Climate change and potato production in contrasting South African agro-ecosystems

2. Assessing risks and opportunities of adaptation strategies

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Abstract

This study aims to assess the risks and opportunities posed by climate change to potato growers in South Africa and to evaluate adaptation measures in the form of changes in planting time growers could adopt to optimise land and water use efficiencies in potato, using a climate model of past, present-day and future climate over southern Africa and the LINTUL crop growth model. This was done for distinct agro-ecosystems in South Africa: the southern Mediterranean area where potato still is grown year round with a doubling of the number of hot days between 1960 and 20150 , the Eastern Free State with summer crops only and Limpopo with currently autumn, winter and spring crops where the number of hot days increases seven fold and in future the crop will mainly be grown in winter. A benefit here will be a drastic reduction of frost days from 0.9 days per winter to 0. Potato crops in the agro-ecosystems will benefit considerably from increased CO_2 levels such as increased tuber yield and reduced water use by the crop, if planting is shifted to appropriate times of the year. When the crop is grown in hot periods, however, these benefits are counteracted by an increased incidence of heat stress and increased evapotranspiration, leading in some instances to considerably lower yields and water use efficiencies. Therefore year round total production at the Sandveld stabilizes at around 140 Mg ha^{-1} (yield reduction in summer and yield increase in winter), increases by about 30 % in Free State and stay at about 95 t ha^{-1} at Limpopo where yield increase due to CO_2 is annulled by a shorter growing season. When the crop is grown in a cool period, there is an additional benefit of a reduced incidence of cold stress and a more rapid canopy development in the early stages of crop growth. In all three areas, potato growers are likely to respond to climate change by advancing planting. In Limpopo, a major benefit of climate change is a reduction in the risk of frost damage in winter. The relevance of these findings for potato grown in agro-ecosystems elsewhere in the world is discussed.

Keywords: yield, water use, water use efficiency, planting time, length of growing season, crop model

Introduction

Climate change in potato production areas of South Africa is expected to lead to higher temperatures, increasing the incidence of heat stress and dry spells, but lowering the risk of frosts during the growing season in the mid to high altitude areas. Moreover, increased CO_2 levels are likely to enhance photosynthetic rate and reduce water use in potato. In the first paper of this series (Haverkort et al. 2013), an ensemble of high-resolution simulations of present-day and future climate over southern Africa, consisting of daily weather data for the period 1961 - 2050, were used to assess past and future yields and water need of potato crops in distinct agro-ecologies in South Africa. From literature, it was found that radiation use efficiency of potato increased with elevated CO_2 concentrations by almost 0.002 g MJ^{-1} ppm^{-1}. This ratio was used to calculate the CO_2 effect on yields between 1960 and 2050, when CO_2 concentration increases from 315 to 550 ppm. Within this range, evapotranspiration by the potato crop reduces by about 13% according to literature, assuming all other environmental factors remain the same. A crop growth model was used to calculate climate change effects on potato yields between 1960 and 2050 with current planting times. Yield increase was strongest in the Mediterranean climate type in winter (the Sandveld) and least in the hot dry summer conditions (the Sandveld) and in the continental climate type (Limpopo) in winter. In warmer climates, increased heat stress for potato crops partly offset the beneficial effects of increased CO_2 levels on photosynthetic rate. Similarly, water use efficiency increased most in the cool rainy winter conditions and least when potato grows in hot environments.

The projections in the first paper (Haverkort et al. 2013) were carried out in a ‘business as usual’ scenario, assuming that potato growers will plant and harvest at the same time as they do currently. The extent to which farmers are affected by climate change depends on their actual exposure to climate change, the sensitivity of their farming system and their adaptive capacity (IPCC 2001). Adaptation options can be categorised into four main types: (i) farm production practices, (ii) technological developments, (iii) farm financial management, and (iv) government programs and insurance (Smit and Skinner 2002). In this paper, we primarily deal with the first two types of adaptation options. It is very likely that potato farmers in South Africa will adopt adaptation measures by changing farm production practices, especially by changing planting times and adopting varieties with different durations (differences in earliness) to take maximum benefit of changing growing conditions and the suitable growing season, while avoiding sub-optimal temperatures. The adoption of new varieties, however, depends on the availability of such suitable varieties in the country (i.e. technological developments) that are appropriate in terms of crop duration, growing characteristics and market demands. South African potato farmers currently grow a very limited range of varieties and 60% of the table potatoes are supplied by a single variety Mondeal (Potatoes South Africa 2011). The genetic variability in heat tolerance among different potato varieties is limited and it is unlikely that more heat-tolerant potato varieties will be available to farmers in the near future. Water shortages due to current over-use of resources, an increasing demand for water from other sectors, and possibly climate change are likely to restrict irrigation and increase costs of irrigating potatoes across South Africa in future. These should further encourage potato farmers to adapt practices, such as planting times, in order to optimise water use efficiency.

It is clear that the most likely changes in production practices to adapt to climate change are related to planting time, crop duration and water management, which are all interrelated with technological developments. In this paper we make use of a crop growth model to evaluate the effect of changes in planting time and cropping season on yields and water use efficiencies. Technological innovations that can help improve yield and/or water use efficiencies, irrespective of climate change impacts (e.g. different irrigation strategies or decision support systems) are not considered here, while we know from previous work in the Sandveld region of South Africa that there is considerable scope to improve water use efficiencies with current technologies (Franke et al. 2011). We also assume that growers will introduce and use varieties with an earliness or lateness such that their growth cycle matches that of the shortened (winter) or lengthened (summer) seasons. We do not address other altered management practices such reduced or increased irrigation or increased N-fertilization when higher yields lead to increased N-uptake. Nor do we address likely increased nitrification with higher soil temperatures, higher CO_2 concentrations and higher soil moisture levels resulting from improved water use efficiency.

The objectives of this second paper in the series are:

1. to assess the risks and opportunities posed by climate change to potato growers in South Africa and in similar agro-ecosystems elsewhere;
2. to evaluate adaptation measures in the efficiencies in potato in response to climate change and anticipated restrictions on form of changing planting times and the length of the growing season, which growers could adopt to optimise land and water use water use.

