SA-TIED

Southern Africa – Towards Inclusive Economic Development

Climate uncertainty and agricultural vulnerability in South Africa

Faaiqa Hartley, Sherwin Gabriel, James Cullis and Channing Arndt

SA-TIED Working Paper 162# | February 2021

UNITED NATIONS UNIVERSITY
UNU-WIDER

national treasury
Department:
National Treasury
REPUBLIC OF SOUTH AFRICA

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE
IFPRI

planning, monitoring & evaluation
Department:
Planning, Monitoring and Evaluation
REPUBLIC OF SOUTH AFRICA

the dtic
Department:
Trade, Industry and Competition
REPUBLIC OF SOUTH AFRICA

SARS

TIPS

About the project

Southern Africa –Towards Inclusive Economic Development (SA-TIED)

SA-TIED is a unique collaboration between local and international research institutes and the government of South Africa. Its primary goal is to improve the interface between research and policy by producing cutting-edge research for inclusive growth and economic transformation in the southern African region. It is hoped that the SA-TIED programme will lead to greater institutional and individual capacities, improve database management and data analysis, and provide research outputs that assist in the formulation of evidence-based economic policy.

The collaboration is between the United Nations University World Institute for Development Economics Research (UNU-WIDER), the National Treasury of South Africa, the International Food Policy Research Institute (IFPRI), the Department of Monitoring, Planning, and Evaluation, the Department of Trade and Industry, South African Revenue Services, Trade and Industrial Policy Strategies, and other universities and institutes. It is funded by the National Treasury of South Africa, the Department of Trade and Industry of South Africa, the Delegation of the European Union to South Africa, IFPRI, and UNU-WIDER through the Institute's contributions from Finland, Sweden, and the United Kingdom to its research programme.

Copyright © Authors 2021

The views expressed in this paper are those of the author(s), and do not necessarily reflect the views of the of the SA-TIED programme partners or its donors.

Towards Inclusive Economic Development in Southern Africa

SA-TIED | Working Paper # | January 2021

Climate uncertainty and agricultural vulnerability in South Africa

Faaiqa Hartley, Sherwin Gabriel, James Cullis and Channing Arndt

ABSTRACT

Climate change poses a serious threat to many countries, particularly to developing countries, which often have large sections of the population without resources to adapt to changes in their environment. One of the key ways in which climate change affects countries is its impact on agricultural production. This paper extends the analysis by Cullis et al. (2015) by unpacking the impacts of climate change on crops and regions across South Africa. Furthermore, it looks at the impact of climate change on household food consumption and its implications for food security. The analysis suggests that, while the impacts of climate change are likely to be negative, the size of impacts can be highly variable, depending on the resulting climate. The largest range of vulnerability lies along the eastern coast of the country, where there is also the greatest poverty. Other regions, such as the Western Cape, show clear signs of declining production across the likely range of future potential climates, although some of these threats can be addressed through adaptation. Shifting to irrigated agriculture offsets some of the negative impacts on production but is insufficient to fully offset the decline in output. It also puts agriculture into increasing competition with other sectors, such as municipal and industrial water usage. Key crops, such as summer cereals, oilseeds and deciduous fruits, are negatively affected by climate change. Climate change negatively affects household welfare both nationally and sub-nationally, with certain parts of the country worse affected than others. Its impacts are through both the effect on household incomes and through higher food prices, which negatively affect household food consumption.

Keywords: Climate change, agriculture, household welfare

1 INTRODUCTION

Climate change poses a serious threat to many countries, particularly developing countries, which often have large populations and institutions without the resources to adapt to changes in their environment. Changes in climatic conditions negatively affect people's livelihoods through its impact on agriculture and food security, but also through impacts on basic infrastructure such as roads, power generation and water availability, which support economic activity. Over the past decade, the frequency of disastrous climate-related events such as droughts, floods and fires has increased, negatively affecting millions of people. To limit the impacts of changes in climate on economic activity and livelihoods, policy planning and implementation is needed immediately.

Broadly, studies for South Africa show that climate change is expected to result in an increase in temperatures and increased variability in precipitation. The median increase in temperature is estimated to be between 1 and 3 degrees Celsius (^{o}C) by 2050 under the RCP8.5 pathway. Lower increases are expected in the southern and coastal regions, while an increase of as much as 3^{o}C can be expected in northern parts. Changes in rainfall are more uncertain than changes in temperature, but increased rainfall is more likely across the central interior and east coast whilst increased drying is expected in the western interior the north east, and the southwestern Cape winter rainfall region (Engelbrecht et al. 2019). Cullis et al. (2015) produce similar findings, with temperature increases ranging between 1.5 and 3 °C by 2050 and precipitation changes showing an increased likelihood of drying conditions, with a median 3.6% reduction in average annual precipitation for all secondary water catchments across the country. The latter, however, is more variable, with some models indicating an increase in precipitation. Evaporation rates are likely to increase, with the national average rising by 4.7%. Whilst studies confirm the negative impacts of climate change on the economy, the range of these impacts is broad and varies depending on the climate models considered. The wide range of outcomes is primarily a result of differences in precipitation projections (Calzadilla et al. 2015; Ziervogel et al. 2014; Dube et al. 2013). This is highlighted in Cullis et al. (2015), who assesses the impact of nearly 400 potential climate futures for South Africa.

