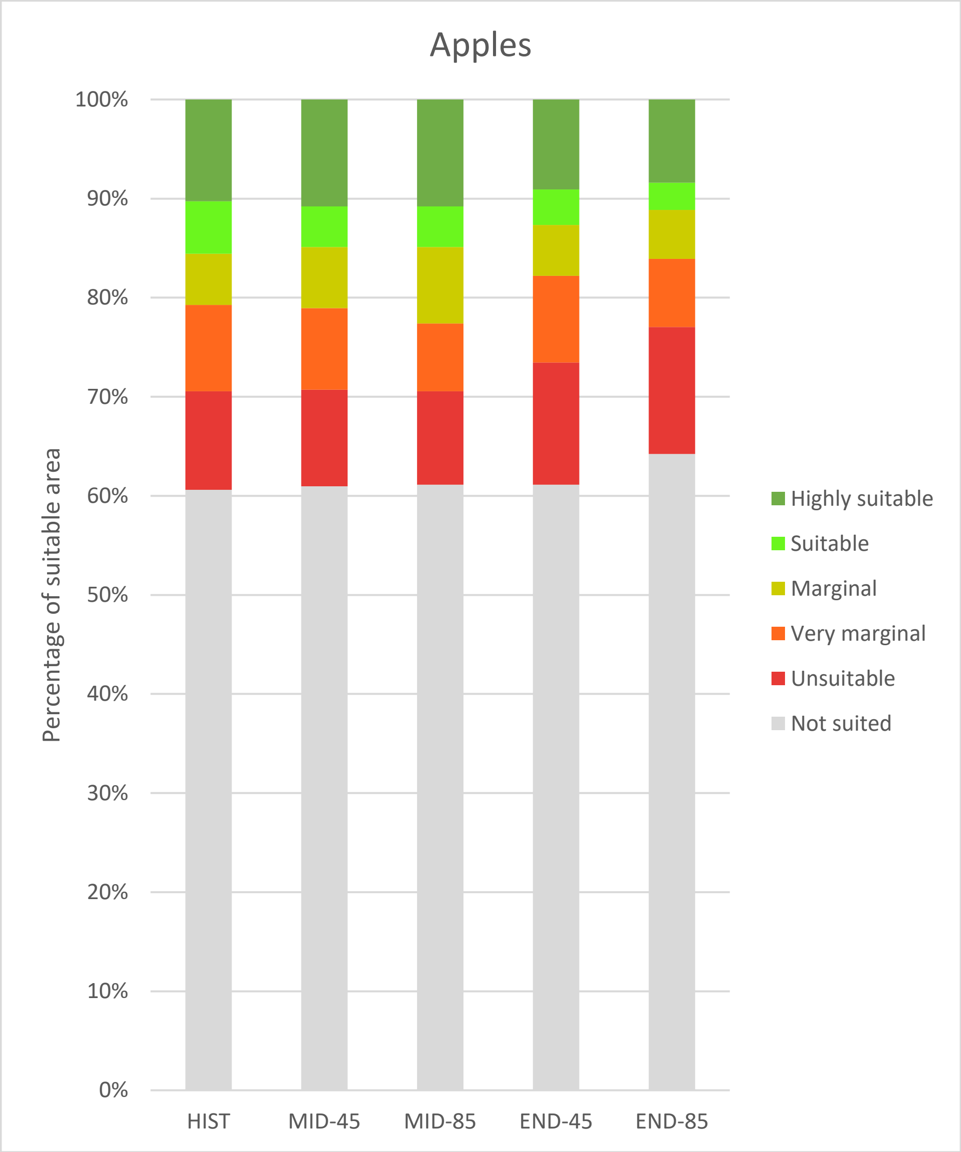

Figure 47: Percentage of land area classified by suitability categories for apple production

For both future time periods and both representative concentration pathways, apple suitability generally decreases in space, with a large portion of the country experiencing a negative change (figure 48). Apple suitability distribution increases around the Lesotho highlands and northern parts of the Eastern Cape, especially in END-85 in which suitability increases of up to 0.6 are projected. However, END-85 also sees the strongest and most widespread suitability decreases for apples. These impacts are spotty and negligible in the mid-century, and very mild in the end-of-century, having suitability score decreases of up to -0.2 and increases of between 0.1 to 0.3 under RCP4.5. These changes in suitability strengthen ever so slightly under RCP8.5 and are much stronger and more consistent by the end of the century. Suitability scores for the western half of the country remain unchanged throughout the 21st century under both RCPs. KwaZulu Natal and Mpumalanga remain very suitable for apple growth throughout.

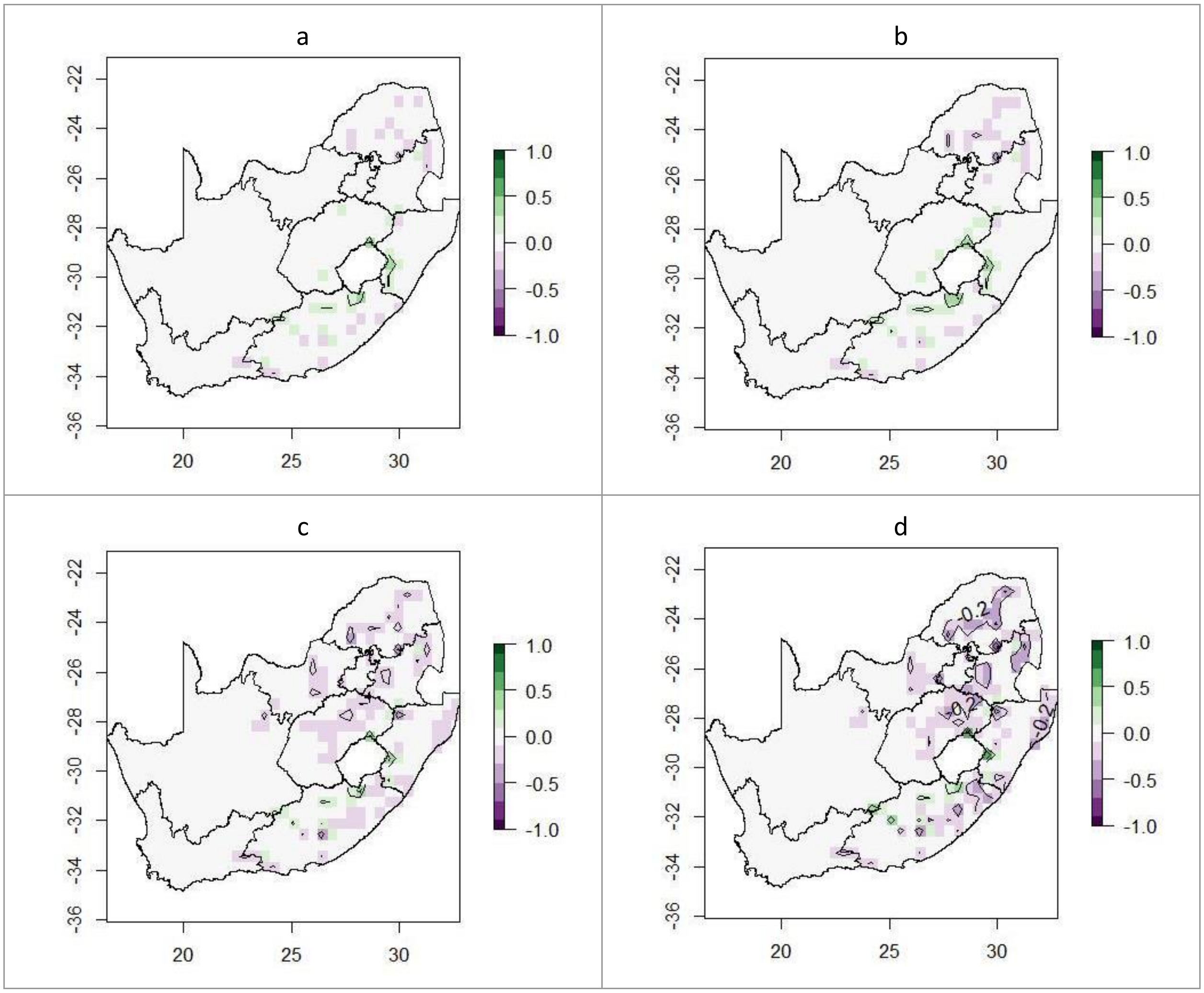

Figure 48: Apple suitability score anomalies from historical period to (a) MID-45, (b) END-45, (c) MID-85 and (d) END-85

Pears

'Highly suitable' land area for pears stayed relatively constant throughout the 21st century, although there is a slight decrease from the historical period in all future cases, while 'suitable' land area increased substantially from 2.4% in the historical period to 5.3% in MID-45 and 6.3% in MID-85, and 6.7% in END-45 and 9.2% in END-85 (figure 49).

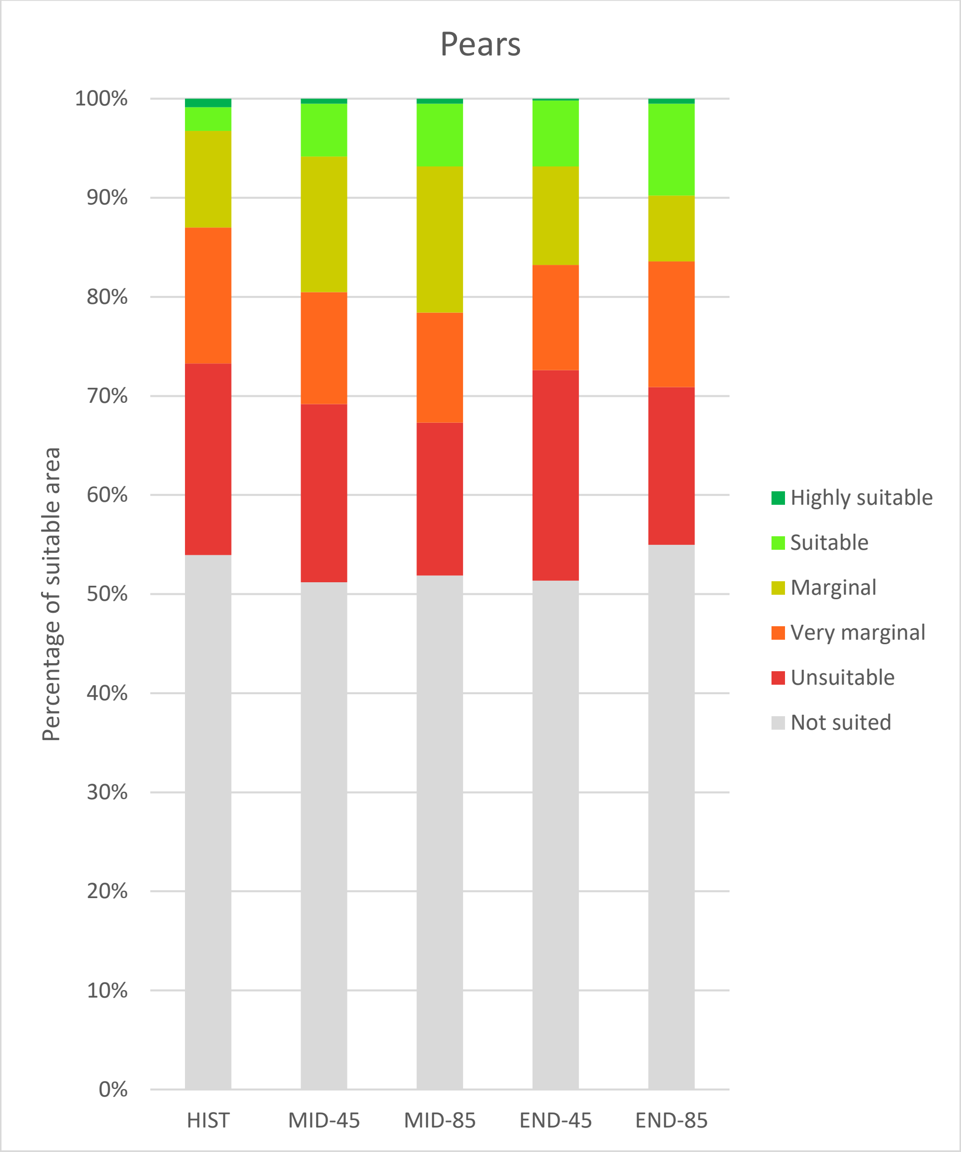

Figure 49: Percentage of land area classified by suitability categories for pear production

In all cases, pear suitability increases over the eastern escarpment and the highveld (figure 50). In END-45 and END-85, suitability decreases are projected for the lowveld of Limpopo and Mpumalanga, northern KwaZulu Natal and southern Eastern Cape. These effects are amplified in END-85, with projected suitability score increases of 0.4 and decreases of -0.4. Pear suitability scores in the west remain largely unchanged. Suitability remains marginal in the central provinces and good along the KwaZulu Natal coastline. Improvements in suitability along the escarpment and the highveld make this region fairly well suited (0.6-0.8) for pear production, especially in END-45 and END-85.

