Impact of climate change on yield and water use efficiencies of potato in different production regions of South Africa

AC Franke[1]*, LN Muelelwa[1] and JM Steyn[2]

[1] *University of the Free State, Department of Soil, Crop and Climate Sciences, Bloemfontein 9301, South Africa*
[2] *University of Pretoria, Department of Plant and Soil Sciences, Pretoria 0002, South Africa*
**Corresponding author, email: FrankeAC@ufs.ac.za*

In South Africa, the potato is produced in regions with different climates. Climate change is expected to result in higher temperatures, thus increasing the incidence of heat stress, but lowering the risk of frosts in mid-altitude areas. Increasing ambient carbon dioxide levels can enhance photosynthetic rates and reduce water use of potato. This study assessed the impact of climate change on potential yield and water use efficiency (WUE) in twelve potato production regions of South Africa using the LINTUL-POTATO crop model. With current planting times, simulated yields between 1 961 and 2 050 increased by 0.02 and 0.40 t ha^{-1} y^{-1} and WUE by 0.00 and 0.08 g l^{-1} y^{-1} evapotranspired. Improvements in yields and WUE were close to zero when the crop was grown in hot periods, as an increasing incidence of heat stress and higher evapotranspiration largely discounted benefits of higher CO_2 levels. This was particularly the case in the interior production regions, where expected temperature increases were most severe. In many regions, potato growers are likely to respond to climate change by advancing planting time. Often a trade-off existed between maximising yield and WUE. A compromise could be achieved by planting as early as possible in the optimum spring planting window for summer crops.

Keywords: CO_2 fertilization, climate change adaptation, crop modelling, heat stress, yield variability

Introduction

Potato is adapted to cool conditions and is regarded as a heat-sensitive crop due to its originating in the cool Andes mountains, as well as early potato breeding work done in Europe (George et al. 2017). Soil temperatures above 18 °C tend to reduce tuber yields, especially when combined with high ambient temperatures (above 30°C day / 23 °C night) (Monneveux et al. 2014). Photosynthetic rates of potato drop due to excessive respiration as air temperatures increase beyond 30 °C and come to a standstill with temperatures above 35 °C (Haverkort and Struik 2015).

In South Africa, potato is often grown under relatively warm conditions, with frequent occurrences of climatic stresses such as frost, heat and hail (van der Waals et al. 2016). Temperatures in South Africa are increasing due to climate change, with the already warm interior regions anticipating temperature increases of twice those of the global average (Engelbrecht et al. 2015). It is thus likely that climate change will lead to increased heat stress in potato in South Africa, which may be compounded by increased drought stress if supplementary irrigation is insufficient (George et al. 2017). Potato is also a crop that responds strongly to increases in ambient CO_2 levels, showing higher photosynthesis rates and lower water use with higher CO_2 levels. This beneficial impact of enhanced ambient CO_2 levels is likely to be stronger in longer-duration potato varieties than in short-duration varieties (Schapendonk et al. 2000). The positive impact of higher CO_2 levels has the potential to counteract the negative impacts of increased heat stress due to climate change, depending on local growing conditions.

In South Africa, potato is grown as both a summer and a winter crop in a diverse range of climates. The impacts of changing climate variables on yields and water use efficiency are non-linear, interact with each other, and are likely to differ between regions. Haverkort et al. (2013) and Franke et al. (2013) used climate predictions and a potato crop growth model (LINTUL-POTATO) to assess the impact of climate change in three regions of South Africa: the Sandveld, Limpopo (Dendron area) and the Eastern Free State. They reported that increased CO_2 levels are likely to enhance photosynthetic rate and reduce water use by potato. Furthermore, they observed that yield and water use efficiency of potato can benefit from climate change if potato can be grown in the most suitable period of the year. In the Eastern Free State, potato farmers can further benefit from a lengthening of the frost-free period suitable to grow potato if varieties with longer growing periods can be made available. In Limpopo, the length of the season suitable to grow potato is determined by the heat-free period, which is likely to shorten due to climate change, and the optimum planting time is likely to shift from late winter to autumn, as winter frost may well disappear. The studies highlighted that the impact of climate change on potato yield is highly region-specific, and among others, depends on the current climatic conditions during the growing season. Similarly, the possibilities for farmers to adapt to climate change differed between regions.

The LINTUL-POTATO model calculates potato dry matter production from the amount of radiation intercepted by its green foliage and a conversion factor (radiation use efficiency (RUE)) on a daily basis. In the model, RUE depends on temperature as well as ambient CO_2 levels. The model has been described in detail by Haverkort et al. (2015) and validated across a range of climates and varieties in the Netherlands, Hawaii, Israel, the Philippines, Peru and Tunisia (Kooman 1995; Raymundo et al. 2014). Besides the studies on the impact of climate change on potato production (Franke et al. 2013; Haverkort et al. 2013), the model has been used to quantify and explain gaps between actual yields and potential yields at the farm and regional level in South Africa (Franke et al. 2011; Steyn et al. 2016), Argentina (Caldiz et al. 2002) and Chile (Haverkort et al. 2014).