Material and Methods

Climate projections were obtained by downscaling the output of different coupled climate models (CGCMs), which contributed to Assessment Report Four (AR4) of the Intergovernmental Panel on Climate Change (IPCC), to high spatial resolution over southern Africa (Engelbrecht et al. 2009; 2013). Calibration of the weather set was conducted as described in detail by Haverkort et al. (2013). Only the CSIRO model was used for the current study and not the weather data of all six models, as the results of Haverkort et al. (2013) showed highly comparable trends for all six models.

Daily reference evapotranspiration rate (ETo) was calculated using daily maximum (Tmax) and minimum (Tmin) temperatures, relative humidity, wind speed and solar radiation, following the procedures of Smith et al. (1996) and Allen et al. (1996). Projections of Tmax, Tmin, precipitation, solar radiation and ETo were used as input to the LINTUL crop growth model. The model was explained in detail by Haverkort et al. (2013) and Franke et al. (2011) and was partially based on crop input parameters from Spitters (1990) and Kooman and Haverkort (1994). In this model, Radiation Use Efficiency (RUE) equalled 1.25 g MJ^{-1} intercepted global radiation in 1990 at optimal temperatures, and decreased linearly to 0 when the maximum day temperature (Tmax) decreased from 16^0C to 8^0C or increased from 30^0C to 35^0C at all CO_2 levels. We followed Jaggard et al.'s (2010) assumption that yields - hence RUE – increased by 28.5% with an increase in the CO_2 concentration from 370 to 550 ppm, while water use reduced by 11% over the same CO_2 range.

The model used in the current study was adjusted to account for frost events during the growing season after crop emergence. The model assumed that frost before full ground cover is reached (Leaf Area Index (LAI) < 3) leads to a loss of 85% of all biomass and a loss of all leaves. Leaf area development restarts the following day as if the crop has just emerged. When frost occurs after the crop has reached full ground cover, crop growth is terminated. Tuber mass and evapotranspiration accumulated over the season at that moment is taken as final yield and total evapotranspiration. Harvest index of the crop increased as a function of growing days from 0.3 at full soil coverage, when LAI reaches a value of 3, to 0.75 when the crop is fully mature.

We ran the model for three contrasting localities (agro-ecosystems) where potato is an important part of the cropping system, as explained by Haverkort et al. (2013): (i) the Sandveld (Leipoldtville), representative of a Mediterranean climate with cool, wet winters, and hot and dry summers, (ii) the Eastern Free State (Reitz-Bethlehem): a continental mid-altitude climate with a cold and dry winter and a warm and rainy summer; the growing season is interrupted by frosts during winter, and (iii) Limpopo (Dendron): a tropical dry climate with a dry winter and a warm and rainy summer. Two types of simulation were conducted, different from the assessments done by Haverkort et al. (2013). One type of simulation involved planting of potato every 15th day of the month with a crop that stayed in the field for 120 days. To condense results, we presented simulation results for planting in three periods of ten years each: 1961-1970, 2001-2010 and 2040-2049. Note that these are years of planting and for instance, a potato crop planted in late 2049 grows into year 2050. The second type of simulation reflected the hypothetical situation of a potato crop growing throughout the suitable growing season (therefore the growing season may be shorter or longer than 120 days, depending on suitable temperatures), assuming that ideal varieties with the appropriate growing duration are available. In the Free State, planting was done two weeks after the last frost event in spring and the potato crop was harvested with the first frost in autumn. In Limpopo and the Sandveld, planting was done after the last heat period in autumn and harvesting was done after the occurrence of the first heat period in spring. In Limpopo, the growing season in winter is occasionally interrupted by frost. In the case of frost after the crop reached full crop cover, crop growth is terminated as described above.

The following information obtained from the weather data projections are presented in this paper: (i) the number of days during which Tmax exceeds 30^0C. On such days we assume that crop photosynthesis is reduced. (ii) The number of days during which Tmax exceeds 35^0C. At such temperatures the crop will stop photosynthesis, suffers damage and will lose leaves, reducing the capacity to intercept solar radiation. (iii) The number of frost days. (iv) The number of dry spells, defined as the frequency of periods of at least 10 days with less than 5 mm rainfall. Although all potato crops in South Africa are irrigated – except for about 6% of the annual national crop in the Eastern Free State – dry spells are of interest as water use in future is likely to be more restricted than currently. (v) The frost-free period in the Eastern Free State and the heat-free period in Limpopo and the Sandveld in relation to optimal planting time. The heat-free period begins in autumn when average Tmax is less than 30^{0}C for two weeks and ends in spring when average Tmax is more than 30^{0}C over a period of two weeks.

Yields presented in tables or figures are all potential fresh tuber yields with a dry matter percentage of 20%. All crops were assumed to be irrigated when needed and drought stress was not taken into account in the model. The total evapotranspiration from the crop and soil (ET) and the crops' precipitation deficit (calculated as ET minus rainfall not lost as drainage during the season) were considered indicative of the irrigation need of the crops. Water Use Efficiency (WUE) was calculated as the potential fresh tuber yield divided by the ET. Irrigation losses, drainage and other factors were not taken into account.

Results

Climate risks

An overview and summary of the annual occurrence of weather events shows a moderate relative increase of warm days (Tmax > 30^{0}C) in the Sandveld (from 97 to 125 days), and Limpopo (from 95 to 166 days) but a strong relative increase in days with temperatures over 30 ^{0}C in the Free State (from 26 to 82) (Table 1). The number of hot days (Tmax > 35 ^{0}C) however, strongly increases at all three areas but especially at the inland localities (Limpopo and the Free State). Although by 2050 the average year-round Tmax is higher in Limpopo than in the Sandveld, the number of hot days is similar (50 and 47 respectively). This is because the warmest period in Limpopo coincides with the rainy and cloudy season whereas in the Sandveld it coincides with the dry and sunny period. Tmax in the Sandveld during winter is lower than in Limpopo because of cloudiness and the moderating influence of the ocean nearby. The average daily maximum temperature between 1960 and 2050 rises by 1.7 ^{0}C, 2.6 ^{0}C and 2.7 ^{0}C in the Sandveld, the Free State, and Limpopo, respectively, which suggests that the dry matter concentration of potato tubers, assumed to be 20% in the model, will decrease somewhat over time (Haverkort and Harris 1987). Table 1 shows that in the Eastern Free State the number of days with frost (minimum temperature below 0 ^{0}C) goes down from well over 30 per annum in the 1960s to the current 15 and that a further reduction to about 10 frost days is expected over the next 40 years. In Limpopo, night frosts in winter will disappear. The number of dry spells is about twice as high in the Sandveld and Limpopo than in the Free State. Climate change does not have a clear impact on the number of dry spells over the 90-year period.