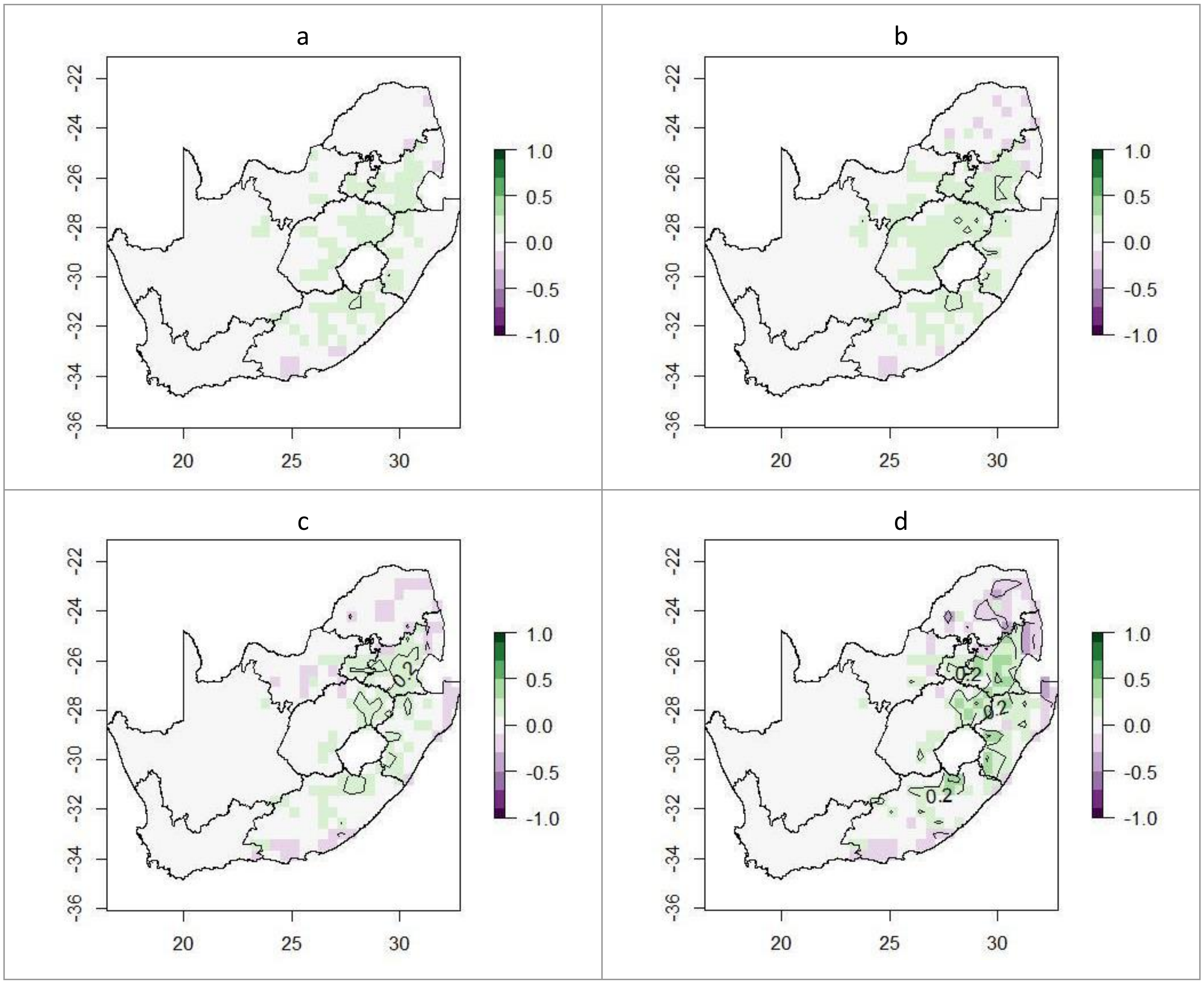

Figure 50: Pear suitability score anomalies from historical period to (a) MID-45, (b) END-45, (c) MID-85 and (d) END-85

Pome fruit suitability change

Both apples and pears have mixed suitability change predictions. In the mid-century period, there is no clear pattern of suitability change for apples, although some spotty increases are seen around the Lesotho highlands and some decreases in the northern interior. At the end-of-century, there is a much stronger and more consistent decreasing suitability signal for apples, where suitability decreases are widespread across the eastern and central provinces, although the Lesotho highlands and eastern midlands (which are 4.5-5°C hotter and 200-300 mm dryer in END-85) become increasingly suitable, there is a net decrease in suitable land area. In the case of pears, suitability increases over the eastern escarpment, Lesotho highlands, eastern midlands and the highveld, and decreases in the lowveld of Limpopo and Mpumalanga, northern KwaZulu Natal and southern Eastern Cape, resulting in a net increase in suitable land area. It is evident that pome fruit suitability increases in high lying land and decreases at lower altitudes.

Pears thrive in a warmer climate than apples, with a minimum optimum temperature 6°C higher than apples' and a maximum optimum 8°C higher than apples'. Apples can only tolerate a maximum temperature of 33°C. Apples generally have higher chilling requirements than pears (Table 4). The common apple varieties grown in South Africa have a high chilling requirement of 850 – 1000+ hours, while the common pear varieties have a more moderate chilling requirement of 450 – 850 hours, some low-chilling varieties as little as 200 hours (Kamas, Nisbett and Stein, 2015b). The reduction of winter chilling in all four future cases at Ceres, Klein Karoo and Groblersdal thus have a stronger negative impact on apples, particularly in Groblersdal which has 550 DPCUs in END-85.

Both pome fruit types prefer high altitude, but apples thrive between 1500 – 2700 m above sea level, while pears can tolerate altitudes as low as 600 m. Pears also require less annual rainfall (900 mm) compared to apples (1000 – 1250 mm).

. Countrywide warming pushes temperatures in these areas above the threshold. Pears, being more tolerant to high temperatures, thrive in these warming conditions over the eastern escarpment, Lesotho highlands and eastern midlands. Enhanced warming in the northern interior makes temperatures become too hot in the lowveld, which is why we see decreases in suitability in this area for both apples and pears.

Stone fruit

Peaches

None of South Africa's land area was classified as 'suitable' or 'highly suitable' for peaches in any of the cases. 'Marginally suitable' and 'very marginally suitable' land areas remained relatively constant from the historical period to the mid-century, while it decreased in the end-of-century period. 'Unsuitable' land area (score of 0-0.2) increased from the historical period to the mid-century and even more so in the end-of-century period.

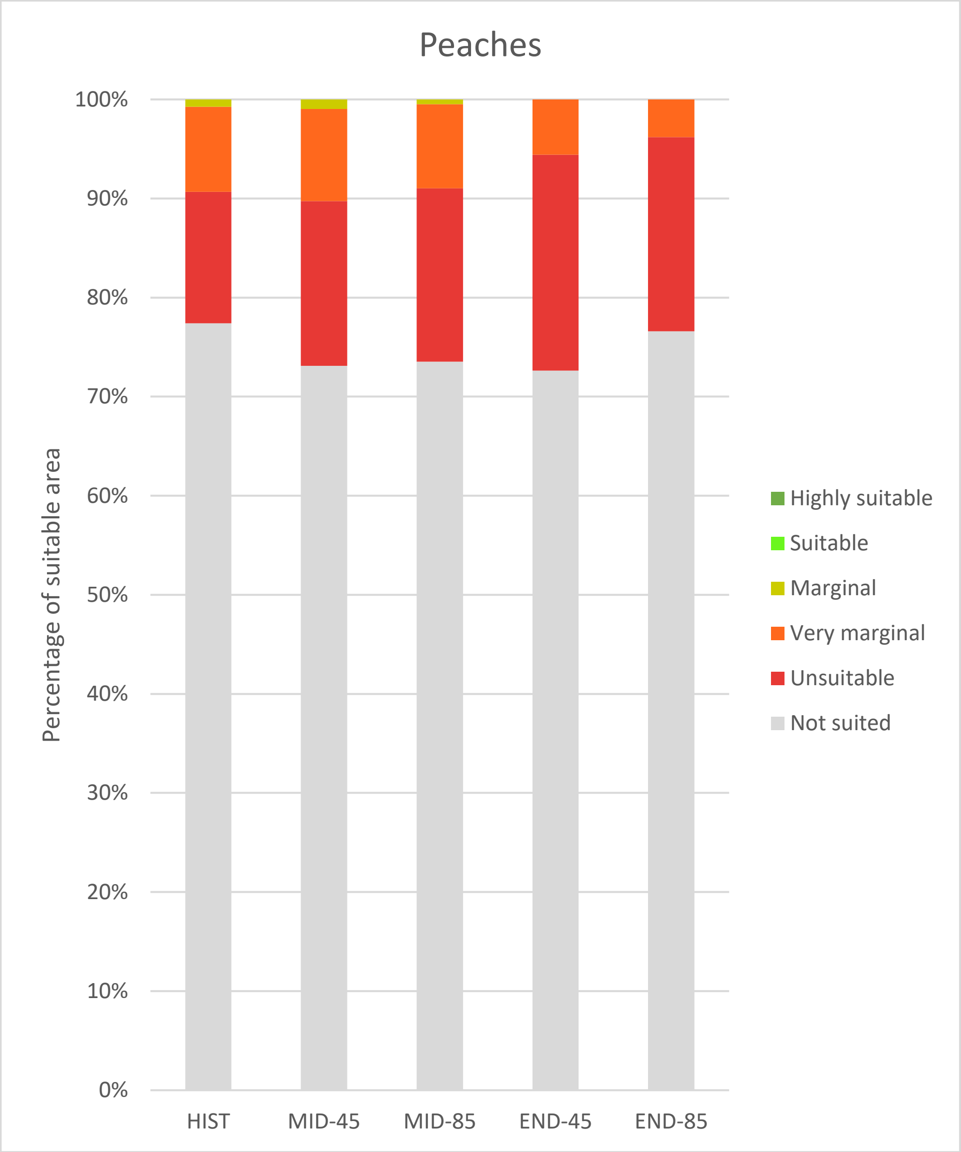

Figure 51: Percentage of land area classified by suitability categories for peach production

Peach suitability distribution changes in the mid-century are negligible. There are weak spotty decreases in suitability over the highveld at the end of the century (Figure 52). Peach suitability scores in the west remain unchanged in all cases.

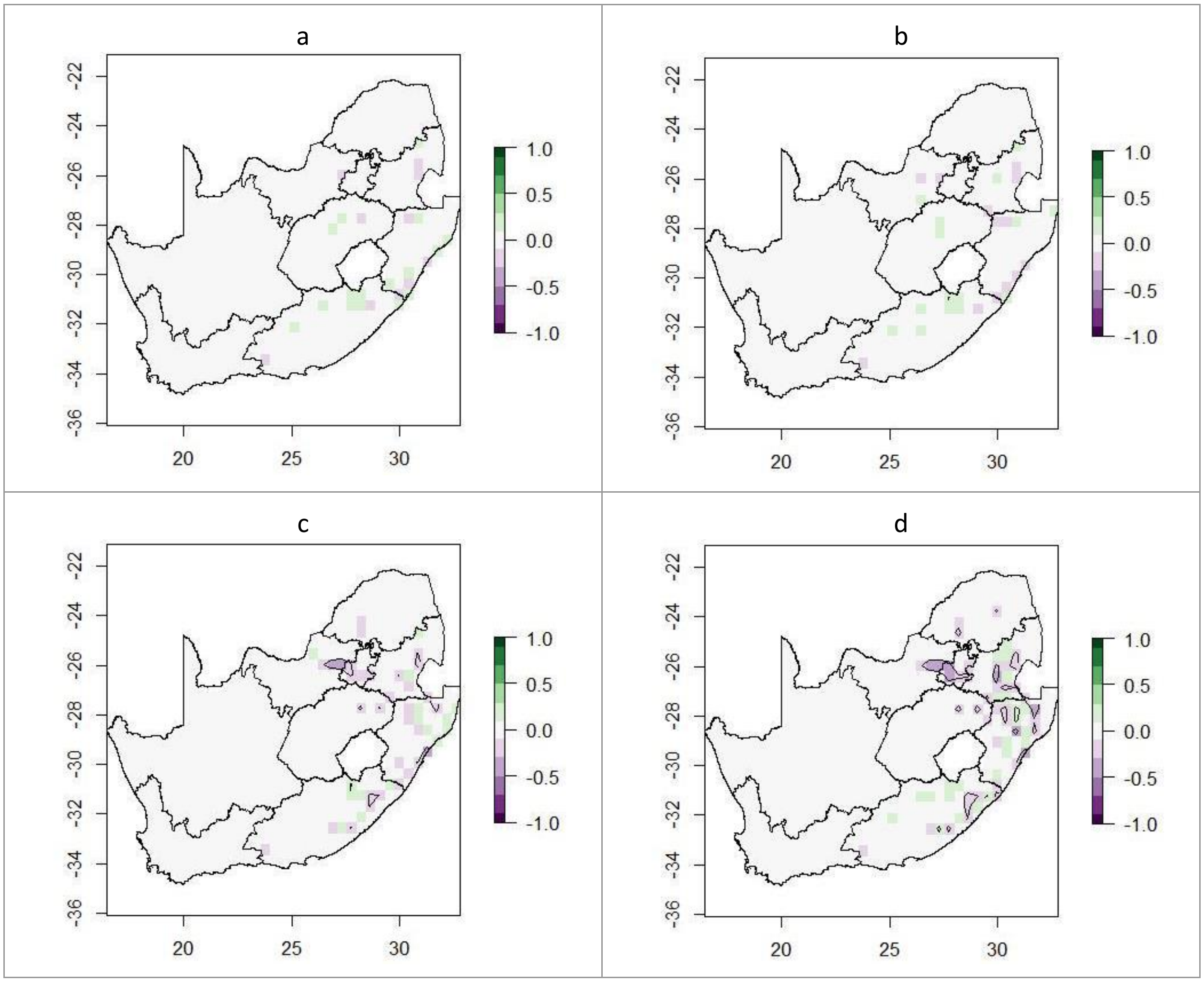

Figure 52: Peach suitability score anomalies from historical period to (a) MID-45, (b) END-45, (c) MID-85 and (d) END-85

Plums

‘Highly suitable’ land area increased from 0% in the historical period to 0.51% and 0.68% in MID-45 and MID-85, and 0.17% in END-45 while remaining at 0.68% in END-85. ‘Suitable’ land area shows an increasing pattern, with a particularly large increase in END-85, while ‘marginally suitable’ land area increases in MID-45, MID-85, and END-45, and then decreases substantially in END-85. This decrease is due to more land area becoming increasingly ‘suitable’ rather than a decrease in suitability (figure 53).