The current study assessed the impact of climate change on the potential yield and potential water use efficiency (WUE), as well as possibilities to adapt to climate change through changes in planting time in the twelve other potato production regions of South Africa (Figure 1). This is relevant, as the impact of climate change is likely to differ between regions. Also, in addition to the studies by Haverkort et al. (2013) and Franke et al. (2013), the current study assessed changes in yield variability over time, testing the common assumption that crop yields in South Africa will become more variable in future due to climate change (Anonymous 2012).

The following research questions were addressed in this study:

1. How will climate change affect climatic conditions (temperature, precipitation, radiation) in the 12 potato growing areas of South Africa?
2. What is the impact of climate change on the potential yields and water use efficiencies of potato in the 12 different regions?
3. What are the possibilities for adaptation to climate change, specifically the possibilities for changing planting times and growing seasons?

Material and methods

The methods largely followed the approaches used by Haverkort et al. (2013) and Franke et al. (2013) to assess the impact of climate change in three other potato production regions of South Africa (Limpopo, the Eastern Free State and the Sandveld). Climate predictions were obtained by downscaling Global Circulation Models (GCMs) for 12 potato production regions in South Africa (Figure 1; Table 1). Daily minimum and maximum temperature, relative humidity, wind speed, rainfall and radiation were simulated for the period 1960 to 2050, using the A2 SRES (between RCP 6.0 and RCP 8.5) scenario for future global greenhouse gas emissions. This scenario assumes that ambient CO_2 levels will increase from 315 ppm in 1960 to around 550 ppm in 2050. Predictions from six CMIP3 GCM downscalings were compared using data from a weather station at Bloemhof between 1999 and

Figure 1: Map of South Africa showing the major potato producing regions.

Table 1: Potato growing regions studied, their coordinates used to downscale climate projections, the name of the weather station used to verify climate predictions, planting dates used in the business-as-usual scenarios and assumed soil properties used in simulations.

Region	Abbreviation	Coordinates	Altitude (m) [1]	Weather station name	Planting date	Predominant soil (silt+clay %)	Soil water content at field capacity (mm/m)	Soil water content at wilting point (mm/m)
Ceres	Ceres	33.5° S 19.5° E	400	Ceres	15 Oct	3–10	80	40
Gauteng	GT	26.0° S 28.5° E	1650	Johannesburg WO	15 July	20–25	220	100
Eastern Cape	ECape	34.0° S 25.0° E	80	Hankey	15 March / 1 Aug	20–30	240	120
Northern Cape	NCape	29.0° S 25.0° E	1200	Kimberly WO	15 Jan	15–25	200	80
North Eastern Cape	NECape	31.0° S 28.0° E	1800	Barkly East (Caerleon)	15 Sep	15–25	200	80
North-West	NW	27.0° S 24.0° E	1300	Vryburg WO	1 Aug / 1 Jan	10–15	160	50
KwaZulu-Natal	KZN	29.0° S 30.0° E	1250	Estcourt WO	1 Aug	20–30	240	120
Mpumalanga	Mp	26.0° S 30.0° E	1600	Ermelo WO	1 Aug	15–25	200	80
Loskop Valley	Loskop	25.0° S 29.0° E	1000	Oudestad	15 June	15–25	200	80
South Western Free State	SWFS	29.0° S 25.5° E	1200	Fauresmith	15 Aug	15–20	200	80
Southern Cape	SCape	34.0° S 22.0° E	200	Mossel Bay WO	15 July	15–20	180	60
Western Free State	WFS	28.0° S 25.0° E	1200	Bloemhof	15 Jan	15–20	180	60

[1] Approximate altitude of production fields nearby the coordinates (source: Google Earth)

2011, representing weather conditions in the potato growing area of the western Free State. The results indicated that none of the six downscalings was consistently better at predicting climate conditions than the others. Therefore, the predictions from the FGDI20 model were arbitrarily chosen for further work in this study.

Predicted weather data were verified and calibrated with data from weather stations in each of the potato production regions. Daily weather data from stations located close to production areas were obtained from the South African Weather Service (SAWS) (Table 1). In Ceres, long-term monthly averages were used since SAWS could not provide the data. Monthly averages were calculated and compared with the simulated data from each of the 12 regions over the same periods. A calibration was made in the simulated data according to the difference between the long-term simulated and observed monthly data. The calibrated simulated data were used to assess how the climate of the main potato growing season changed between 1961 and 2050. The common planting times shown in Table 1 were used and a crop growing period of 120 days was assumed. The verified climate predictions were used as input for the LINTUL-POTATO crop growth model which was adapted to South African growing conditions (Franke et al. 2011; Haverkort et al. 2013; Haverkort et al. 2015). The model calculates, among others, potential yield, potential evapotranspiration, potential WUE (based on potential yield and potential evapotranspiration when water is not limiting), and the irrigation deficit.