In all three regions, the incidence of warm (Tmax > 30 ^{0}C) and hot (Tmax > 35 ^{0}C) days during a 120-day growing season particularly increases with planting in spring or summer (Fig. 1A-C). Although the increase in high temperatures in the Sandveld summer appears to be somewhat dampened by the nearby Atlantic Ocean, the number of warm days with temperatures over 30 ^{0}C when planting in November increases from about 75 to 90 over the 90 year period, some 20% increase (Fig. 1A). The number of prohibitively hot days with temperatures above 35^0C, however, more than doubles from 20 to over 40 days in a 120-day growing season with planting taking place in November. The dampening effect of the ocean is not noticeable in the inland Free State (Fig. 1B) where the number of warm days almost triples in summer and the number of hot days is about five times greater with planting in November. Nevertheless, the number of hot days in the growing season is only 15 when planting in late spring / early summer in the final decade, compared with over 40 days in the Sandveld. The situation of Limpopo resembles somewhat that of the Sandveld, but this inland area closer to the equator clearly has a shorter winter period with fewer days with Tmax below 30^0C. Fig. 1A-C also shows that the impact of climate change will especially manifest during the last 40 years of this 90 year period.

The length of the growing season in the Sandveld and Limpopo is determined by the heat-free period (Fig. 2A & 2C). The two lines indicating the approximate period in which potato can be grown without excessive heat stress converge, indicating a reduction in the suitable heat-free period for potato growth. The trends at Limpopo are very similar to those of the Sandveld, but the cool period appropriate for potato growth is about 45 days shorter in Limpopo. Nevertheless, potato crops in Limpopo are occasionally damaged by frost in winter. Incidences of frost reduce over time, with no frost occurring anymore after 2025 (Fig. 2C). As frost in the middle or end of the growing season usually results in severe crop damage or termination of crop growth, the reduction and disappearance of frost events in Limpopo represent a major reduction in potato production risk. In the Eastern Free State, the growing season is primarily determined by the frost-free period (Fig. 2B). The first day with frost over the 90-year period tends to be later in the year and the last day with frost tends to be earlier, thus lengthening the frost-free season suitable for potato. There is substantial variation between years regarding the last frost in spring and the first frost in autumn. Yet, the period during which potato can be grown without substantial risk of frost considerably lengthens, especially after 2010.

The growth limiting factors, prohibitive high temperatures in summer in Limpopo and low minimum temperatures in the Free State, are schematically presented in Figure 3. The horizontal lines are chosen such as to reflect the current earliest planting dates in autumn in Limpopo, when Tmax decreases below 30 ^{0}C, and the earliest planting in the Free State when Tmin in spring is above 9 ^{0}C. The current late February and March planting in Limpopo is likely to be delayed by approximately three weeks. The still suitable window for potato growth in late spring is reduced, but does not change as much as in autumn. Altogether the length of the cropping season is reduced by about one month. In the Eastern Free State the situation is the reverse. Here the cool winter prohibitive for potato growth will be reduced by some 50 days.

Climate change effects on yields and water use efficiencies

When planting in winter or early spring in the Sandveld, the crop growth model calculates a substantial yield increase over the 90-year period (Fig. 4A) with an increase from 46 to 67 Mg ha^{-1} for the June planting (+ 46%). This increase is more than proportional to the CO_2 response of 28.5% because the rise in temperature not only leads to more efficient photosynthesis, as there are less cold days with temperatures suboptimal for photosynthesis, but also a more rapid development of foliage early in the season due to higher temperatures increasing the crop's ability to intercept solar radiation. Due to the increase in temperature in summer, photosynthesis is negatively affected leading to a yield reduction from 46 to 36 Mg ha^{-1} per hectare when a crop is planted in December. Fig. 3A also shows that the months of planting with the highest yields shifts a month forward from August-September to July-August. WUE, expressed as g potato produced per litre of water evapotranspired, increases especially when planting in autumn and early winter. When planting later in winter or in early spring, the advantage of a lower water use caused by higher CO_2 levels are moderated by higher temperatures enhancing evapotranspiration. In a crop growing in summer, WUE remains approximately the same. Potato growers in the Sandveld currently have a conflict of interest, as the planting period giving the highest potential yield does not coincide with the period giving the highest WUE (Franke et al., 2011). This conflict will become less in future as an advancement of planting time to optimise crop yield will bring the planting time also closer to the time giving the highest WUE.

In the Eastern Free State, the highest absolute yield increases take place in the planting period between June and September (Fig. 4B). The plantings giving the highest yields move forward from October-November to September-October. When planting occurs after October, the increase in warm and hot days that reduce photosynthesis rate annul the benefit of higher CO_2 levels. WUEs in winter were irregular and low, as frost often terminated crop growth before any tuber yield was produced, leading to a WUE of nil. WUE is greatest in September for all three decades assessed. As in the Sandveld, an advancement of planting in the Free State will also move the planting time closer to the time giving the highest WUE (apart from the impact of enhanced CO_2 levels on water use as such). The reduced risk of frosts and higher temperatures lead to earlier planting in spring but at similar temperatures than currently, so leaf area development remains similar, which explains why the yield increases in the Free State spring plantings are less marked than in the Sandveld winter plantings.