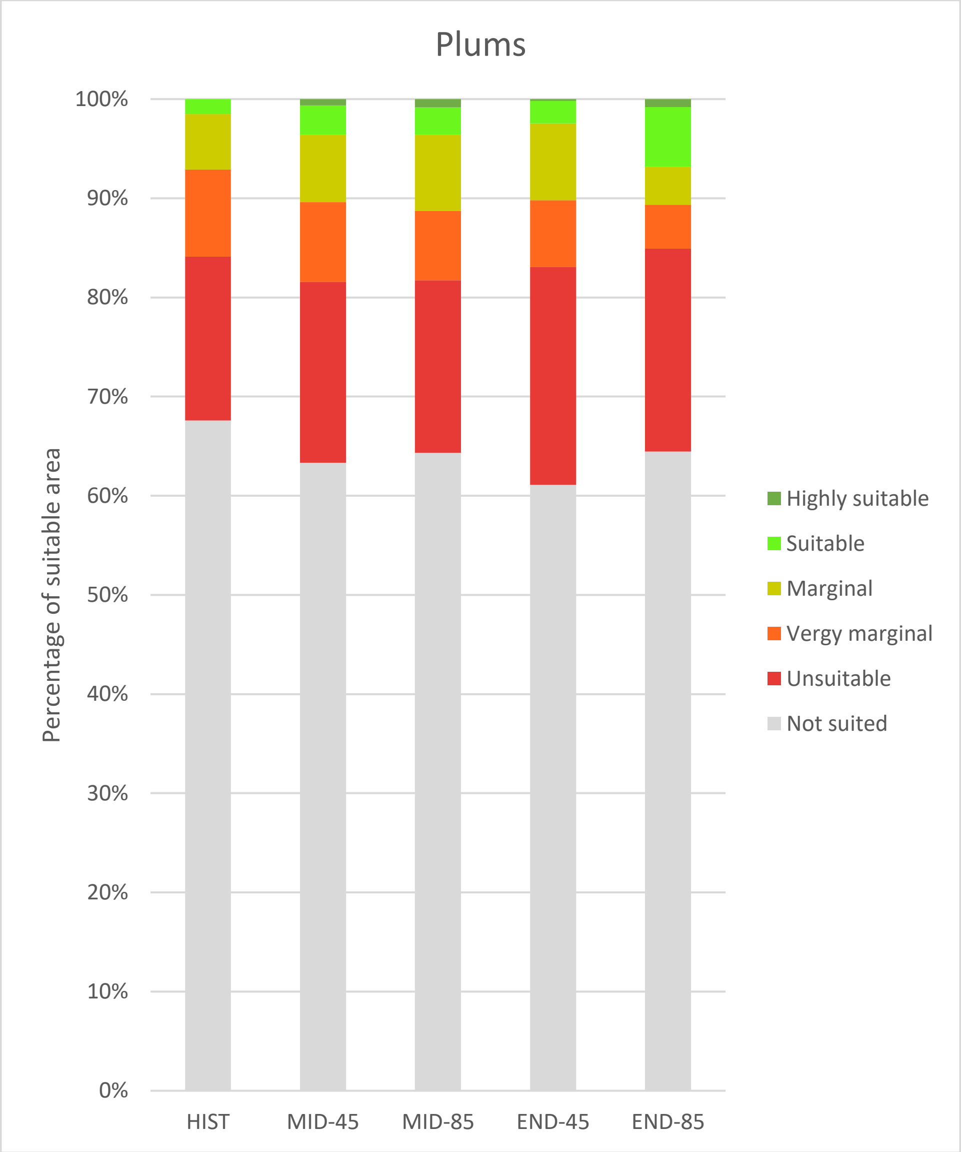

Figure 53: Percentage of land area classified by suitability categories for plum production

There is very little spatial change in plum suitability in the mid-century, although weak spotty increases are seen over the escarpment, highveld and lowveld regions (figure 54). Toward the end-of-century, these effects are amplified, particularly under RCP8.5. In END-85, parts of KwaZulu Natal, Mpumalanga and Gauteng are projected to experience plum suitability score increases of up to 0.5 and become well suited for plum production, while weak suitability decreases are seen over the lowveld.

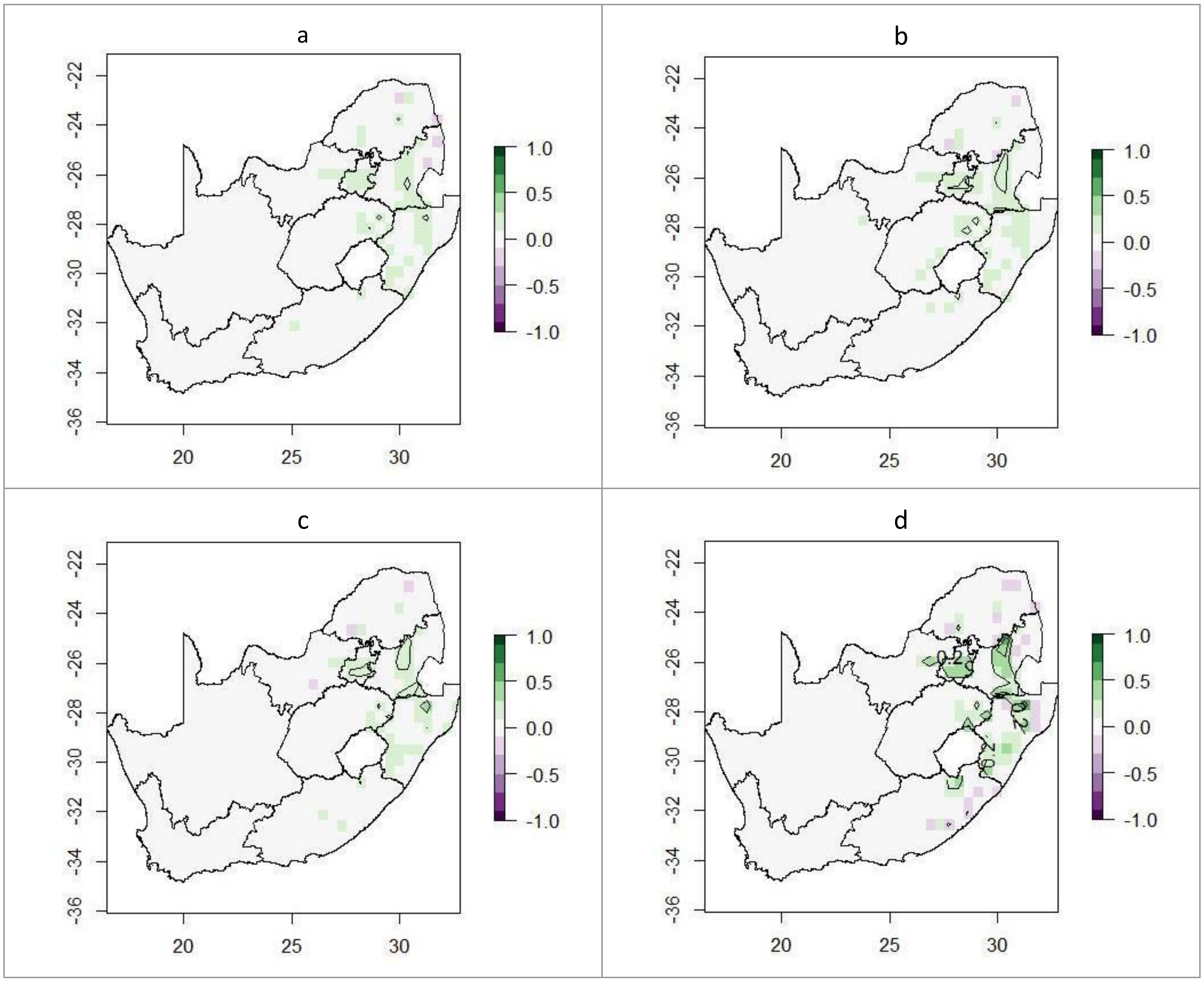

Figure 54: Plum suitability score anomalies historical period to (a) MID-45, (b) END-45, (c) MID-85 and (d) END-85

Stone fruit suitability change

Peach suitability changes in the mid-century are negligible. There are weak spotty decreases in suitability over the highveld at the end of the century (up to -0.2). There is very little change in plum suitability in the mid-century, although weak spotty increases are seen over the escarpment and highveld regions, and weak spotty decreases are observed over the lowveld. Toward the end-of-century, these effects are amplified, particularly under RCP8.5. While both peaches and plums experience minimal spotty changes, there is little agreement between peach and plum suitability projections, as peaches remain unsuitable throughout the 21st century.

The decreases in suitability over the lowveld for both peaches and plums can be explained by high temperatures exceeding their maxima. Additionally, intense drying is expected over this region, bringing the average annual rainfall to 500-1000 mm. This is lower than the optimum minimum rainfall for both peaches and plums, which increases the demand for irrigation, putting pressure on scarce water supply. On the other hand, drying over KZN, Gauteng and Mpumalanga results in these areas becoming better suited to plum production, as their annual rainfall decreases to the range of 1000-1500 mm, within the optimum range for plums and peaches.

Stone fruit typically have a much lower winter chilling requirement than pome fruit, with high-chilling varieties only needing 450-600 DPCUs. Although all four future cases see a reduction in DPCUs in Ceres, Klein Karoo, and Groblersdal, the accumulated winter chill remains sufficient to meet the stone fruits' chilling requirements.

Table grapes

None of the land area was 'suitable' or 'highly suitable' in any of the cases. 'Unsuitable' and 'very marginally suitable' land areas remained very constant throughout, with roughly 30% of total land area fitting into either of these categories in all cases but END-85, where it drops very slightly to 29% (figure 55).

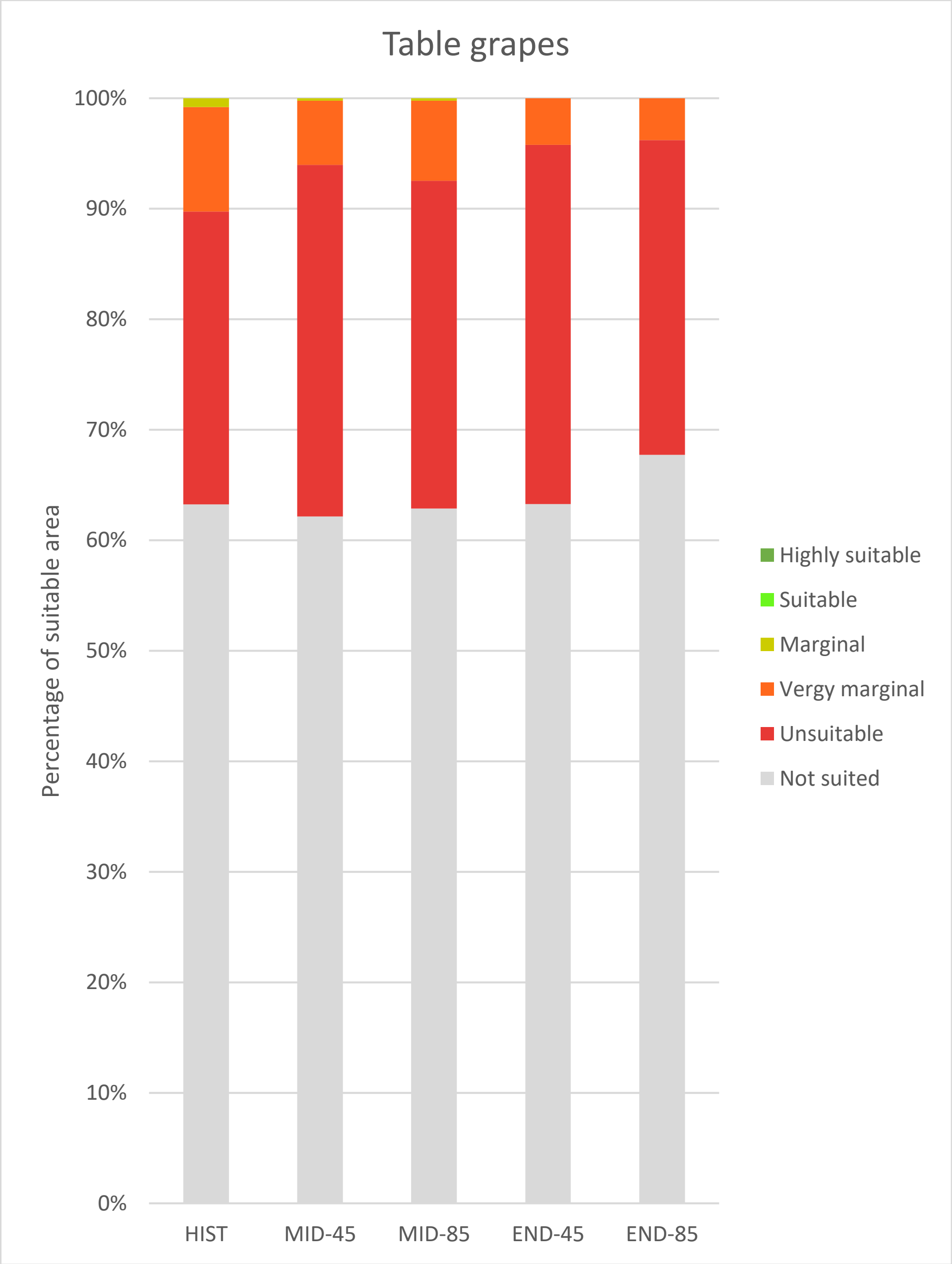

Figure 55: Percentage of land area classified by suitability categories for table grape production