Climate input data required by the model included daily minimum and maximum temperatures, incoming solar radiation and rainfall, reference evapotranspiration and CO_2 concentration. Management input data included the depth and date of planting. Accumulated degree days from planting with a base temperature of 2 °C determined the time to crop emergence and leaf area development. Phenological development of a potato crop depends on temperature. Higher temperatures lead to earlier crop emergence and a more rapid initial leaf growth, resulting in increased interception of solar radiation at early stages of crop growth. In the model, the leaf area index (LAI) increased exponentially from crop emergence until an LAI of 0.75 was achieved, based on degree-days. Thereafter, development depended on temperature until full crop cover is reached (LAI > 3). Daily biomass growth was calculated using the LAI, radiation interception (using an extinction coefficient of 1), and RUE (1.25 g dry matter MJ^{-1} of intercepted total radiation under optimal conditions) of the crop. In the model, photosynthetic capacity was reduced when the average day temperature fell below 16 °C or when the maximum temperature exceeded 30 °C and was completely halted at temperatures below 2 °C and above 35 °C. The harvest index for all cropping situations was set at 0.75. Simulated yields are presented as tuber fresh matter, assuming a tuber dry matter concentration of 20%.

Daily evapotranspiration (ET) for potatoes was calculated from the Penman-Monteith grass reference evapotranspiration (ETo) multiplied by a crop specific coefficient (K_c). Evaporation from the soil was based on the assumption that a soil with an average water holding capacity that is wetted every four days by irrigation or rain has an evaporation rate that is one-third of ETo until emergence of the crop. Thereafter evaporation from the soil linearly decreased with ground cover (calculated from LAI) to 10% of ET at full ground cover at an LAI value of 3 and above (Haverkort et al. 2015). A comparison of calculated irrigation need, based on the LINTUL-POTATO model, and actual irrigation rates in the different growing regions of South Africa was done by Steyn et al. (2016).

In the model, both RUE and the crop coefficient (K_c) were affected by changing ambient CO_2 levels. Jaggard et al. (2010) found a net potato yield increase of 28.5% resulting from CO_2 and O_3 increase between 2010 and 2050, with an expected CO_2 concentration increase of 190 ppm (the FACE experiments took place around the year 2000 with a CO_2 concentration of 360 ppm). In the model, the relative increase (after 1990 when RUE was assessed) or decrease (before 1990) in RUE per ppm CO_2 change was therefore 0.15% of 1.25 g MJ^{-1} = 0.001875 g MJ^{-1} ppm^{-1} CO_2. Similarly, the impact of changing CO_2 levels on the crop coefficient K_c was modelled. Jaggard et al. (2010) assumed an 11% decrease in water use by potato during a crop season of unmodified length between 1990 and 2050, when the CO_2 concentration increased by 190 ppm. Hence between 1960 (315 ppm) and 2050 (550 ppm) potato is expected to use 13.6% less water. In the model, the crop coefficient was thus reduced from 1.20 in 1990 to 1.07 in 2050 and increased before 1990 as a function of atmospheric CO_2 levels.

To estimate ET, WUE by the crop, and drainage, a water balance was determined using the plant available water of the most prominent soil in the region (Table 1). When rainfall was in excess of what the soil can hold, it drained below the rooting zone (assumed to be 0.5 m deep throughout South Africa). The model did not consider the loss of water through run-off, as run-off cannot be reliably estimated based on daily weather data. Farmers were assumed to irrigate when 50% of the plant available water was depleted. In case they irrigated just prior to an excessive rainstorm, most precipitation was lost through drainage according to the model. In case a farmer irrigated just before a rainfall event, 50% of the plant available water was utilised and any excess was lost through drainage. It was, therefore, assumed that only daily rainfall that was not in excess of 25% of the plant available water was available for crop growth. It was also assumed that water was available for irrigation when needed. The most common current planting times were used as input to the model (Table 1). A planting depth of 200 mm was assumed.

To assess adaptation strategies, the potential yield and water use of potatoes in each region were simulated, when planting was done on the 15th day of every month of the year. These simulations were done for three 30-year periods: 1961–1990, 1991–2020 and 2021–2049. The forecasted yields and WUEs for each month of planting were then used to assess which planting months or periods would give the best yields and WUEs for each region in future.

Simple linear regression was used between year and weather parameters and between year and simulated crop parameters to derive an estimate of the value of weather and crop parameters in 1960 and 2050 (Tables 2 and 3). Furthermore, the significance of trends in weather and crop parameters over time was assessed by testing the significance of the slope of the regression lines. The R^2 values generated by the regression analyses represent the percentage of variability in a weather or crop parameter accounted for by year, indicating the importance of long-term climate change in explaining year-to-year variability. The coefficient of variation of yield and water use efficiency (the standard deviation divided by the mean multiplied by 100%) was calculated for three periods (1961–1990, 1991–2020, 2021–2050) for each region to assess changes in variability in these parameters over time (Table 4).

Results

Impact of climate change with current management

The predicted changes in minimum and maximum temperature between 1960 and 2050 varied between 1.4 °C and 2.9 °C for the different regions (Table 2). In general, the interior regions (for example Gauteng, Loskop Valley, Mpumalanga, the Free State and North West) faced stronger increases in minimum and maximum temperatures than the coastal regions (for example Ceres, the Southern Cape and the Eastern Cape) where a moderating influence from the ocean was present. The R^2 values of the regression analyses between year and mean minimum and maximum temperature during the cropping season varied between 20% and 73% (data not given) and the slopes of the regression lines were highly significant for all sites ($p < 0.001$).