In Limpopo there are currently two main planting periods, namely an early planting, which starts after the high summer temperatures have started subsiding in autumn (late February to March), and the main planting period, which starts in May and continues through the winter until the end of July, with June as peak planting month. Fig. 4C shows higher yields when planting outside this window, but growers try to avoid too hot conditions in summer due to its negative repercussions for emergence and tuber quality, as well as the high water needs during summer in this area with reclining water levels. In addition, the niche winter crop yields the highest prices on the markets when other regions do not deliver to the market. The results show that with time the period of highest production will coincide with the preferred operational and market requirements. The best months to plant in 2050 will be in April-May, with a strong yield increase over 90 years from 49 to 77 t ha^{-1} (+57 %). This increase is not only due to higher CO_2 levels and more optimal temperatures for photosynthesis, but also due to a reduction in the risk of frost damage. The increase in WUE over this period is from 20 to 30 g l^{-1} (+50 %). Comparable increases are obtained in the Sandveld winter crop. It is obvious that with water scarcities and boreholes that now go to depths well over 100 m, whereas 30 meter sufficed 20 years ago (data from a Limpopo survey by the authors, other results not shown), planting when WUE is highest is expected to become priority.

A crop grown for a fixed number of days, as assessed above, may also be replaced in the model by a crop growing for a fixed number of degree days. With increasing temperatures in summer the crop growth period in degree days becomes shorter in calendar days and thereby more strongly reduces yields in summer (data not given). A disadvantage of this approach is that growing periods in winter tend to become unrealistically long, as factors other than degree days steering crop maturation (e.g. cold stress) are not taken into account by the model.

Another way of assessing the influence of climate change is to calculate the crop performance for the entire period of the year suitable for crop growth, based on (theoretical) varieties that can complete a full growth cycle in such an available growing season. Fig. 5A-C and Table 2 show that the annual average yield increase is strongest in the Eastern Free State because of a combined effect of a lengthening growing season and a higher photosynthesis rate. Increased heat stress in summer slightly diminishes the increase. This region shows a high year-to-year variability in yield. This is because of the great variability in the length of the growing season as both the last frosts in spring and earliest frosts in autumn show a large variation (also see Fig. 2). The variation in yield is less for the Sandveld, where frost plays no role and the length of the growing period is determined by the heat-free period. Overall, yields in the Sandveld do not show any clear trend over the 90-year period, as the gradually shortening growing season is compensated for by a higher potato growth rate, especially in winter. In Limpopo, yields were highly irregular in the first 50 years assessed. Potentially, the growing season is longest in this period, relative to the later years, as heat stress in autumn and spring is less frequent. Frost in winter, however, regularly damages the crop in the first 50 years, occasionally leading to minimal yields. Over time, yields become more stable, as frost incidences reduce and eventually disappear. The results in Limpopo are somewhat unexpected, but make sense given that there is a long growing season which is occasionally interrupted by frost in the early years, leading to very low yields if occurring soon after full ground cover is reached. Average yields do not change much in Limpopo, but the disappearance of frost risk should be a major advantage of climate change for the growers, as shown clearly in the figures.

WUEs improve for all three areas, but more in Limpopo and the Sandveld than the Free State (Table 2). The avoidance of hot summers in Limpopo and the Sandveld, combined with large improvements in WUE in the winter months, are responsible for this. Evapotranspiration declines for all three areas because of lower water use by the crop and in Limpopo and the Sandveld also because of a shortening growing season. As rainfall is not greatly affected by climate change, the precipitation deficit decreases with approximately the same amount as the evapotranspiration in all three areas.

Discussion

The climate projections of past, present and future climate over southern Africa provided valuable input data to model potato growth in three distinct areas (ago-ecosystems) in the past and future. Potato crops in all three areas can reap benefits of increased CO_2 levels, increasing photosynthetic rate and reducing water use by the crop, if planting can be shifted to appropriate times of the year. In all three areas, potato growers are likely to respond to climate change by advancing planting. In Limpopo, there may be a shift in preferred planting from late winter to autumn. Water use efficiencies of the crop in the Sandveld and Limpopo are likely to further improve as an advancement of planting coincides with the period when water use efficiency is higher, irrespective of the effects of climate change. Changing lengths of the growing season could also affect yield and water use efficiency if suitable varieties with appropriate growing periods can be found. The ability of farmers to optimally use a changing length of the growing season depends on the availability of appropriate varieties. Moreover, early potato varieties tend to benefit less from increased atmospheric CO_2 levels than late varieties. Schapendonk et al. (2000) observed a CO_2 effect on potato productivity of 23% for an early variety and 49% of a late variety, presumably because the late variety with a relatively large sink capacity shows less photosynthetic acclimation to elevated CO_2 levels. Jaggard et al.'s (2010) value for the impact of elevated CO_2 (excluding damaging effects of ozone) on productivity, used in our study, was the average of the values found by Schapendonk et al. (2000) for an early and a late variety. For farmers, it means that early varieties may enable farmers to avoid heat stress in the crop, but could reduce the yield-enhancing effects of increased CO_2 levels. Breeding to reduce photosynthetic acclimation to elevated CO_2 levels especially in late varieties, as suggested by Schapendonk et al. (2000) may on the other provide opportunities to increase benefits from elevated CO_2 levels in areas where the growing season in prolonged by climate change.

As discussed by Haverkort et al. (2013), the potential yields and water use efficiencies simulated by the model are considered indicative of what can be achieved in each area. Whether actual yields and water use efficiencies in farmers' fields will change proportionally to the potential values calculated by the model depends on various other factors, especially farmers' ability to adjust management and crop genotypes to changing environmental conditions. Apart from adjustments in planting and harvest time and water management, South African farmers would, among others, need to adjust pest and pathogen management strategies (Van der Waals et al. 2013) as well as nutrient management in order to take advantage of a higher potential yield. Alternative crops for irrigated plots that are economically viable are scarce in all three regions, and shifts in crop rotation on these plots as a result of climate change are not likely to happen in the near future. The ability of farmers to respond to climate change in general differs between individual farmers (Reidsma et al. 2010). Potato farmers in the regions assessed in this study are all large-scale commercial farmers and face relatively homogenous agro-ecological environments within regions. Access to water, however, especially the depth of the soil water table and the associated irrigation costs, and therefore also the urgency to optimise water use efficiency, can differ considerably between farmers within regions. Changes in profitability of potato production, possibly indirectly steered by climate change in various ways, is however likely to affect the intensity of potato production on-farm, e.g. by reducing the length of the fallow in between potato crops or the number of irrigated fields, which on its turn has implications for other crop production factors such as pest and disease pressure. It is not unlikely that for some farmers in Limpopo costs of irrigation increase to such an extent that irrigation crop production becomes economically unsustainable. Some farmers in these regions have substantial other income generating activities besides potato cropping, e.g. cattle rearing, game farming or farm tourism, reducing their dependence on potato farming as a prime source of income and giving them more flexibility to ex- or intensify potato production than others.