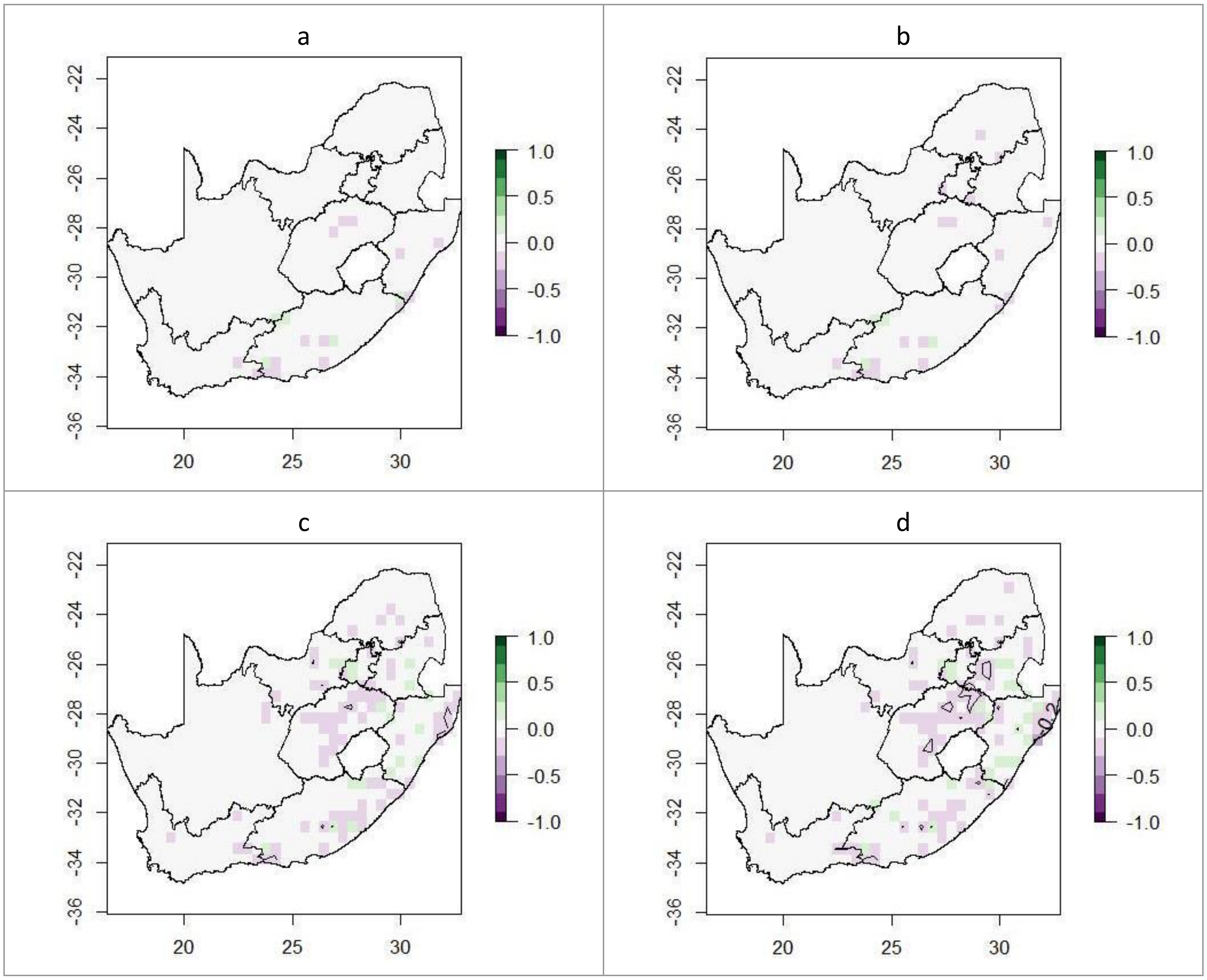

Figure 56: Grape suitability score anomalies historical period to (a) MID-45, (b) END-45, (c) MID-85 and (d) END-85

The distributional change in grape suitability from the historical period into the mid-century is negligible under both RCPs (figure 56). Grapes have a low chilling requirement of about 400 DPCUs, so they would receive sufficient winter chilling in all future cases. By the end-of-century period, stronger decreases in grape suitability (up to -0.4) are seen, especially in northern KwaZulu Natal, the Garden Route area of Eastern Cape and the highveld regions of the Free State and Mpumalanga. These are all regions which historically had the highest grape suitability scores. Grape suitability remains 'unsuitable' to 'very marginal' over the whole country.

Northern KZN becomes too hot, with the mean monthly maximum reaching 28°C in END-85. The annual rainfall in this area (1000 mm) also exceeds the optimum. The highveld also becomes very hot at 28-30°C, although the lower annual rainfall of 750 mm falls within the optimum range.

Table 10: Summary of changes in crop suitability in each case

	MID-45	MID-85	END-45	END-85
Oranges	Small increases	Small increases	Small increases	Increases up to 0.6 along eastern escarpment and highveld
Lemons	Substantial increases along eastern escarpment and highveld	Substantial increases along eastern escarpment and highveld	Substantial increases along eastern escarpment and highveld	Very large increases along eastern escarpment and highveld
Mandarins	Negligible	Negligible	Negligible	Very small increases along eastern escarpment
Grapefruit	Negligible	Negligible	Negligible	Negligible
Apples*	Negligible	Negligible	Small decreases in the east and increases over Lesotho highlands	Small decreases in the east and increases over Lesotho highlands
Pears*	Slight increases over Lesotho highlands	Slight increases over Lesotho highlands	Moderate increases over Lesotho highlands and eastern escarpment, slight decreases in Lowveld	Moderate increases over Lesotho highlands and eastern escarpment, moderate decreases in Lowveld
Peaches*	Negligible	Negligible	Weak decreases over highveld and eastern escarpment	Weak decreases over highveld and eastern escarpment
Plums*	Weak increases over highveld and eastern escarpment	Weak increases over highveld and eastern escarpment	Weak increases over highveld and eastern escarpment	Moderate increases over highveld and eastern escarpment
Grapes	Negligible	Negligible	Negligible	Very weak widespread decreases

*Given that the known production regions (i.e. Western Cape) are poorly captured by the empirical approach, an absence of change in this summary does not suggest that there will be no change in suitability of these crops in those regions.

4.3. Model Representativeness

It is important to query whether crop ecological suitability does indeed constrain their geographic distribution. Ecological suitability is but one limiting factor of crop production, it is expected that crops may be absent or scarce in highly 'suitable' areas - there may be factors other than climatic suitability which account for the crops scarcity, such as more valuable use of the land - but they should not be present in climatically 'unsuitable' areas. There is no available gridded observation data for these crops in South Africa. This study made use of scarce data on the production areas of the fruit crops to validate Ecocrop, so the assessment of crop model representativeness is limited. The suitability score results produced by Ecocrop for the historical period indicate that citrus crops are most suitable on the east coast of KwaZulu Natal, Mpumalanga, Limpopo, and the Eastern Cape coast, which are known citrus growing regions. Apples and pears are almost exclusively grown in the Western Cape, which Ecocrop also fails to capture, but it suggests a high pome fruit suitability in KwaZulu Natal, and the highveld and lowveld regions in Limpopo, Free State, Mpumalanga and Gauteng, where very little pome fruit is grown. The vast majority of peaches and plums are grown in the Western Cape, followed by the Northern provinces, Free State and Mpumalanga. Ecocrop recognizes that these regions are suitable, however, it also suggests that KwaZulu Natal is the most suitable area for peach and plum production, but no stone fruit is grown there. 80 percent of table grapes are grown in the Western Cape, which Ecocrop deems unsuitable for grape production, and the rest in the Northern Cape and Limpopo for which Ecocrop calculates marginal suitability scores. Ecocrop's most suitable regions for grapes are in KwaZulu Natal, Free State and the Eastern Cape, which are not strong grape-producing regions. It is important to note that 'suitable' areas may be climatically suitable, but there may be other crops or land uses in those areas which are a more valuable use of the space. Perhaps a different crop is *more* climatically suited to the location or provides more income, or it could be a residential or industrial area, a protected area, a forest or a grassland. Climatically suitable areas need to be assessed to determine whether these locations also have favourable environmental conditions for the particular crop, i.e. suitable soil characteristics, availability of water for irrigation, transport logistics, nearness to processing plants, etc.

For example, KwaZulu Natal and Mpumalanga are estimated suitable by Ecocrop for producing many of the fruit crops in this study, but these regions produce most of the country's sugarcane, which makes an important contribution to employment, particularly in rural areas, to sustainable development, and to the national economy (SASA, 2022). Furthermore, the areas may be built-up, and it would not be possible to plant fruit trees. The lack of gridded fruit data makes it difficult to validate Ecocrop's representativeness, however, the 'suitable' areas often overlap with the crop data, so it can be inferred that Ecocrop represents suitable fruit-growing regions reasonably well, except for the Western Cape where it fails to account for mesoclimatic effects due to complex topologies existing at finer scales than the GCMs can capture.

There is significant scope for improvement in the modelling approach and it has been acknowledged that various environmental influences other than mean and minimum temperature will affect the future suitability of these crops. Ecocrop model development should prioritise perennial crops' physiological processes and mesoclimatic effects attributed to complex small-scale topologies to improve model representativeness. There is also a dire need for improved crop data and horticultural crop mapping in South Africa for effective model validation. Despite the limitations which have been addressed, the modelling approach that was conducted provides a coarse understanding of the potential impacts of a changing climate on the spatial suitability distribution of South Africa's major fruit crops.

4.4. Comparison of RCP4.5 with RCP8.5 climate projections for the mid-century and end-of-century time periods and the effect on suitability

RCP4.5 is a stabilization scenario that involves the implementation of climate policies to mitigate warming. Under this pathway, atmospheric greenhouse gas concentrations rise to a peak of about 550 ppm around the mid-century and then stabilize. Radiative forcing reaches 4.5 W/m^2, which equates to about a 2.4°C warming at stabilization. Conversely, RCP8.5 involves no intervention to limit radiative forcing. Greenhouse gas concentrations continue to rise throughout the 21st century and peak at about 1370 ppm by 2100, resulting in a global temperature increase of 4.9°C.

Climate projections averaged across all models show a very similar pattern of change in temperature and precipitation in both RCPs. However, because radiative forcing stabilizes at the mid-century under RCP4.5 but not under RCP8.5, there is a large difference in temperature increase at the end of the century between the two RCPs, while temperature change by the mid-century is similar for both RCPs. Additionally, mean temperatures in END-45 are similar to both the mid-century cases due to the stabilization. All three of these cases have mean monthly temperatures ranging from 16-24°C across the country. END-85 sees substantially higher temperatures than the other three cases, with mean monthly temperatures ranging from 18-26°C across the country, 2°C warmer than the other cases. Mean monthly maxima and minima are also about 2°C warmer under END-85 than the other cases.

In terms of precipitation, the pattern of change is once again similar in all cases. For the mid-century period, the magnitude of drying is comparable for both RCPs, but MID-85 simulations result in a patch of wetting over the central interior. At the end-of-century, there is more severe and widespread drying projected under RCP8.5 than RCP4.5. There is lower certainty in precipitation projections for the end of the century period. Rainfall was not included as a crop suitability modelling parameter, so not conclusions can be inferred based on the projected changes in rainfall.

In summary, RCP8.5 simulations project a hotter and generally drier future than RCP4.5, especially at the end of the century. There is very little difference in temperatures projections for RCP4.5 and RCP8.5 at the mid-century, translating into very little differences in crop suitability. While at the end of the century, there is a much larger difference in climate between RCP4.5 and RCP8.5 projections, resulting in stronger increases and decreases in suitability in END-85, as well as a larger gap between END-45 and END-85 suitability scores.