Changes in rainfall over the growing season between 1960 and 2050 were relatively small (Table 2) and were likely to be the result of stochastic effects, rather than real long-term trends. Changes in rainfall over time were not significant ($p < 0.1$). Annual variability in rainfall was high, irrespective of any impact of climate change. The R^2 values of the regression between year and rainfall was below 2% for all sites, indicating that long-term trends explained almost nothing of the annual variability in rainfall.

No significant trends in daily radiation were observed between 1960 and 2050 ($p > 0.1$), although in most sites there was a slight decrease in radiation over the study period, presumably due to a higher degree of cloudiness. The number of hot days (Tmax > 30 °C reducing photosynthesis rate) and very hot days (Tmax > 35 °C with photosynthesis coming to a standstill) drastically increased in the interior growing regions (the Northern Cape, North West, and the Western Free State) (Table 2). They increased moderately in Ceres, KwaZulu-Natal, Loskop Valley and the south western Free State, but in 2050 temperatures only occasionally passed 35 °C in these regions. In the coastal production regions (the Eastern and Southern Cape), the North Eastern Cape (mid-altitude) and in Mpumalanga (mid-altitude and planting in late winter) hot days remained a scarce phenomenon in 2050.

For all sites, potential fresh tuber yields increased between 1960 and 2050 (Table 3). In all situations, the potato crop benefitted from elevated CO_2 levels reaching 550 ppm in 2050, but in some cases this was strongly counteracted by increased heat stress. The simulated yield increases were especially large (≥ 0.22 t ha^{-1} y^{-1}) for regions where the crop is planted in winter or early spring (June–August) at mid-altitudes (Mpumalanga, Loskop Valley, the Eastern Cape, the Southern Cape, and Gauteng). Later in the study period, frost events in winter plantings became less frequent and eventually disappeared in many of the current growing seasons. Also in the North Eastern Cape (mid-altitude) with planting in September, substantially higher yields were achieved towards 2050 for the same reasons, although frost damage did not entirely disappear over the study period. Small or close to zero yield increases were simulated in North West (planting in January and August), the Northern Cape and the western Free State (Table 3). In all these situations, the average Tmax during the growing season was around 30 °C in 2050 and the number of hot and very hot days during the growing season greatly increased over the study period (Table 2). While these interior regions recorded some of the highest yields in 1961 due to high radiation levels, the yields were below the average of the 12 regions (69.6 t ha^{-1}; Table 3) by 2050.

Regional trends in WUE followed, in large lines, the patterns in yields (Table 3) with WUE increasing in all situations. Evapotranspiration did not greatly change between 1961 and 2050 (Table 3). Warmer temperatures, leading to higher evapotranspiration, are compensated for by higher CO_2 levels, reducing water use by the crop (if all else stays the same). The substantial improvements in WUE could be primarily attributed to higher yields, and to a lesser extent to lower seasonal evapotranspiration. Accumulated rainfall during the growing season (Table 2) was in all cases well below the evaporative demand of the crop (Table 3), implying that supplementary irrigation is required. Precipitation deficits, being a proxy of the amount of irrigation water needed, were not greatly affected over

Table 2: Mean maximum and minimum temperature, accumulated rainfall, mean daily radiation and the number of hot (Tmax > 30°) and very hot (Tmax > 35 °C) days during the growing season in 1960 and in 2050. Values were predicted by regression models.

	Tmax (°C)		Tmin (°)		Rain (mm)		Radiation (MJ m^{-2} d^{-1})		No. of hot days		No. of very hot days	
	1960	2050	1960	2050	1960	2050	1960	2050	1960	2050	1960	2050
Ceres / Oct	24.3	26.0	10.1	12.0	99	107	16.9	16.5	17	28	1	4
ECape / March	19.5	21.0	12.8	14.8	241	223	14.9	14.7	0	0	0	0
ECape/ August	18.9	20.3	13.2	14.9	208	219	21.0	20.3	0	1	0	0
GT / Aug	22.6	25.3	10.2	12.6	286	279	17.5	17.7	3	15	0	1
KZN / Aug	23.1	25.8	8.8	11.1	226	218	13.2	13.0	15	34	0	5
Loskop / June	24.4	27.2	6.5	9.1	59	54	17.2	17.2	16	35	1	7
Mp / Aug	21.0	23.7	7.9	10.2	305	297	19.3	19.4	1	10	0	0
NCape / Jan	28.2	30.4	13.6	15.9	240	262	19.2	18.9	42	59	5	20
NECape / Sep	21.8	24.0	6.1	8.4	278	290	17.1	16.7	0	6	0	0
NW / Aug	26.8	29.7	7.9	10.7	109	109	21.4	21.3	44	73	3	17
NW / Jan	27.7	30.1	11.9	14.6	255	280	19.6	19.2	38	64	0	17
SCape / July	18.6	20.0	10.3	12.1	228	240	11.8	11.5	5	6	1	1
SWFS / Aug	23.2	26.0	5.1	7.8	121	125	22.1	21.8	16	37	0	4
WFS / Jan	27.3	29.8	11.1	13.6	234	262	19.6	19.3	31	58	0	13

Table 3: Simulated fresh yield, water use efficiency (WUE), evapotranspiration (ET), and precipitation deficit in 1961 and 2050 and the annual change therein. Values were predicted by a regression model.