The results of this study conducted for South Africa are also of relevance for other potato producing regions. There are many tropical and sub-tropical regions where the crop is rapidly expanding as an irrigated winter crop in a similar continental climate type as in Limpopo. For instance, in southern China and northern India millions of hectares of potatoes are grown as a winter crop between two rice crops. Jaggard et al. (2010) projected that rice will have a 10% yield benefit from increased CO_2 levels, but a 4% negative effect of higher O_3 levels, resulting in a net yield increase of only 6%, while potato is expected to have a net benefit of 28.5%. The increase in WUE is also important for these areas where paddy rice in the dry hot pre-monsoon period uses a multiple amount of water of that of a potato crop. Potato is an important vegetable in Mediterranean climates such as North Africa, where a spring and an autumn crop is often grown. In these areas, a relative shift from spring to autumn crops may occur, as projected for Limpopo and the Sandveld. In some areas production may be further concentrated in winter as currently already is the case in countries such as Egypt. The most dominant potato cropping system – where potato is often considered a staple food – are located in areas with a rainy summer and a prohibitively cold winter, such as in the northern part of North America, northern and eastern Europe and much of northern China. As in the Eastern Free State, the crops are likely to benefit in those areas from a longer growing season and from increased CO_2 levels. Wheat and maize, which are often rotated with potato in these regions, benefit far less from climate change: wheat yields will increase by only 6%, while maize yields will even decline by 5% (Jaggard et al. 2010), as C4 crops do not benefit from higher CO_2 levels but suffer from increased O_3 levels. Overall, the strong response of potato to increased CO_2 levels, relative to other crops, could lead to a shift away from other crops to potato in the decennia to come in those areas that do not become prohibitively hot for potato growth.

Haverkort and Verhagen (2008) reviewed climate change and its repercussions for the potato supply chain in temperate regions and did not take the beneficial effects of the increased CO_2 concentration into consideration. If they had done so, and if they had addressed the comparative advantage of potato versus other crops in e.g. Europe, they likely would not have reached the conclusion that potato yield would only increase in the north-west of the continent and that the crop would become less prominent in other areas of the continent. Similarly, Archer et al. (2009) who discussed climate change and commercial agribusinesses in the semi-arid northern Sandveld did not take the beneficial effect of increased CO_2 on potato production and water use efficiency into account, which may have changed the conclusions from their study. While most of the impact of climate change on potato cultivation is still ahead, studies and policies on food production efficiency, food security and water use should take the expected impacts into account.

Conclusions

- The results from this study suggest that potato crops in all of the studied agro-ecosystems will benefit from increased CO_2 levels due to increased yields and reduced crop water use if planting can be done at appropriate times of the year.
- When the crop is grown in hot periods of the year these benefits are counteracted by an increased incidence of heat stress and higher evapotranspiration, often leading to lower yields and water use efficiencies.
- In all agro-ecosystems, potato growers are likely to respond to climate change by advancing planting dates to avoid heat stress in late spring and summer. Changing lengths of the growing season could further affect crop performance, if varieties with suitable growing durations are available. In warmer areas with cold winters, such as Limpopo, a further benefit of climate change is a reduction in the risk of frost.
- While most of the impact of climate change on potato cultivation is still ahead, studies and policies on food production efficiency, food security and water use should take the expected impacts into account.

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Table 1. Occurrence of weather events in the three potato growing regions of South Africa (annual average per decade).

Phenomenon	Sandveld			Eastern Free State			Limpopo		
	1961-1970	2001-2010	2040-2049	1961-1970	2001-2010	2040-2049	1961-1970	2001-2010	2040-2049
Days with Tmax > 30^0C	97	105	125	26	36	82	95	120	166
Days with Tmax > 35^0C	25	29	47	2	4	15	8	18	50
Average Tmax (^{0}C)	25.5	25.9	27.2	22.5	23.3	25.1	26.6	27.7	29.3
Average Tmin (^{0}C)	11.3	11.6	12.8	7.3	8.3	9.7	12.0	13.1	14.6
Number of frost days y^{-1}	0	0	0	33	17	10	0.9	0.4	0
Number of dry spells y^{-1}	23.8	24.1	27.0	12.6	11.8	13.0	20.9	22.5	21.2

Table 2. Results of regression analyses on crop model calculations (between brackets the R^2 of the equation y=a+bx, with y the phenomenon and x the year), calculations based on a theoretical crop that completes a cycle during the frost-free (the Free State) or heat free (the Sandveld and Limpopo) period. Note that the variance in Limpopo is for none of the parameters constant (variability is higher in the first 50 years and in the last 40 years) and therefore results of the regression analyses should be treated with caution.

	Sandveld	Free State	Limpopo
Yield 1961 (t ha^{-1})	143	129	93
Yield 2050 (t ha^{-1})	149	172	101
Δ Yield (t ha^{-1} y^{-1})	0.07 (0.001)	0.48 (0.13)	0.22 (0.09)
WUE 1961 (g l^{-1})	15.4	8.05	13.8
WUE 2050 (g l^{-1})	23.5	11.4	26.7
Δ WUE (g l^{-1} y^{-1})	0.09 (0.79)	0.04 (0.14)	0.14 (0.48)
ET 1961 (mm $season^{-1}$)	896	1605	628
ET 2050 (mm $season^{-1}$)	629	1524	370
Δ ET (mm $season^{-1}$ y^{-1})	-3.0 (0.34)	-0.9 (0.07)	-2.9 (0.09)
Precipitation Deficit 1961 (mm $season^{-1}$)	694	1113	540
Precipitation Deficit 2050 (mm $season^{-1}$)	441	991	329
Δ Precipitation Deficit (mm $season^{-1}$ y^{-1})	-2.8 (0.33)	-1.4 (0.06)	-2.4 (0.08)