The crops examined in this study have optimum maximum temperatures between 27 and 35°C according to Ecocrop's crop ecological requirements database. Alongside hotter average temperatures, South Africa is projected to experience an increase in the number of hot days (where temperature hotter than the 90th percentile) and very hot days (days where the maximum exceeds 35°C) under both RCP4.5 and RCP8.5 (Department of Environmental Affairs, 2018; Kruger, et al., 2019). At the end of the century under RCP8.5, increases as many as 80 very hot days are projected over large parts of the entire South African interior, and 120 very hot days over the western interior (Department of Environmental Affairs, 2018). The severe warming in END-85 as well as the expected increase in heat waves and high fire risk associated with climate change will likely push peak summer temperatures to those exceeding the threshold of these fruit crops and pose a threat to crops and farm labour. Drying will increase drought risk and increase irrigation demands, threatening water security. However, some crops – oranges and lemons in particular – will benefit from warming in some areas as the future mean temperatures better align with their ecological thresholds, increasing the suitable land area.

4.5. Response planning and adaptation to climate change impacts on fruit crops

The results show large temperature increases projected in the 21st century, especially in END-85, which will likely result in heat stress. The projected increase in hot days and very hot days will put stress on fruit crops and farm laborers. Hotter temperatures will also increase the risk of wildfires which can damage fruit trees. Increased mean minimum temperatures put the deciduous fruit at risk of not meeting their winter chill requirement, which results in reduced flowering, reduced fruit set and quality in terms of size and shape, as well as uneven ripening (Schulze and Maharaj, 2007; Atkinson, Brennan and Jones, 2013). Higher temperatures, particularly in the winter, may advance the timing of flowering and ripening, putting the fruit at risk of damage by late-season frosts, ultimately reducing yield. Higher temperatures during the ripening period will affect fruit composition, generally increasing sugar levels.

Projected drying over South Africa paired with hotter temperatures will likely increase the risk of droughts as well as enhance evapotranspiration, putting strain on the water supply and resulting in increased irrigation demands. Water stress may result in a reduced yield due to decreased fruit size and bud fertility, and a decline in fruit quality due to modified fruit composition (Ripoll et al., 2014; Sharma and Manjeet, 2020). Additional rainfall-related concerns are increased rainfall variability, making it difficult to predict rainfall, increased extreme rainfall events and increased risk of hail damage. It is also vital to improve weather and fire risk forecasting, monitoring, and early warning systems to ensure rapid response to these hazards.

To combat the direct effects of rising temperatures and reduced rainfall, horticulturalists should invest in cooling infrastructure and shelter such as shade netting and fruit bagging to prevent sunburn (Allen, et al., 1999; Sharma and Manjeet, 2020). Building of dams and reservoirs to store rainwater will assure water supply and aid farmers in times of drought and unpredictable rainfall (Teel, 2019). Investments should be made in sustainable groundwater and wastewater use for irrigation to save water and assure supply. There should be a focus on improvements in technologies that farmers can use to maintain and increase their productivity in future climates, such as FruitLook, a state-of-the-art tool that allows farmers to improve their water use efficiency using information from remote sensing derived spatial data (Roux , Jarmain and Goudriaan, 2016). Mulching will also reduce the loss of soil moisture, and making use of reflective, low density and organic mulch will reduce the surface radiation by reflection and dissipating radiative heat (Sharma and Majeet, 2020).

Geneticists should develop new resistant seed varieties that are more tolerant to drought, high temperatures, pests and diseases. Farmers should invest in these genetically modified crops to ensure better crop survival and yield. It would also be beneficial to select low chill cultivars of deciduous fruit to ensure their winter chill requirement is met under higher minimum temperatures. Alternatively, dormancy can be artificially induced by defoliating the trees, or using rest-breaking agents, enabling the trees to continue their crop cycle without necessarily meeting their chill requirement (Campoy, Ruiz and Egea, 2011; Yang et al., 2021). Another method to increase chilling hours is by utilising the effect of evaporative cooling. Evaporative cooling will help to reduce the temperature under warmer winter conditions to induce bud burst (Allen, et al., 1999; Haokip, Shankar and Lalrinngheta, 2020).

Changing climate, especially temperature increase, is a major driver of pest population dynamics, and can result in an expansion of pests' geographic distribution, increased survival during winter (overwintering), more generations per season, altered interspecific interaction, increased risk of invasion by migratory pests, and reduced effectiveness of biological control (Skendžić et al., 2021). Hence, crop economic losses are at high risk. Climate change adaptation strategies for pests must be prioritised, including integrated pest management strategies, monitoring of pest populations, and using crop models which integrate pest management to improve crop management, yield and quality and reduce pesticide input requirements

4.6. Sources of uncertainty and recommended improvements

4.6.1. Climate data

The GCM data used in this study accounted for a fair amount of uncertainty, due to their coarse resolution. The projected changes in temperature and precipitation showed considerable variation between the 5 GCMs. To improve model certainty, further research in model calibration is required. Additionally, the advancements in downscaling models and techniques and the development of regional climate models with finer spatial resolutions would yield more accurate results. Further research needs to be done on improving predictions in areas where smaller-scale processes have a significant impact on climate and where parameterization schemes do not capture these processes.

4.6.2. Crop data

Availability and access to detailed observational data for fruit crops in South Africa is poor, making crop model calibration a challenge. T To address this, remote sensing and other means of crop data retrieval and recording must be improved. Such data should be placed on accessible online platforms such as FAOSTAT. It is also crucial to obtain and compare crop thresholds and information from many different sources to reduce uncertainty.

4.6.3. Crop suitability model

Although the Ecocrop model has the advantage of a large spatial scale, which allows it to be applied to a large geographical domain such as South Africa, and is also well suited to large temporal scales such as this study, which in so doing effectively analyses climate spatial variability, it does come with limitations. Ecocrop is a basic statistical model which uses only two ecological ranges (absolute and optimum) for temperature and rainfall to determine suitability for a given crop. It does not consider other biophysical and physiological processes such as water flow, evapotranspiration, soil conditions, waterlogging, drought, excessive heat or cold during key physiological stages (flowering, fruit filling, etc.), winter chill fulfillment, crop genetics, etc. and therefore it cannot capture the effect of all these interactions which occur within the crops and alter their suitability. Additionally, Ecocrop does not consider external effects such as pests and diseases, climatic factors such as humidity and altitude, farming practices and technological advancements, resulting in over- or underestimation of crop suitability.

The crops in this study are all perennial crops, meaning that they do not need to be replanted each year and continue to grow after harvest. It is more difficult to calibrate models for these perennial fruit crops because they are productive for decades (rather than just a season) which means that they are exposed to threatening conditions continuously year-after-year, and may be at risk of freezing temperatures, heat stress, pest and disease pressure, pollination risk, and exposure to extreme weather, all factors which are not accounted for by Ecocrop.

Another weakness of Ecocrop is its reliance on monthly data. Adverse weather conditions such as heat waves or flooding may occur at much smaller time scales and will not be captured by monthly climate data.

An unanticipated shortfall of this study is that the Ecocrop outputs do not show any suitability scores or changes for any of the fruit crops in the Western Cape, which is the major fruit-growing region in South Africa. The crops in the study are irrigated, so the dry conditions in this region should not be cause for the 'unsuitable' results. Even though the rainfed variable is set to 'false' and the rainfall parameter is disregarded, Ecocrop computes the region to be unsuitable. This is an unexpected result, likely due to the GCMs' inability to capture the complex mountain topography and ocean influence. Current GCMs have insufficient spatial resolution to resolve many important processes or provide the spatial details required for impact studies, and therefore have systematic errors, or biases, in their outputs. Climate models tend to overestimate the amount of rainy days and underestimate extreme rainfall events. Temperatures, amount of seasonal rainfall, and the timing of events can also be miscalculated. These biases are caused by a range of factors, but often due to a low spatial resolution, i.e. large grid sizes, simplified thermodynamic and physical processes, as well as a limited understanding of the global climate system (Copernicus Climate Change Service, n.d.). The CMIP5 GCMs used in this study all have a grid resolution between 155 km and 310 km, so the topography is represented as an average altitude across each 155 km x 155 km (or larger) grid. This averaging results in the highest altitude represented by the models being hundreds of meters lower than what it is in reality, meaning that the GCMs are not able to capture smaller scale physical processes that would influence the climate, such as the interaction of mid-latitude cyclones with the topography. Furthermore, The CORDEX data obtained for this study is not bias-corrected. Numerous biases exist across a set of GCMs, but each model has variable simulations strengths and weaknesses (when compared to current climate). It is widely agreed that an average over the set of models provides a superior simulation to any individual model (CCSP, 2008), which justifies the multi-model aggregate approach used in this study.

The Ecocrop model is able to identify specific locations of crop suitable areas, although the locations identified as 'suitable' should be interpreted as areas with climatic conditions that are suited for growing each crop (Makinano-Santillan and Santillan, 2015). Other factors such as land-use or land-cover and socioeconomic conditions are not accounted for. These factors need to be accounted for to narrow down the 'suitable' locations to those where it is indeed possible or feasible to grow the fruit crops. For example, one would need to determine whether a specified 'suitable' area has other land-uses; perhaps a different crop is more suited to the location or provides more income, or it could be a protected area, or a forest or grassland, and to determine whether these locations have favourable environmental conditions for the particular crop, i.e. suitable soil characteristics, availability of water for irrigation, transport logistics, nearness to processing plants, etc.

Despite these shortcomings, Ecocrop was deemed the most appropriate tool for this study. The aim of this study is to assess the likely impact of climate change on the statistical large scale suitability of growing citrus and deciduous fruit in South Africa in the 21st century. Taking the objective of calculating the spatial extent of suitable areas into account, as well as the very large geographical domain of the study area, the range of potential climate scenarios, the wide range of fruit crops, and the large time frame of this study, Ecocrop produces climate suitability results most effectively. Ecocrop is a statistical tool that calculates suitability scores based on empirical data, rather than biophysical processes.

5. Conclusion

The quality and quantity of fruit produced in South Africa greatly depends on the local climate. Climate change impacts may undermine the potential contributions of important fruit crops toward South Africa's foreign exchange earnings, national food security, and local employment. This study assessed the potential impacts of climate change on South Africa's major export fruit crops, namely citrus, pome fruit, stone fruit and table grapes. Spatial suitability change was studied for each of the crops under a low mitigation scenario, RCP8.5, and a stabilization scenario, RCP4.5, at the mid-century and the end of the century.

Key findings

Objective 1:

The first objective of the study was met by extensive literature review. The temperature, precipitation, and soil requirements of each crop were studied to understand their respective climatic requirements. Processes by which crop suitability is impacted were explored, and drought, extreme weather events, heat stress, pests and diseases, and shifts in phenology were found to be the major drivers of change. To assess changes in winter chill accumulation, the Daily Positive Chill Unit model from the R package *chillR* was applied to four climate change cases in Ceres, Klein Karoo, and Groblersdal. Winter chilling decreased at Ceres, Klein Karoo, and Groblersdal, with largest decreases seen in END-85. Ceres and Klein Karoo had 1764 DPCUs and 1094 DPCUs accumulated over the winter season respectively under the most intense warming scenario, which is more than sufficient to meet the chilling requirements of stone fruit and table grapes. Pome fruit, particularly apples, may be negatively impacted by the decrease in winter chilling in these two areas, as high-chilling apple cultivars require more than 1000 DPCUs. Groblersdal, a fruit-growing region in Limpopo, historically accumulated 1380 DPCUs over winter, projected to decrease to 550 DPCUs in END-85. Such a reduction in winter chill units would adversely affect the production of apples, pears, and possibly high-chilling stone fruit cultivars which require up to 650 DPCUs over winter, including irregular bud break, poor fruit development, small fruit size, and uneven ripening times.

Objective 2:

Climate projection results from a multi-model mean of 5 CORDEX GCMs showed patterns of warming across South Africa under all 4 future cases, with the strongest warming anticipated for the interior and the weakest warming along the coast. Warming of 1-2°C is predicted in MID-45 with mild drying (50-100 mm less than historical period) in the southern and eastern coastal regions. Warming of 2-3°C and slightly increased drying signal in MID-85 and END-45. Extreme warming of 3-5°C and more prevalent drying (up to 400 mm dryer than historical period) is predicted in END-85.

Objective 3:

Analysing large-scale spatial and temporal suitability of fruit crops was met by applying the crop suitability model Ecocrop to the four potential future climates. Ecocrop produced suitability scores between 0 and 1 for each case, and composite maps of these scores were plotted and compared. To evaluate the model's performance, historical suitability of each fruit was compared to their known producing regions. The model was unable to identify the major fruit growing region of the Western Cape, which is a severe limitation of this study, as a large proportion of the fruit is grown there. Potential reasons for this misrepresentation have been discussed in Section 2.5 and point the blame toward biases in climate modelling and Ecocrop's simplistic approach to suitability modelling which does not take into account plant physiological processes. The inability of Ecocrop to identify the major fruit producing region reduces our confidence in the results produced by the model.

The results indicated that the crops examined in this study do not respond homogeneously to climate change. This is due to variable sensitivities to environmental conditions such as temperature, rainfall, humidity, and altitude, as explored in the literature review.