Region/ planting month	Tuber yield (t ha^{-1})			WUE (g l^{-1} ET)			ET (mm)			Precipitation deficit (mm)		
	1961	2050	Δ yr^{-1}	1961	2050	Δ yr^{-1}	1961	2050	Δ yr^{-1}	1961	2050	Δ yr^{-1}
Ceres / Oct	55.0	73.2	0.21	6.5	8.9	0.03	565	548	-0.2	457	440	-0.2
ECape / March	36.0	50.8	0.16	8.2	12.5	0.05	416	397	-0.2	190	176	0.2
ECape / Aug	63.9	88.3	0.27	11.5	12.9	0.06	512	498	-0.3	154	147	-0.1
GT / Aug	54.0	80.8	0.30	11.7	17.2	0.06	464	476	0.1	187	208	0.2
KZN / Aug	39.6	52.0	0.14	8.7	11.5	0.03	452	449	0.0	170	179	0.1
Loskop / June	37.3	56.7	0.22	11.6	17.1	0.06	317	329	0.1	268	288	0.2
MP / Aug	53.6	89.5	0.40	12.1	19.0	0.08	445	479	0.4	156	198	0.5
NECape / Sep	38.8	64.2	0.28	8.7	14.6	0.07	426	434	0.1	124	113	-0.1
NCape / Jan	61.0	67.1	0.07	10.0	11.9	0.02	610	570	-0.4	384	325	-0.7
NW / Jan	60.4	67.1	0.07	10.3	12.2	0.02	583	555	-0.3	340	295	-0.5
NW / Aug	60.5	62.6	0.02	9.2	9.7	0.00	653	643	-0.1	518	501	-0.2
SCape / Aug	51.7	73.8	0.25	11.7	18.1	0.07	434	404	-0.3	223	182	-0.5
SWFS / Aug	55.3	80.3	0.28	10.5	14.3	0.04	527	565	0.4	385	413	0.3
WFS / Jan	56.6	68.1	0.13	9.6	11.7	0.02	586	581	-0.1	358	330	-0.3
Unweighted mean of all regions	51.7	69.6	0.20	10.0	13.7	0.04	524	517	-0.1	252	245	-0.1

time, suggesting that potato can be grown with the same amount of irrigation water per unit area in future. The precipitation deficit, however, did greatly differ between regions, with some regions requiring considerably more additional irrigation than others.

Yield stability

Variability in yield and WUE was generally high in areas where potato was occasionally affected by frost (e.g. Loskop Valley, Gauteng, Mpumalanga, the north Eastern Cape and the south western Free State) (Table 4). Early in the season, frost damages the canopy, but the crop may recover at this stage. Later in the season, frost terminates crop growth. In these areas, variability in yield and WUE generally decreased over time, as frost events became rarer although they did not entirely disappear in areas such as the North Eastern Cape and Loskop Valley, with planting in June. In most other areas, the variability in yield and WUE increased over time (Table 4) due to an increased incidence of heat stress. Towards the end of the study period, heat stress became increasingly detrimental to crop yield, especially in the interior regions (the western Free State, North West and the Northern Cape), but in relatively cool years yields were high due to the positive effects of elevated CO_2 levels leading to more erratic yields, as indicated by a high coefficient of variation (Table 4). In some regions, e.g. in the South Western Free State, both processes (reduced frost incidence and increased heat incidence over time) occurred.

Adaptation of planting time

In general, the planting month that provided the highest potential fresh tuber yield was not the same as the month giving the highest WUE (Figure 2). Crops growing in summer tended to give the highest potential yields due to the high radiation available in summer, provided major heat stress could be avoided. Crops growing in cooler periods of the year tended to achieve a higher WUE, despite lower yields (Figure 2). In many regions, the optimum planting time for yield in late winter and spring advanced by approximately one month over the study period (Figure 2). In all regions where farmers currently plant in late winter or early spring (the Eastern, north Eastern and Southern Cape, Gauteng, Loskop Valley, Mpumalanga, KwaZulu-Natal and the south western Free State), the current planting dates were not the dates giving the highest potential yield (Figure 2). Towards the end of the study period, current planting dates were closer to the optimum date for yield and WUE. In Loskop Valley, the optimum planting period shifted from late winter / spring to late summer / early autumn, when potential yields and WUE became highest. Farmers in the interior regions, whose main planting time is in January and August / September (the Northern Cape, North West, and the western Free State) had few opportunities to change planting time to avoid heat stress and their current planting times remained optimal towards 2050. In the Ceres region, the current planting time (October) will remain the most optimal towards 2050.