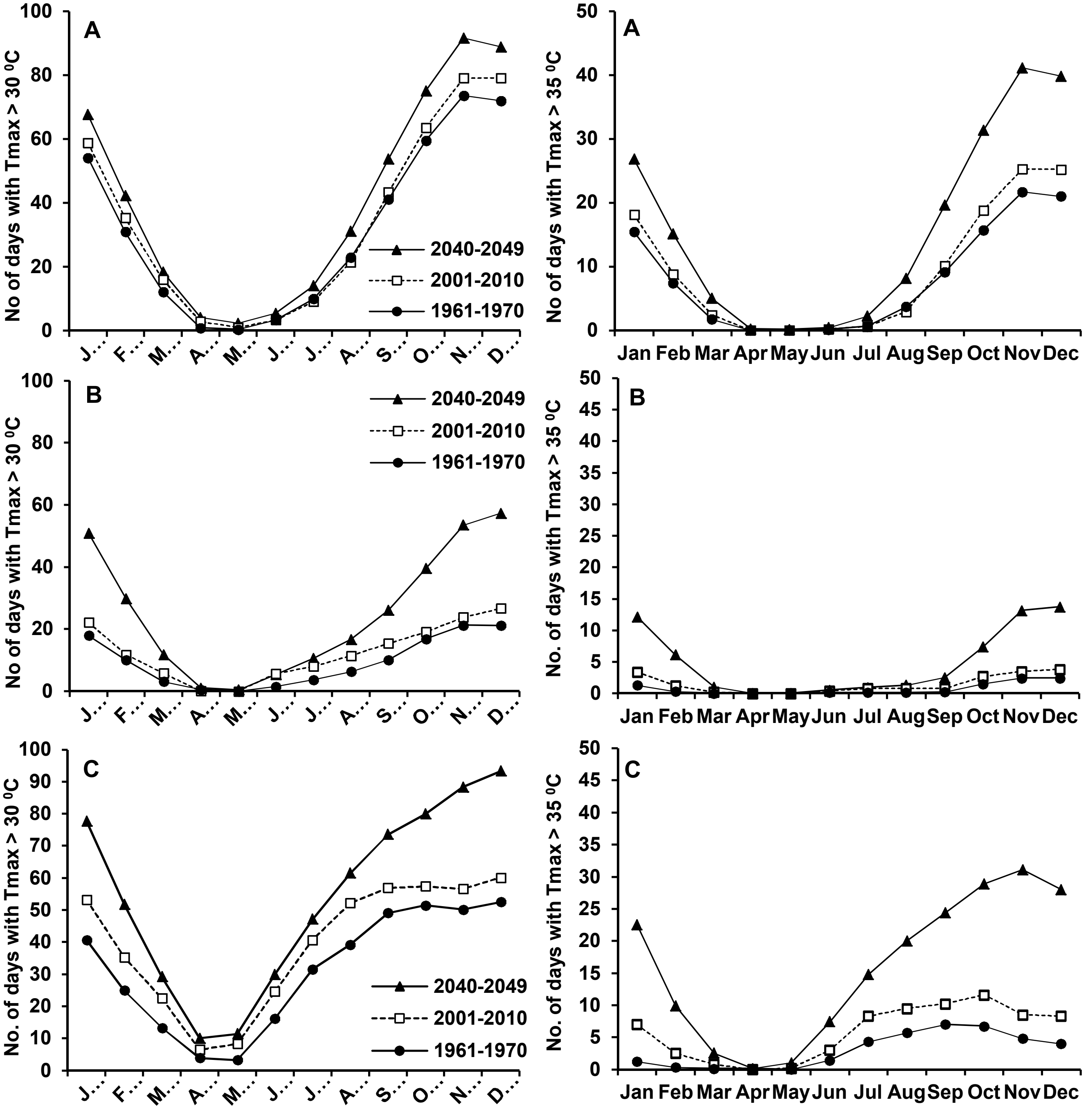

Figure 1. Number of warm (Tmax > 30^{0}C, left) and hot (Tmax > 35^{0}C, right) days during a 120-day growing period following planting on the 15th of each month for A. the Sandveld, B. the Eastern Free State, and C. Limpopo.