The four citrus fruits all responded in a similar pattern, however, the magnitude of change was different. There was a general pattern of suitability increase along the eastern escarpment, the highveld and the central interior, while suitability decreased along the east coast and the lowveld. These effects were strongest in lemons and oranges, and negligible in mandarins and grapefruit.

The pome fruit had mixed suitability change projections. Increases in suitability over the Lesotho highlands were seen for both pome fruit but more so for pears, particularly at the end of the century. Both fruits also had decreased suitability in the lowveld and northern KwaZulu Natal. At the end-of-century, there is a much stronger and widespread decreasing suitability signal for apples. It appears that pome fruit suitability increases in high-lying land and decreases at lower altitudes. Pears thrive in a warmer climate than apples, whereas apples can only tolerate a maximum temperature of 33°C. This explains why apples become less suitable in the future as countrywide warming pushes temperatures in above the threshold. Apples' requirements for more rainfall, more winter chilling hours and higher altitude may explain why they become less suitable in the future. Pears, being more tolerant to high temperatures, thrive in these warming conditions over the eastern escarpment, Lesotho highlands and eastern midlands, where altitude is also in its favour. Enhanced warming in the northern interior makes temperatures become too hot in the lowveld, which is why we see decreases in suitability in this area for both apples and pears.

Peaches see a general decrease in suitability while plums see a general increase. This may be due to future temperatures being too hot for peaches which have a lower temperature threshold. The suitability of peaches decreases over the lowveld, as this region becomes too hot and dry, especially in the later months. The effects of changing climate on both peach and plum suitability are weak as both fruits have a wide range of optimal temperatures, do not have high winter chilling requirements, and prefer a relatively drier climate.

There is an unclear pattern of change for table grapes. Suitability changes in the mid-century are negligible under both RCPs, however, by the end of the century, weak widespread decreases in suitability are seen in northern KwaZulu Natal, the Garden Route and the highveld – all areas which had the highest suitability indices in the historical period. These decreases may be attributed to future temperatures exceeding the optimum maximum of 30°C as well as decreased chill unit accumulation under RCP8.5.

While there are varied effects of climate change on suitability for the fruit crops, all the effects were felt strongest under RCP8.5 at the end of the century period. This is to be expected as higher emissions under this RCP result in higher temperatures and more intense drying, so the crops respond to greater changes in Ecocrop's suitability parameters, resulting in greater changes in suitability.

Learnings and limitations

With evidence based on climate suitability this study allows us to observe large temporal and geographical scale variation of major fruit production suitability in South Africa. Known model limitations do not account for known pockets of fruit production, but despite such challenges, future fruit suitability is expected to change measurably in some areas such as the highveld and eastern escarpment, especially for citrus crops, pears, and plums, positively or negatively. While confidence in the results is low, large shifts in climatically suitable areas are to be expected due to the projected warming of the country, which could inform production in those areas on geographical and time scales, and may affect even highly productive pockets of fruit growing areas in the long term.

While this study looks at suitability over the whole country, it is important to note that the Ecocrop model failed to capture any suitability scores over the Western Cape which is the primary fruit-growing region, especially for pome fruit and stone fruit. While we cannot conclude any anticipated changes in suitability of these crops in the Western Cape in the 21st century, the temperate climate in the Western Cape is very suitable for these crops, and there is potential for some improvements in fruit suitability with a warming climate in the 21st century, so long as their winter chill requirements are met. However, rainfall predictions over the Western Cape indicate mild drying, which can be detrimental for fruit farming in this already dry area. While most fruit crops are not rainfed in South Africa, they still rely on well-distributed rain to ensure enough water is available for irrigation. Irrigation demands will be higher in hotter and drier weather, increasing the pressure on water supply.

Ecocrop does not consider biophysical processes which may have an impact on crop suitability, such as soil moisture, drought, excessive heat or cold during key physiological stages, winter chill fulfilment, crop genetics, etc. Furthermore, Ecocrop neglects external effects such as pests and diseases, altitude, farming practices and technological advancements, resulting in over- or underestimation of crop suitability. Nevertheless, utilizing global climate models enabled us to meet some objectives of this study, so as to gain understanding of the long-term climatic change to be expected in South Africa under varied emission scenarios. While the study endeavored to use these projections to assess the likely impacts on the large scale spatial and temporal shifts in suitability of the crops, the results obtained from Ecocrop are not robust, due to limitations in modelling capacity and data accessibility, and we have low confidence in their credibility. Nevertheless, this study found that a reduction of winter chilling and an increase in temperatures are expected in the mid and late-21st century, which can be used to guide farmers in decision-making regarding selection of appropriate fruit crops, selection of resilient cultivars or low-chill cultivars, and adaptive measures such as artificial dormancy release techniques, shading and evaporative cooling, and mulching to mitigate the harsh effects of climate change.

Future studies should explore seasonal changes in crop suitability to complement spatial change patterns. Additionally, advancements in suitability modelling need to be prioritized, where biophysical and indirect impacts are considered. Studies should also utilize regional climate models to improve the accuracy of results.

Knowledge contribution

Similar research has examined suitability shifts of non-perennial field crops due their importance as staple foods, as well as suitability of trees for reforestation purposes, yet little attention has been given to high value export crops which provide foreign exchange earnings and employment for thousands of South Africans. This study strengthened the knowledge of large scale shifts in suitability of a variety of fruit crops in a changing climate in the South African context, reinforcing our ability to adapt to climate change impacts and ensuring high commodity crops can meet their production demands in terms of both quality and yield. Climate change can potentially displace fruit production areas, which would cause suffering to the farmers and labourers who work in the industry, and the limitations faced by this study highlight the need to improve access to quality and complete crop data in South Africa, to enable more rigorous modelling of climate change impacts on complex crops such as fruit trees. More research is required to guide policymakers in this regard, to reduce the risks associated with climate change and agriculture, and to allow farmers to plan their practices well in advance. For agriculture to be successful in the changing climate of the 21st century, planning needs to go beyond response and priority must be given to strategic planning for future changes. Although confidence in results is low, some fruit crops in this study showed reduced suitability in the future, others show promise of suitability improvements where moderate warming and drying shift areas into optimal growing conditions. Where this is not the case, shifting to more resilient cultivars and climate-smart agricultural practices can mitigate adverse climate effects without negatively impacting profitability or jobs. This study also highlights the importance of reducing emissions to mitigate climate change as it exposes the potential extreme changes in climate that can be expected by the end of the century under RCP8.5, compared to moderate impacts felt under RCP4.5.

6. Reference list

Abobatta, W.F., 2019. Influence of climate change on citrus growth and productivity (effect of temperature). *Adv. Agric. Technol. Plant Sci*, *2*, p.180036.

Adams, H., Williams, A., Xu, C., Rauscher, S., Jiang, X. and McDowell, N., 2013. Empirical and process-based approaches to climate-induced forest mortality models. *Frontiers in Plant Science*, 4.

Agribook Digital. 2017. Horticulture - Agribook Digital. [online] Available: https://agribook.co.za/horticulture/ [1 June 2020].

Allan, P. 1999. Measuring winter chilling in areas with mild winters. *Deciduous Fruit Grower* 49(10), S1-S10.

Allan, P., Savage, M.J., Criveano, T., Mork, T. and Blore, N. (1999). SUPPLEMENTING WINTER CHILLING IN KIWIFRUIT IN SUBTROPICAL AREAS BY EVAPORATIVE COOLING AND SHADING. *Acta Hortic*. 498, 133-142

Allen, L. 2000. Evapotranspiration Responses of Plants and Crops to Carbon Dioxide and Temperature. *Journal of Crop Production*, 2(2), pp.37-70.

Asseng, S., Zhu, Y., Basso, B., Wilson, T., Cammarano, D., 2014. Simulation Modeling: Applications in Cropping Systems. *Encyclopedia of Agriculture and Food Systems*. Pages 102-112. ISBN 9780080931395. (https://www.sciencedirect.com/science/article/pii/B9780444525123002333)

Atkinson, C., Brennan, R. and Jones, H., 2013. Declining chilling and its impact on temperate perennial crops. *Environmental and Experimental Botany*, 91, pp.48-62.

Bebber, D., Ramotowski, M. and Gurr, S., 2013. Crop pests and pathogens move polewards in a warming world. *Nature Climate Change*, 3(11), pp.985-988.

Beck, H.E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., & Wood, E.F. 2018. "Present and future Köppen-Geiger climate classification maps at 1-km resolution". *Nature Scientific Data*. DOI:10.1038/sdata.2018.214.

Bellinger, G. 2004. "Modeling & simulation: An introduction," in *Mental Model Musings*. Available at: http://www.systems-thinking.org/modsim/modsim.htm.

Benhin, J., 2006. *Climate Change And South African Agriculture: Impacts And Adaptation Options*. CEEPA Discussion Paper No. 21 Centre for Environmental Economics and Policy in Africa, University of Pretoria.

Blanc, E. 2012. "The Impact of Climate Change on Crop Yields in Sub-Saharan Africa," American Journal of Climate Change, Vol. 1 No. 1, pp. 1-13. doi: 10.4236/ajcc.2012.11001.

Bradshaw, C. D., Hemming, D., Baker, R., Everatt, M., Eyre, D., & Korycinska, A., 2019. A novel approach for exploring climatic factors limiting current pest distributions: A case study of Bemisia tabaci in north-west Europe and assessment of potential future establishment in the United Kingdom under climate change. *PloS one*, 14(8), e0221057. https://doi.org/10.1371/journal.pone.0221057

Cairns, J.E., Hellin, J., Sonder, K. *et al.* 2013. Adapting maize production to climate change in sub-Saharan Africa. *Food Sec.* **5,** 345–360. https://doi.org/10.1007/s12571-013-0256-x

Campoy, J., Ruiz, D. and Egea, J., 2011. Dormancy in temperate fruit trees in a global warming context: A review. *Scientia Horticulturae*, 130(2), pp.357-372.

Citrus Growers Association, 2020. Key Industry Statistics For Citrus Growers. Available: http://www.citrusresourcewarehouse.org.za/home/document-home/information/cga-key-industry-statistics/6550-cga-key-industry-statistics-2020 [24 January 2021]

Chérif, Ahmat & Sode, Idelphonse & Houndonougbo, Juliano & Idohou, Rodrigue & Fandohan, Adandé & Glele Kakaï, Romain Lucas & Assogbadjo, Achille. 2022. Habitat suitability modeling for the conservation and cultivation of the multipurpose fruit tree, Balanites aegyptiaca L., in the Republic of Chad, Sahel. *Modeling Earth Systems and Environment*. 8. 1-11. 10.1007/s40808-022-01416-4.

Chmielewski, F., Blümel, K. and Pálešová, I. 2012. Climate change and shifts in dormancy release for deciduous fruit crops in Germany. *Climate Research*, 54(3), pp.209-219.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., et al. 2007. Regional climate projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 847-940.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W.J., et al. 2013. Long-term Climate Change: Projections, Commitments and Irreversibility. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Cooke, J.E.K., Eriksson, M.E., Junttila, O. (2012). The dynamic nature of bud dormancy in trees: environmental control and molecular mechanisms. *Plant Cell Environ* 35, 1707-1728

Coombe, B. 1987. *Influence Of Temperature On Composition And Quality Of Grapes*. *Acta Horticulturae*, (206), pp.23-36.

Copernicus Climate Change Service. (n.d.). *Gloabl Impacts.* Retrieved from Copernicus Climate Change Service: https://climate.copernicus.eu/sites/default/files/2021-01/infoCopernicus Climate Change Service. (n.d.). Gloabl Impacts. Retrieved from Copernicus Climate Change Service: https://climate.copernicus.eu/sites/default/files/2021-01/infosheet7.pdf sheet7.pdf

Cordex. 2020. *Cordex – Coordinated Regional Climate Downscaling Experiment*. [online] Available at: <https://cordex.org/> [Accessed 13 April 2020].

Craig, M., Kleinschmidt, I., Le Sueur, D. and Sharp, B., 2004. Exploring 30 years of malaria case data in KwaZulu-Natal, South Africa: Part II. The impact of non-climatic factors. *Tropical Medicine and International Health*, 9(12), pp.1258-1266.

DAFF, 2010. Plum Production Guidelines [online] Available: https://www.nda.agric.za/Resource-Centre [16 October 2021].

DAFF, 2012. Grape Production Guidelines [online] Available: https://www.nda.agric.za/Resource-Centre [13 April 2020].

DAFF, 2017a. Profile of the South African Peach Market Value Chain[online] Available: https://www.nda.agric.za/Resource-Centre [13 April 2020].

DAFF, 2017b. Profile of the South African Plum Market Value Chain [online] Available: https://www.nda.agric.za/Resource-Centre [13 April 2020].

DAFF, 2018a. Profile of the South African Citrus Market Value Chain[online] Available: https://www.nda.agric.za/Resource-Centre [13 April 2020].

DAFF, 2018b. Profile of the South African Apple Market Value Chain [online] Available: https://www.nda.agric.za/Resource-Centre [13 April 2020].

DAFF, 2018c. Profile of the South African Pear Market Value Chain [online] Available: https://www.nda.agric.za/Resource-Centre [13 April 2020].