Discussion

Potato is a crop that responds strongly to the fertilizing effect of increasing ambient CO_2 levels. While most staple crops such as maize, wheat and rice only respond modestly to rising CO_2 levels, potato is expected to grow 28.5% faster and use 11% less water if CO_2 levels increase from 360 ppm (year 2000) to 550 ppm (2050). These figures have been confirmed by various studies (Miglietta et al. 1998; Schapendonk et al. 2000; Vorne et al. 2002; Magliulo et al. 2003; Jaggard et al. 2010). These studies did not, however, take into account the impact of changing temperatures on potato yields. In this study, where potato is grown in an already hot environment, increasing temperatures due to climate change intensified heat stress and negatively affected yield and yield stability. In relatively cool environments, increasing temperatures enhanced the beneficial impact of rising CO_2 levels on yield, leading to higher yield increases than expected from increases in CO_2 levels alone. In areas where frost was a risk to potato production, rising temperatures reduced the risk of frost, which improved yield stability. This corroborates findings in Europe, where irrigated potato yields are expected to increase in future due to higher CO_2 levels (Wolf and van Ooijen 2002) and crop development is expected to be

Table 4: The Coefficient of Variation (%) of the simulated fresh tuber yield and water use efficiency (WUE) for the periods 1961–1990, 1991–2020, and 2021–2050.

Region/planting month	Tuber yield			WUE		
	1961–1990	1991–2020	2021–2050	1961–1990	1991–2020	2021–2050
Ceres / Oct	4.1	4.4	6.7	4.9	5.3	8.2
ECape / March	4.8	4.6	5.3	5.4	5.2	7.6
ECape / Aug	4.1	4.7	6.0	3.4	3.6	7.1
GT / Aug	9.1	6.6	7.1	4.6	6.4	10.3
SCape / Aug	4.7	4.7	6.2	4.5	4.1	6.4
KZN / Aug	6.8	7.7	7.4	10.1	13.2	10.4
Loskop / June	16.6	31.6	14.7	14.5	30.0	16.0
MP / Aug	15.2	7.6	7.3	7.7	5.6	8.7
NECape / Sep	33.5	42.9	17.9	27.0	31.7	11.7
NCape / Jan	9.6	15.6	13.5	9.3	15.9	16.5
NW / Jan	11.3	17.4	15.8	9.3	15.6	16.7
NW / Aug	11.0	18.8	17.4	14.0	18.4	18.9
SWFS / Aug	17.3	12.9	12.7	13.6	13.1	12.9
WFS / Jan	12.3	21.7	17.4	10.1	19.5	19.3