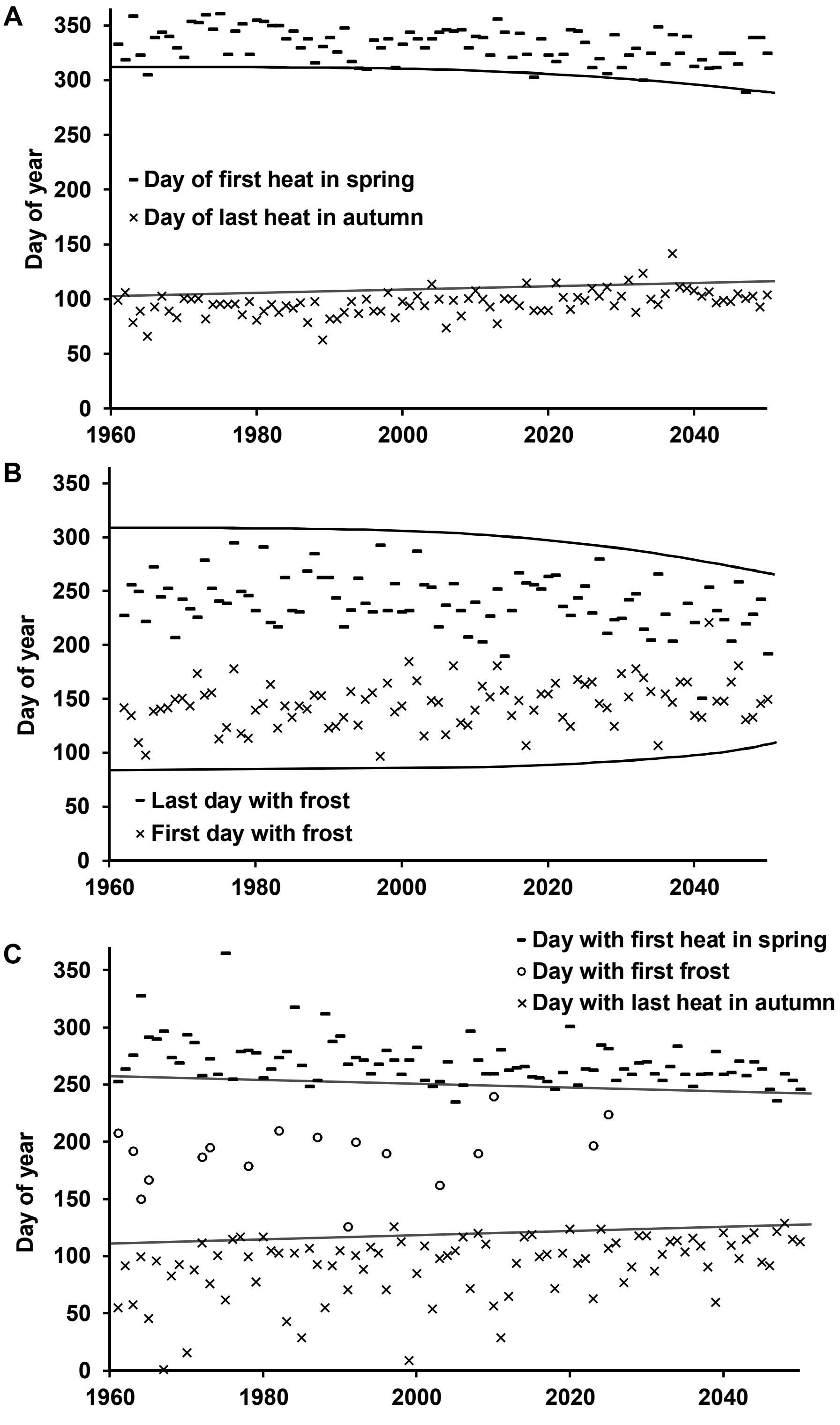

Figure 2. Changes in the length of the growing season between 1961 and 2050: Day of the year with the last heat in autumn and the first heat in spring in A. the Sandveld and C. Limpopo, and the first and last frost of the year in B. the Eastern Free State. In Limpopo, frost events, occasionally interfering in the cropping season, are also indicated. In the Sandveld and Limpopo, the lines indicate approximate planting (lower) and harvest time (upper) of a crop avoiding most of the heat. In the Free State, the lines indicate approximate planting (upper) and harvest time (lower) of a crop grown in the period with a low risk of frost.

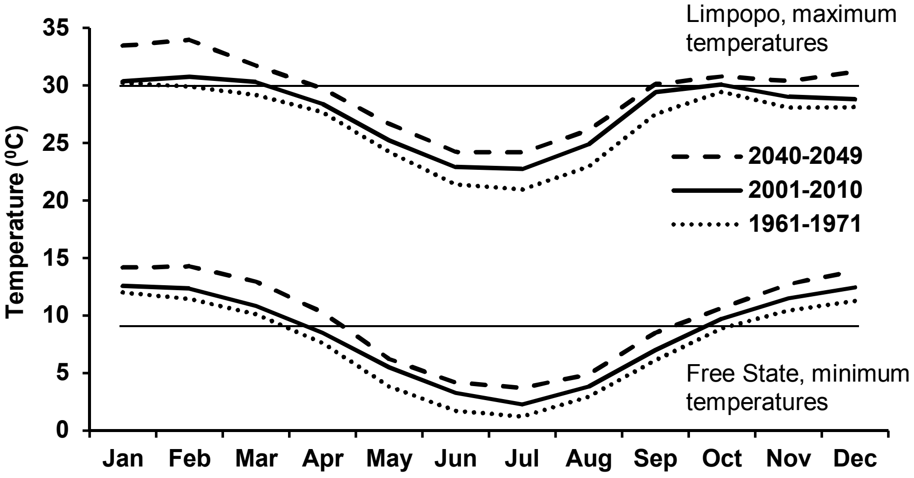

Figure 3. Maximum temperatures in Limpopo and minimum temperatures in the Eastern Free State for three different decades. The horizontal lines indicate the average maximum or minimum temperature during the current prevailing planting time.