Department of Environmental Affairs, 2013. Long-Term Adaptation Scenarios Flagship Research Programme (LTAS) for South Africa. Climate Trends and Scenarios for South Africa. Pretoria, South Africa.

Department of Environmental Affairs, 2017. South Africa’s 2nd Annual Climate Change Report. Pretoria: Department of Environmental Affairs

Department of Environmental Affairs, 2018. South Africa’s Third National Communication under the United Nations Framework Convention on Climate Change.

Dokoozlian, N.K. 1999. Chilling Temperature and Duration Interact on the Budbreak of ‘Perlette’ Grapevine Cuttings. *Hortscience* 34(6)

Dosio, A., Jones, R.G., Jack, C., Lennard, C., Nikulin, G. and Hewitson, B. 2019. What can we know about future precipitation in Africa? Robustness, significance and added value of projections from a large ensemble of regional climate models. *Climate Dynamics*, 53(9-10), pp.5833-5858. https://doi.org/10.1007/s00382-019-04900-3

Egbebiyi, T., Crespo, O., Lennard, C., Zaroug, M., Nikulin, G., Harris, I., Price, J., Forstenhäusler, N. and Warren, R. 2019. Investigating the potential impact of 1.5, 2 and 3 °C global warming levels on crop suitability and planting season over West Africa. *PeerJ*, 8, p.e8851.

Engelbrecht, F., McGregor, J. and Engelbrecht, C. 2009. Dynamics of the Conformal-Cubic Atmospheric Model projected climate-change signal over southern Africa. *International Journal of Climatology*, 29(7), pp.1013-1033.

Estes, L., Beukes, H., Bradley, B., Debats, S., Oppenheimer, M., Ruane, A., Schulze, R. and Tadross, M., 2013. Projected climate impacts to South African maize and wheat production in 2055: a comparison of empirical and mechanistic modeling approaches. *Global Change Biology*, 19(12), pp.3762-3774.

FAO, 2000. In: FAO (Ed.), The Ecocrop Database. Rome, Italy.

Fischer, G., Mahendra, S., Tubiello, F.N. & Van Veldhuizen, H. (2005) 'Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080', *Philosophical Transactions of the Royal Society B*, 360(1463), 2067–2083.

Frecon, J. 2002. *Best Management Practices For Irrigating Peach Trees*. New Jersey: Rutgers Cooperative Extension. Available: https://njaes.rutgers.edu/drought/pdfs/BMP-Irrigating-Peaches.pdf [11 March 2020].

FPEF, 2020. 2020 Fresh Fruit Export Directory. Fresh Produce Exporter's Forum. Available: https://www.fpef.co.za/wp-content/uploads/2020/07/FPEF-ED-2020-lo-res-JULY.pdf

Gizaw, M. and Gan, T. 2016. *Impact of climate change and El Niño episodes on droughts in sub-Saharan Africa. Climate Dynamics*, 49(1-2), pp.665-682.

Goldammer, T. 2018. *Grape Grower's Handbook*: *A Guide To Viticulture for Wine* Production 3rd ed. Virginia: APEX Publishers.

Griesbach, J. 2007. Growing Temperate Fruit Trees in Kenya. World Agroforestry Centre, Nairobi. 128pp.

Gutowski Jr., W. J., Giorgi, F., Timbal, B., Frigon, A., Jacob, D., Kang, H.-S., Raghavan, K., Lee, B., et al. 2016. WCRP COordinated Regional Downscaling EXperiment (CORDEX): a diagnostic MIP for CMIP6, *Geosci*. Model Dev., 9, 4087–4095, https://doi.org/10.5194/gmd-9-4087-2016

Hadebe, S., Mabhaudhi, T. and Modi, A., 2020. Sorghum best practice management recommendations based on AquaCrop modeling scenario analysis in various agro-ecologies of KwaZulu Natal, South Africa. *Physics and Chemistry of the Earth, Parts A/B/C*, 117, p.102866.

Haokip, S.W., Shankar, K. and Lalrinngheta, J., 2020. Climate change and its impact on fruit crops. *Journal of Pharmacognosy and Phytochemistry*, 9(1), pp.435-438.

Harris, I., Osborn, T.J., Jones, P. *et al.* 2020*.* Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Sci Data* **7,** 109. https://doi.org/10.1038/s41597-020-0453-3

Hayhoe, K., Edmonds, J., Kopp, R.E., LeGrande, A.N., Sanderson, B.M., Wehner, M.F., and Wuebbles, D.J. 2017. Climate models, scenarios, and projections. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 133-160, doi: 10.7930/J0WH2N54.

Hertel, T. and Rosch, S., 2010. Climate Change, Agriculture, and Poverty. *Applied Economic Perspectives and Policy*, 32(3), pp.355-385.

Hewitson, B.C. and Crane, R.G. 2006. Consensus between GCM climate change projections with empirical downscaling: precipitation downscaling over South Africa. *International Journal of Climatology,* 26(10), pp.1315-1337.

Hijmans, R.J, Phillips, S., Leathwick, J. and Elith, J. (2011), Package ‘dismo’. Available online at: http://cran.r-project.org/web/packages/dismo/index.html.

Hortgro, 2019. Key Deciduous Fruit Statistics. Available at: https://www.hortgro.co.za/markets/key-deciduous-fruit-statistics/ [Accessed 17 March 2020]

Hunter, J. and Bonnardot, V., 2011. Suitability of Some Climatic Parameters for Grapevine Cultivation in South Africa, with Focus on Key Physiological Processes. *South African Journal of Enology and Viticulture*, 32(1).

International Labour Organization, 2019. *Working On A Warmer Planet: The Impact Of Heat Stress On Labour Productivity And Decent Work*. Geneva.

IPCC, 1994: J.T. Houghton, L.G. Meira Filho, J. Bruce, Hoesung Lee, B.A. Callander, E. Haites, N. Harris and K. Maskell (Eds.) Cambridge University Press, UK. pp 339 Available from Cambridge University Press, The Edinburgh Building Shaftesbury Road, Cambridge CB2 2RU ENGLAND

IPCC, 2000: Special Report on Emission Scenarios. Summary for policy makers

IPCC, 2007. Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies. Technical Summary. IPCC Expert Meeting Report. Noordwijkerhout, The Netherlands

IPCC, 2013a: Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2013b: Annex II: Climate System Scenario Tables [Prather, M., G. Flato, P. Friedlingstein, C. Jones, J.-F. Lamarque, H. Liao and P. Rasch (eds.)]. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. pp. 1422

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp

IPCC, 2018: Summary for Policymakers. In: *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland, 32 pp

James, R. and Washington, R. 2013. Changes in African temperature and precipitation associated with degrees of global warming. *Climatic Change*, 117(4), 859-872.

Jayathilaka, P., Soni, P., Perret, S., Jayasuriya, H. and Salokhe, V., 2011. Spatial assessment of climate change effects on crop suitability for major plantation crops in Sri Lanka. *Regional Environmental Change*, 12(1), pp.55-68.

Johnston, P., Oosthuizen, H., Schulze, R., Crespo, O., Louw, D., Tadross, M., Waagsaether, K., Arowolo, S. 2016. *Modeling Impacts Of Climate Change On Selected South African Crop Farming Systems*. WRC Report No 1882/1/16. Cape Town: Water Research Commission. Available: http://www.wrc.org.za/wp-content/uploads/mdocs/1882-1-161.pdf [19 October 2020].

Kamas, J., Stein, L. and Nisbett, M. 2010. *Peaches*. Texas: Texas A and M University. Available: https://aggie-horticulture.tamu.edu/fruit-nut/files/2010/10/peaches.pdf [11 March 2020].

Kamas, J., Nisbett, M. and Stein, L. 2015a. *Apples*. Texas: Texas A and M University. Available: https://aggie-horticulture.tamu.edu/fruit-nut/files/2015/04/apples.pdf [11 March 2020].

Kamas, J., Nisbett, M. and Stein, L. 2015b. *Pears*. Texas: Texas A and M University. Available: https://aggie-horticulture.tamu.edu/fruit-nut/files/2015/04/pears.pdf [11 March 2020].

Karami, M. and Asadi, M., 2017. The Phenological Stages of Apple Tree in the North Eastern of Iran. *Computational Water, Energy, and Environmental Engineering*, 06(03), pp.269-280.

Keller, M. 2010. Managing grapevines to optimise fruit development in a challenging environment: a climate change primer for viticulturists. *Australian Journal of Grape and Wine Research*, 16, pp.56-69.

Kindt R, Abiyu A, Borchardt P, Dawson I, Demissew S, Graudal L, Jamnadass R, Lillesø J-PB, Moestrup S, Pedercini F, Wieringa J, Wubalem T. 2021. A climate change atlas for Africa of tree species prioritized for forest landscape restoration in Ethiopia. https://atlas.worldagroforestry.org/. [Accessed on 27 August 2022]

Kniveton, D., Layberry, R., Williams, C. and Peck, M. 2009. Trends in the start of the wet season over Africa. *International Journal of Climatology*, 29(9), pp.1216-1225.

Kogo, B., Kumar, L., Koech, R. and Kariyawasam, C., 2019. Modeling Climate Suitability for Rainfed Maize Cultivation in Kenya Using a Maximum Entropy (MaxENT) Approach. *Agronomy*, 9(11), p.727.

Kruger A.C. & Shongwe S. 2004. Temperature trends in South Africa: 1960–2003. *International Journal of Climatology*, 24(15), pp.1929–1945.

Kruger, A.C., Rautenbach, H., Mbatha, S., Ngwenya, S., & Makgoale, T. 2019. Historical and projected trends in near-surface temperature indices for 22 locations in South Africa. *South African Journal of Science*, *115*(5-6), 1-9. https://dx.doi.org/10.17159/sajs.2019/4846

A, Lane & A, Jarvis. 2007. Changes in Climate will modify the Geography of Crop Suitability: Agricultural Biodiversity can help with Adaptation. *Journal of SAT Agricultural Research*. 4.

Luedeling, E. 2022. ChillR: Statistical Methods for Phenology Analysis in Temperate Fruit Trees. R package version 0.72.7

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

Linvill, Dale E. 1990. "Calculating Chilling Hours and Chill Units from Daily Maximum and Minimum Temperature Observations." *HortScience* 25 (1): 14–16. https://doi.org/10.21273/HORTSCI.25.1.14.

Longstroth, M. 2016. How Should Fruit Growers Respond To Hail And Severe Storms? [online] MSU Extension. Available: https://www.canr.msu.edu/news/how_should_fruit_growers_respond_to_hail_and_severe_storms [19 June 2020].

Lyon, B. 2009. Southern Africa summer drought and heat waves: observations and coupled model behavior. *Journal of Climate*, 22(22), 6033-6046.

Makinano-Santillan, M. and Santillan, J. 2015. *GIS-Based Ecocrop Modeling To Assess Potential Climate Change Effects On Sago Palm Suitability Distribution.*

Mariotti, L., Coppola, E., Sylla, M.B., Giorgi, F. and Piani, C. 2011. Regional climate model simulation of projected 21st century climate change over an all-Africa domain: comparison analysis of nested and driving model results. *Journal of Geophysical Research D: Atmospheres*, 116(D15), D15111, doi:10.1029/2010JD015068.

Masui, T., Matsumoto, K., Hijioka, Y., Kinoshita, T., Nozawa, T., Ishiwatari, S., Kato, E., Shukla, P., et al. 2011. An emission pathway for stabilization at 6 Wm^{-2} radiative forcing. *Climatic Change*, 109(1-2), pp.59-76.

Matthews, H. and Caldeira, K. 2008. Stabilizing climate requires near-zero emissions. *Geophysical Research Letters*, 35(4).

Maúre, G., Pinto, I., Ndebele-Murisa, M., Muthige, M., Lennard, C., Nikulin, G., Dosio, A. and Meque, A. 2018. The southern African climate under 1.5 °C and 2 °C of global warming as simulated by CORDEX regional climate models. *Environmental Research Letters*, 13(6), p.065002.

Merow, C., Smith, M.J. & Silander, J.A. (2013) 'A practical guide to MaxEnt for modeling species' distributions: what it does, and why inputs and settings matter', *Ecography*, 36(10), 1058–1069.

Midgley, S.J.E., New, M., Methner, N., Cole, M., Cullis, J., Drimie, S., Dzama, K., Guillot, B., et al. 2016. *A Status Quo Review of Climate Change and the Agriculture Sector of the Western Cape Province*. Report submitted to the Western Cape Department of Agriculture and the Western Cape Department of Environmental Affairs and Development Planning. Cape Town.

Midgley, S.J.E. 2016. *Commodity value chain analysis for apples*. WWF-SA, South Africa.

Mohamed, A.K.A and El-Sese, A.M. 2009. Chilling and Heat Requirements of Some Grape Cultivars (Vitis vinifera L). *International Journal of Applied Agricultural Research* ISSN 0973-2683 Volume 4 Number 3 (2009) pp.193–202

Moise, A.F. and Hudson, D.A. 2008. Probabilistic predictions of climate change for Australia and southern Africa using the reliability ensemble average of IPCC CMIP3 model simulations. *Journal of Geophysical Research D: Atmospheres,* 113(15), D15113, doi:10.1029/2007JD009250.