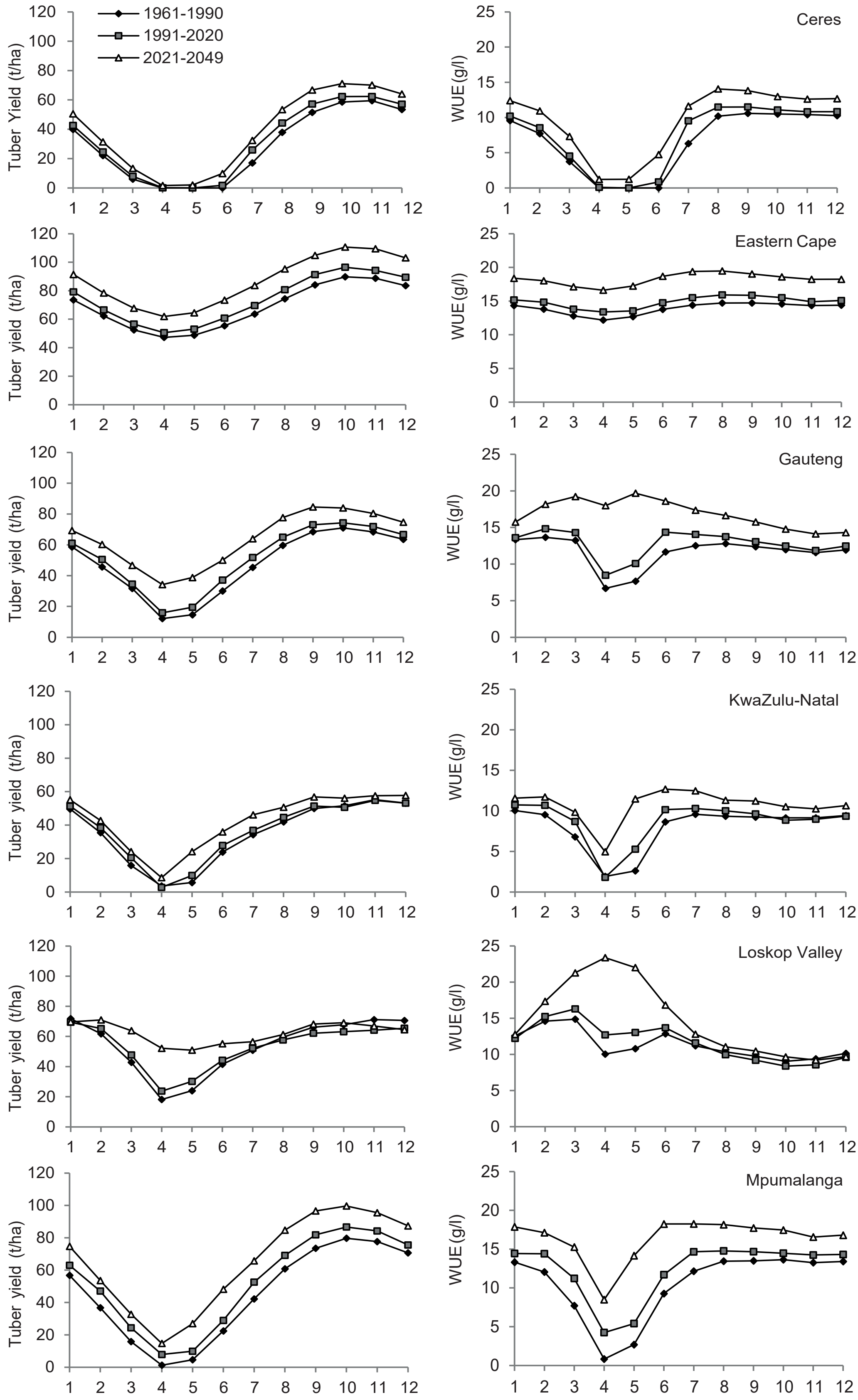
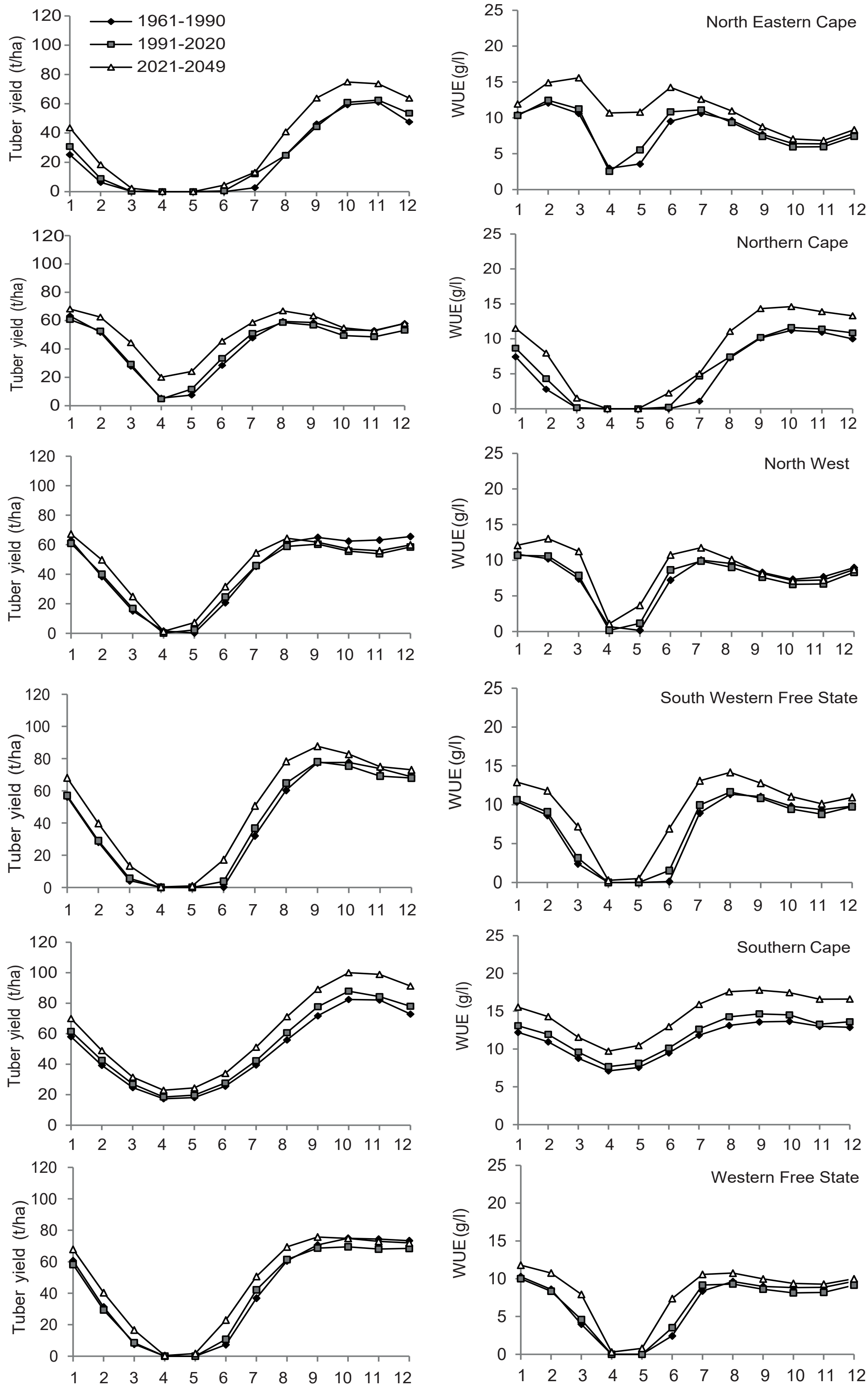


Figure 2: Impact of planting month on fresh tuber yield and water use efficiency (WUE) different growing regions. Values on the *x*-axes indicate the planting month.

Figure 2: continued.



enhanced in cool environments as temperatures increase in the future (Pulatov et al. 2015).