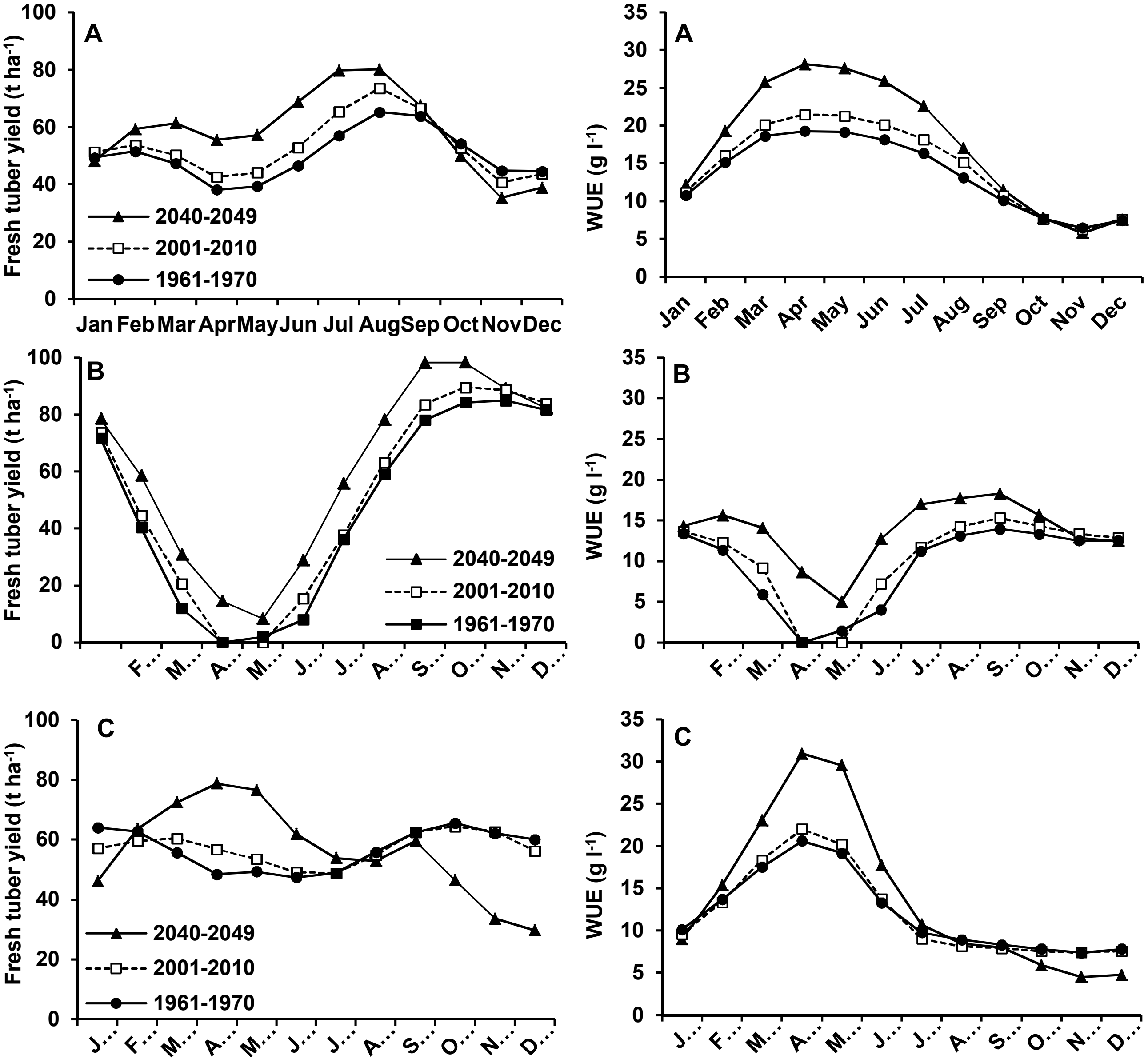

Figure 4. Calculated potential fresh tuber yield (left) and water use efficiency (WUE) (right) of a 120 day crop planted on the 15th of each month grown for A. the Sandveld, B. the Eastern Free State, and C. Limpopo.

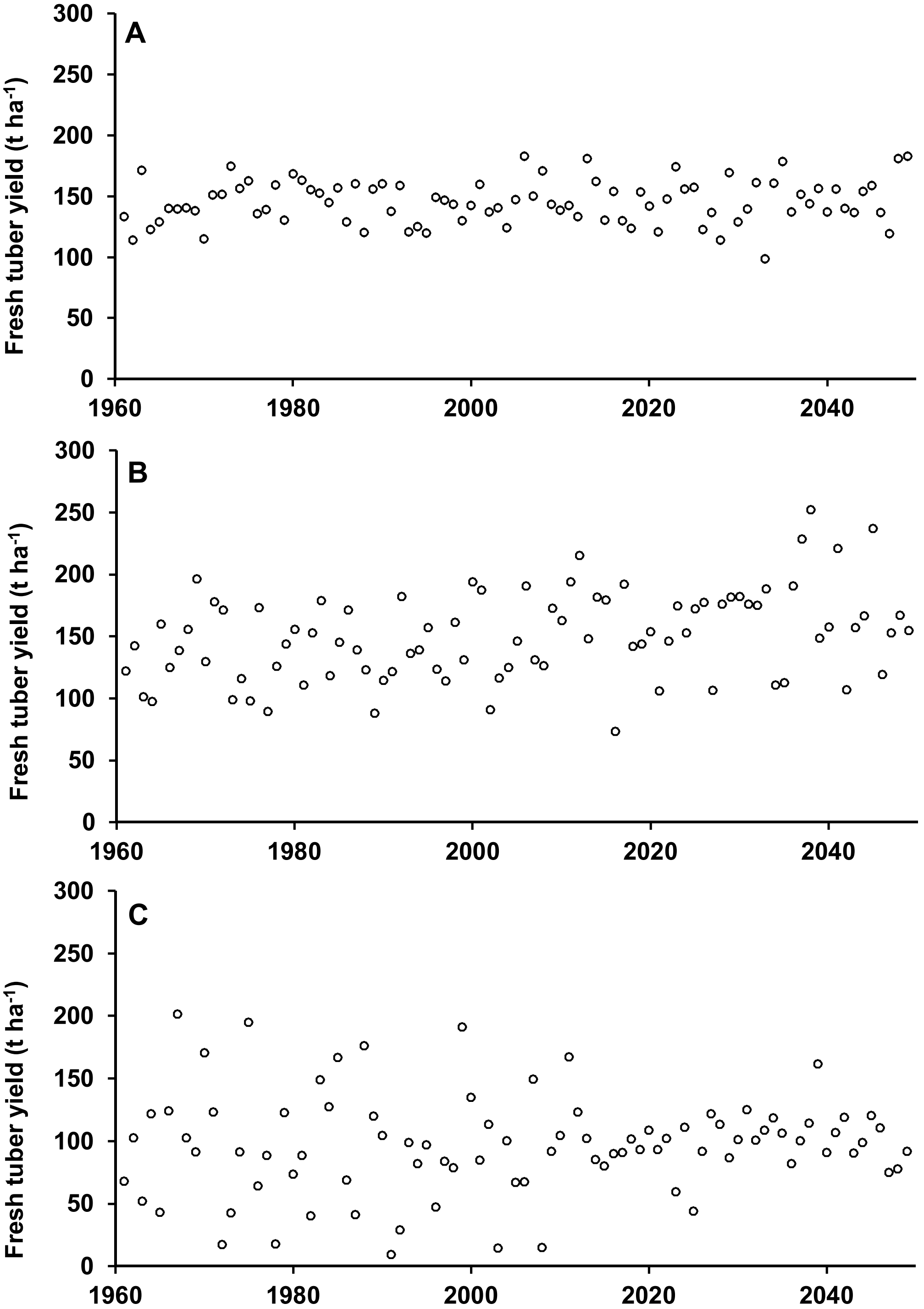

Figure 5. Fresh tuber yield from a theoretical crop that can utilise the complete frost-free and heat-free period between 1961 and 2049 in A. the Sandveld, B. the Eastern Free State, and C. Limpopo.