Mora, C., Frazier, A., Longman, R., Dacks, R., Walton, M., Tong, E., Sanchez, J., Kaiser, L. et al. 2013. The projected timing of climate departure from recent variability. *Nature*, 502(7470), pp.183-187.

Moss, R., Edmonds, J., Hibbard, K., Manning, M., Rose, S., Vuuren, D., Carter, T., Emore, S., et al. 2010. The Next Generation of Scenarios for Climate Change Research and Assessment. *Nature*. 463. pp.747-56. 10.1038/nature08823.

National Department of Agriculture, 2000. Cultivation of Citrus [online] Available: https://www.nda.agric.za/docs/Citrus/citrus.htm [18 Mach 2020]

New, M., Hewitson, B., Stephenson, D.B., Tsiga, A., Kruger, A., Manhique, A., Gomez, B., Coelho, C.A.S., et al. 2006. Evidence of trends in daily climate extremes over southern and west Africa. *Journal of Geophysical Research D: Atmospheres,* 111(D14), D14102, doi:10.1029/2005JD006289.

Nikulin, G., Lennard, C., Dosio, A., Kjellström, E., Chen, Y., Hänsler, A., Kupiainen, M., Laprise, R., et al. 2018. *The effects of 1.5 and 2 degrees of global warming on Africa in the CORDEX ensemble*. *Environmental Research Letters*, 13(6), p.065003.

Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J., and Urquhart, P. 2014. Africa. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199-1265.

Ogundeji A.A. and Jordaan H. 2017. *A simulation study on the effect of climate change on crop water use and chill unit accumulation*. *South African Journal Science*. 2017;113(7/8), Art. #2016-0119, 7 pages. Available: http://dx.doi.org/10.17159/sajs.2017/20160119

Oteng-Darko, P., Yeboah, S., Addy, S., Amponsah, S. and Owusu Danquah, E., 2012. Crop modeling: A tool for agricultural research – A review. *E3 Journal of Agricultural Research and Development*, [online] 2(1), pp.1-6. Available at: <http://www.e3journals.org/> [Accessed 6 July 2022].

Orlowsky, B. and Seneviratne, S.I. 2012. *Global changes in extreme events: regional and seasonal dimension*. *Climatic Change*, 110(3-4), 669-696.

Piikki, K.; Winowiecki, L.; Vågen, T.-G.; Ramirez-Villegas, J.; Söderström, M. 2017. Improvement of spatial modeling of crop suitability using a new digital soil map of Tanzania. *S. Afr. J. Plant Soil*, *34*, 243–254.

Postharvestinnovation.org.za. 2022. *Post-Harvest Innovation Programme*. [online] Available at: <https://postharvestinnovation.org.za/> [Accessed 9 June 2022].

Possingham, J.V. 2004. *On The Growing Of Grapevines In The Tropics.* Acta Hortic. 662, pp.39-44. DOI: 10.17660/ActaHortic.2004.662.2

Rai, R., Joshi, S., Roy, S., Singh, O., Samir, M. and Chandra, A., 2015. Implications of changing climate on productivity of temperate fruit crops with special reference to apple. *Journal of Horticulture*, *2*(2), pp.135-141.

Ramirez-Cabral, N.Y.Z., Kumar, L. & Shabani, F. 2017. 'Global alterations in areas of suitability for maize production from climate change and using a mechanistic species distribution model (CLIMEX)', *Scientific Reports*, 7(1), 5910.

Ramirez-Villegas, J., Jarvis, A. and Läderach, P. 2013. Empirical approaches for assessing impacts of climate change on agriculture: The Ecocrop model and a case study with grain sorghum. *Agricultural and Forest Meteorology*, 170, pp.67-78.

Ramirez-Villegas J, Thornton PK. 2015. Climate change impacts on African crop production. *CCAFS Working Paper no. 119*. Copenhagen, Denmark: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., et al. 2011. RCP 8.5—A scenario of comparatively high greenhouse gas emissions. *Climatic Change*, 109(1-2), pp.33-57.

Ripoll, J., Urban, L., Staudt, M., Lopez-Lauri, F., Bidel, L. and Bertin, N. 2014. *Water shortage and quality of fleshy fruits—making the most of the unavoidable.* Journal of Experimental Botany, 65(15), pp.4097-4117.

Riter, D. 2021. *Cut-Off Low pressure systems*. [online] Eumetrain.org. Available at: <http://www.eumetrain.org/satmanu/CM4SH/S_Africa/COL> [Accessed 4 October 2021].

Rogelj, Joeri & Meinshausen, Malte & Knutti, Reto., 2012. *Global Warming under Old and New Scenarios Using IPCC Climate Sensitivity Range Estimates*. Nature Climate Change. 2. 248-253. 10.1038/nclimate1385.

Rosenzweig, C., Jones, J.W., Hatfield, J.L., Ruane, A.C., Boote, K.J., Thorburn, P., *et al*. (2013) 'The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies', *Agricultural and Forest Meteorology*, 170, 166–182.

Roux, A., Jarmain, C., and Goudriaan, R. 2016. FRUITLOOK: A SPACIAL APPROACH TO ASSESS AND IMPROVE WATER USE EFFICIENCY OF VINEYARDS AND DECIDUOUS FRUIT ORCHARDS IN SOUTH AFRICA. 2nd World Irrigation Forum (WIF2) 6-8 November 2016, Chiang Mai, Thailand. W.1.4.30

Sanderson, M.G., Hemming, D.L., and Betts, RA. 2011. Regional temperature and precipitation changes under warming. *Philosophical Transactions of the Royal Society* A, 369(1934), 85-98.

SASA. 2022. *The Sugar Industry at a Glance | The South African Sugar Assocciation*. [online] Available at: <https://sasa.org.za/the-sugar-industry-at-a-glance/> [Accessed 22 July 2022].

Schaffer, B., Andersen, P. and Ploetz, R. 1992. *Responses of Fruit Crops to Flooding*. Horticultural Reviews, pp. 257-313.

Schulze, R.E. and Maharaj, M. 2007. *Positive Chill Units*. *In:* Schulze, R.E. (Ed). 2007. South African Atlas of Climatology and Agrohydrology. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/06, Section 10.1.

Shabani, F., Kumar, L. and Taylor, S., 2012. Climate Change Impacts on the Future Distribution of Date Palms: A Modeling Exercise Using CLIMEX. *PLoS ONE*, 7(10), p.e48021.

Sharma, S. and Manjeet, M., 2020. Heat Stress Effects in Fruit Crops. *Agricultural Reviews*, 41(01).

Shongwe, M.E., Van Oldenborgh, G.J., Van Den Hurk, B.J.J.M., De Boer, B., Coelho, C.A.S., and Van Aalst, M.K. 2009. *Projected changes in mean and extreme precipitation in Africa under global warming. Part I: southern Africa*. Journal of Climate, 22(13), pp.3819-3837

Skendžić, S., Zovko, M., Živković, I., Lešić, V. and Lemić, D. 2021. The Impact of Climate Change on Agricultural Insect Pests. Insects, 12(5), p.440.

Solomon, S., Plattner, G., Knutti, R. and Friedlingstein, P. 2009. Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences*, 106(6), pp.1704-1709.

Sillmann, J. and Roeckner, E. 2008. Indices for extreme events in projections of anthropogenic climate change. *Climatic Change*, 86(1-2), 83-104.

Singh, P., Upadhyay, R. K., Bhatt, H. P., Oza, M. P., and Vyas, S. P.: CROP SUITABILITY ANALYSIS FOR CEREAL CROPS OF UTTAR PRADESH, INDIA, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-5, 353–360, https://doi.org/10.5194/isprs-archives-XLII-5-353-2018, 2018.

SATGI, 2020. South African Table Grape Industry. [online] Available: https://www.satgi.co.za [18 March 2020].

Stein, L., Kamas, J. and Nisbett, M. 2015. *Plums and Stone Fruit*. [ebook] Texas: Texas A and M University. Available: https://aggie-horticulture.tamu.edu/fruit-nut/files/2015/04/plums_and_stone_fruit.pdf [11 March 2020].

Tabor, K. and Williams, J., 2010. Globally downscaled climate projections for assessing the conservation impacts of climate change. *Ecological Applications*, 20(2), pp.554-565.

Tadross, M., Suarez, P., Lotsch, A., Hachigonta, S., Mdoka, M., Unganai, L., Lucio, F., Kamdonyo, D., et al. 2009. Growing-season rainfall and scenarios of future change in southeast Africa: implications for cultivating maize. *Climate Research*, 40(2-3), pp.147-161.

Teixeira, A.H. de C., Tonietto, J., Pereira, G.E., Hernandez, F.B.T., Angelotti, F. and Lopes, H.L. 2014. *Agro-Climatic Suitability Delimitation For Table And Wine Grape Crops Under Irrigation Conditions In Northeastern Brazil*. Acta Hortic. 1038, pp.277-286
DOI: 10.17660/ActaHortic.2014.1038.33

Teel, W. 2019. Catching Rain: Sand Dams and Other Strategies for Developing Locally Resilient Water Supplies in Semiarid Areas of Kenya. In: Bamutaze, Y., Kyamanywa, S., Singh, B., Nabanoga, G., Lal, R. (eds) *Agriculture and Ecosystem Resilience in Sub Saharan Africa.* Climate Change Management. Springer, Cham. https://doi.org/10.1007/978-3-030-12974-3_15

Tharaga, P.C. 2014. *Impacts of Climate Change on Accumulated Chill Units at Selected Fruit Production Sites in South Africa*. University of the Free State

Thomson, A., Calvin, K., Smith, S., Kyle, G., Volke, A., Patel, P., Delgado-Arias, S., Bond-Lamberty, B., Wise, M., Clarke, L. and Edmonds, J. 2011. RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Climatic Change*, 109(1-2), pp.77-94.

Tuma, M. 2018. *WCRP Spotlight: The Coordinated Regional Climate Downscaling Experiment (CORDEX)*. [online] Wcrp-climate.org. Available: https://www.wcrp-climate.org/news/wcrp-newsletter/wcrp-news-articles/1347-wcrp-spotlight-the-coordinated-regional-climate-downscaling-experiment-cordex [13 April 2020].

United Nations, 2015. *Paris Agreement*. Paris: United Nations, pp.1-27.

CCSP, 2008. Climate Models: An Assessment of Strengths and Limitations. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Bader D.C., C. Covey, W.J. Gutowski Jr., I.M. Held, K.E. Kunkel, R.L. Miller, R.T. Tokmakian and M.H. Zhang (Authors)]. Department of Energy, Office of Biological and Environmental Research, Washington, D.C., USA, 124 ppUsman, M. and Reason, C. 2004. Dry spell frequencies and their variability over southern Africa. *Climate Research*, 26, pp.199-211.

Vanalli, C., Casagrandi, R., Gatto, M., Bevacqua, D. 2021. Shifts in the thermal niche of fruit trees under climate change: The case of peach cultivation in France. *Agricultural and Forest Meteorology*, 300 (2021) 108327.Van den Bergh I, Ramirez J, Staver C, Turner DW, Jarvis A, Brown D. Climate change in the subtropics: The impacts of projected averages and variability on banana productivity. In: Wuensche JN, Gubbuk H, Reinhardt DH, Staver C, Van den Bergh I, Albrigo LG, eds. *Acta Horticulturae* 928 XXVIII International Horticultural Congress on Science and Horticulture for People (IHC2010): International Symposium on Citrus, Bananas and other Tropical Fruits under Subtropical Conditions. Lisbon, Portugal: International Society for Horticultural Science. p. 89-99

van Leeuwen, C. and Darriet, P. 2016. The Impact of Climate Change on Viticulture and Wine Quality. *Journal of Wine Economics*. 11. 150-167. 10.1017/jwe.2015.21.

Verma, M. 2014. Pear Production Technology. In: S. Singh, A. Munshi, K. Prasad and A. Sureja, ed., *Training manual on teaching of post-graduate courses in horticulture (Fruit Science)*, 1st ed. New Delhi: Post Graduate School, Indian Agricultural Research Institute.

Walther G.R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J.C., Fromentin, J.M., Guldberg, H.O. et al. 2002. Ecological responses to recent climate change. *Nature* 416: 389–95.

Wayne, G. 2013. *The Beginner'S Guide To Representative Concentration Pathways*. Available: https://www.skepticalscience.com/rcp.php [2 April 2020].

White, J.W., Hoogenboom, G., Kimball, B.A. & Wall, G.W. (2011) 'Methodologies for simulating impacts of climate change on crop production', *Field Crops Research*, 124(3), 357–368.

Williams, M. 1978. *Pear Production*. Washington, D.C.: U.S. Dept. of Agriculture, Science and Education Administration.

Yang, Q., Gao, Y., Wu, X. et al. 2021. Bud endodormancy in deciduous fruit trees: advances and prospects. *Hortic Res* 8, 139. https://doi.org/10.1038/s41438-021-00575-2

Zinyengere, N., Crespo, O., Hachigonta, S., Tadross, M. 2015. Crop model usefulness in drylands of southern Africa: an application of DSSAT. South African Journal of Plant and Soil, Foundation for Education Science and Technology. Bureau for scientific publications., 2015, 32 (2), pp.95-104. ff10.1080/02571862.2015.1006271ff. ffhal-01161900v2f