In this study, optimum planting dates for highest yields often did not coincide with the highest WUE. Crops required up to 60% more water per unit of potato produced (Figure 2) due to the higher evaporative demand during the hotter summer months when potential yields were highest. There was thus often a high water use penalty to achieve highest yields. With an increasing pressure to reduce water use for crop production, growers should select planting dates that will give the best compromise between high yields and WUE. This was generally achieved by planting as early as possible in the optimum spring planting window for summer crops. Farmers planting in winter or early spring currently tend to plant earlier than optimal for yield, and as a result crop development is slowed down by cold early in the season and crops are occasionally damaged by frost. Farmers who plant in August typically try to take advantage of the December markets when potato prices tend to be high. Also in October and November, output prices tend to be better, as market supply is low. According to this study, due to increasing temperatures, planting in winter or early spring (June–August) became increasingly feasible towards the end of the study period, which brought the planting date closer to the optimum date for highest WUE. This suggests that it will become easier in future to supply the market with potato in late spring and early summer, when there is currently a dip in the supply.

This study predicting the future impact of climate change on crop production depended on a number of assumptions. Firstly, global circulation models use predicted emission levels of CO_2 and other greenhouse gases, while future emissions of these gases depend on factors such as economic growth and worldwide efforts to curb greenhouse gas emissions. Global circulation models themselves are imperfect. While these models appear fairly accurate in predicting future average temperatures for given emission scenarios, they are not strong at reliably estimating future rainfall. The climate predictions used in this study did not indicate any major changes in rainfall in any of the production areas, but we are not sure how reliable these predictions are. Changes in future rainfall and other climatic variables in the production regions as well as the greater catchments that provide water to the production regions affect the amount of water available for potato production in various manners, which have not been assessed in this study. The GCM models are also known to be poor at estimating the future occurrence of extreme events, which are generally detrimental to crop production. Thirdly, most crop models including LINTUL-POTATO, simulate potential and water- or nutrient-limited yield, but not actual yields achieved by farmers. In the areas where, according to this study, climate change offers opportunities to improve yield and/or WUE in future, these benefits will only be realised if farmers can adapt crop management. For instance, warmer temperatures will, in many cases, coincide with a higher pressure of pests and diseases in potato, requiring additional control measures (van der Waals et al. 2013). In addition, higher yields enabled by climate change will only be realised if farmers can adapt nutrient management accordingly. Increasing temperatures as such also affect potato root development, nutrient uptake ability and the translocation of nutrients (Sattelmacher et al. 1990).

New management strategies and technological innovations that help potato farmers to adapt to climate change may become available in the future. In dry climates, which are common in most potato growing regions of South Africa, evaporative cooling can substantially reduce temperatures in the crop canopy, relative to ambient air temperatures, and thus alleviate the impact of heat stress on photosynthesis (van Oort et al. 2014). It is likely that evaporative cooling as a result of sprinkler irrigation can substantially reduce heat stress in potato. Maximising the benefits of evaporative cooling to reduce heat stress in potato could make up an important management tool in hot and dry climates, provided that sufficient water is available for irrigation. This tool has not been studied in any detail, although farmers currently do apply such practices. The breeding of new potato varieties with a higher tolerance to abiotic stresses, such as heat and drought, could play a major role in adaptation to climate change. Up to recently, it has often been assumed that the inherent potential of potato to develop heat tolerance was limited, but this could change with the availability of new breeding tools such as genetic modification and hybrid potato breeding (Lindhout et al. 2011; Stokstad 2019).

Conclusions

Despite potato being a heat-sensitive crop grown under relatively warm conditions in South Africa, the simulated impact of climate change on yield and WUE was positive in most regions. Regarding the possibility to adapt to climate change by changing planting time, potato production regions in South Africa could be divided into three groups, based on the results from this study. The first group represents regions where planting dates could be adapted to avoid heat stress and/or optimise yield and these included the Mpumalanga Highveld, Gauteng, Ceres and Loskop Valley. Yields and WUE improved substantially towards 2050 for these regions. For the second group of regions, the current planting dates remained optimal in future in terms of high yield and WUE. This group included the Eastern Cape, the Southern Cape, the north Eastern Cape and KwaZulu-Natal. Also in these regions, yields and WUE generally increased. The last group represents regions where potato is currently growing in a hot environment and where future increases in temperature were higher than in the coastal regions. This group included the south western Free State, the Northern Cape, the western Free State and North West. Although higher temperatures reduced frost risk and cold stress to the crop, frost did not completely disappear in winter, leaving little opportunity to change planting dates in order to escape heat stress. As a result, the optimal planting window remained the same towards 2050. Increasing atmospheric CO_2 levels had a positive effect on photosynthetic rates, but this was counteracted by higher respiration due to increased heat stress, resulting in only marginal yield increases towards 2050.

Geolocation information

Twelve potato growing regions in South Africa:
33.5° S 19.5° E; 26.0° S 28.5° E; 34.0° S 25.0° E; 29.0° S 25.0° E; 31.0° S 28.0° E; 27.0° S 24.0° E; 29.0° S 30.0° E; 26.0° S 30.0° E; 25.0° S 29.0° E;29.0° S 25.5° E; 34.0° S 22.0° E; 28.0° S 25.0° E.

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ORCIDs

AC Franke – https://orcid.org/0000-0002-4150-7196
JM Steyn – https://orcid.org/0000-0002-9959-3234

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