While the national and sub-national, impacts of climate change in South Africa have been studied in several papers (Mugambiwa and Tirivangasi 2017; Shisanya and Mafongoya 2016; Abidoye and Odusola 2015; Calzadilla et al. 2015; Dube et al. 2013; Mnisi and Dlamini 2012; Schulze 2011), these analyses have often been partial equilibrium studies, focusing on specific crops and regions, thus not accounting for the indirect impacts on the rest of the economy and feedback effects between economic agents. The climate channels considered have also been narrow and have largely focused on the economic impacts of changes in crop yields. To date, Cullis et al. (2015) remains a leading effort in assessing the potential impacts of climate change on the South African economy. The methodology combines climate, biophysical, and economic models in a consistent and robust framework to assess the impacts of key climate channels (namely infrastructure, water availability and crop yield) for a larger number of potential climate outcomes. As such, the lessons derived from the analysis remain important inputs in the development of climate adaptation policy.

This paper extends the analysis by Cullis et al. (2015), by unpacking the modelling effort to understand the drivers of the change in agriculture GVA (gross value added) nationally and at the sub-national level. In addition, the impact of climate changes on regional household welfare and food security is also assessed. The paper is structured as follows: Section 2 presents a summarized version of the methodology implemented by Cullis et al. and the scenarios considered in their analysis; Section 3 briefly describes the agricultural landscape in South Africa; Section 4 presents the analysis of results; and Section 5 concludes with a discussion of the implications of the analysis for climate adaptation policy in South Africa.

2 METHODOLOGY

The Systematic Assessment of Climate Resilient Development (SACRED) approach (Arndt 2011; UNUWIDER 2012; Schlosser and Strzepek 2013), an integrated modelling framework which combines the use of climate, country-specific biophysical and country-specific economic models, is used to consistently assess the impact of climate change in the Southern African Development Community region and in South Africa (see Figure 1). Three key channels of climate change are considered, namely impact on road infrastructure, ability to meet water demand for municipal, industrial and agricultural uses, and impact on agriculture crop yields. Impacts of climate change on temperature, precipitation and evaporation are passed to the biophysical models, which provide inputs to the economic model to assess the impacts on the economy (see Cullis et al. (2015) for further details).

The modelling framework considers the results of nearly 800 climate projections under two global emissions scenarios (approaching 400 climates per scenario). The global emissions scenarios are defined as an unconstrained emissions scenario where efforts to reduce emissions fail and emissions continue to rise, and a Level 1 Stabilisation (L1S) scenario where greenhouse gas concentrations are constrained to the level of 560 ppm by 2100, as defined by Webster et al. (2011). A three-step procedure is used to develop a hybrid frequency distribution of future climates for South Africa:

- First, the Integrated Global Systems Model (IGSM) of MIT is deployed to develop nearly 400 future global climates for each global emissions scenario (Webster et al. 2011).
- While the IGSM determines climate change impacts by latitude band, it does not do so by longitude band. To represent climates in South Africa, regional patterns of impact from 17 general circulation models of the earth and atmosphere (GCMs) from the Climate Model Intercomparison Project (CMIP3, Meehl et al. 2007) is used to estimate climate impacts for South Africa (Schlosser et al. 2012), resulting in 6800 climates (17*400) per global emissions scenario.
- As this number of climates is too large for practical application, an intelligent sampling procedure (Arndt et al. 2015) is deployed to select about 400 climates per global emissions scenario. The procedure was also designed to give approximately equal weight to each of the 17 CMIP3 climate models, or about 23 climates per CMIP3 model.

A key finding from Cullis et al. (2015) is that climate change impacts vary substantially across climates and regions. To represent this variation, we illustrate ranges of results by the 17 CMIP3 models (referred to as climate model) and by the 19 water management areas (WMAs) in South Africa. Figure 2 shows the geographic distribution of the WMAs. In this paper we focus on the unconstrained global emissions scenario.

The climate channels considered are modelled cumulatively. Two additional scenarios, one without climate change and one including the world price effects of climate change (notably for agriculture and fossil fuels) as defined by Palsev (2012) are also run with the latter representing the benchmark to which climate change impacts are assessed. Table 1 presents the scenarios considered by Cullis et al (2015). In this paper, we will focus on the full impact of climate change, namely scenario 'Dry agriculture/Total'.

Key assumptions included in the model include perfectly competitive markets; full sub-national employment with labour able to freely move between sectors; and nationally mobile capital.

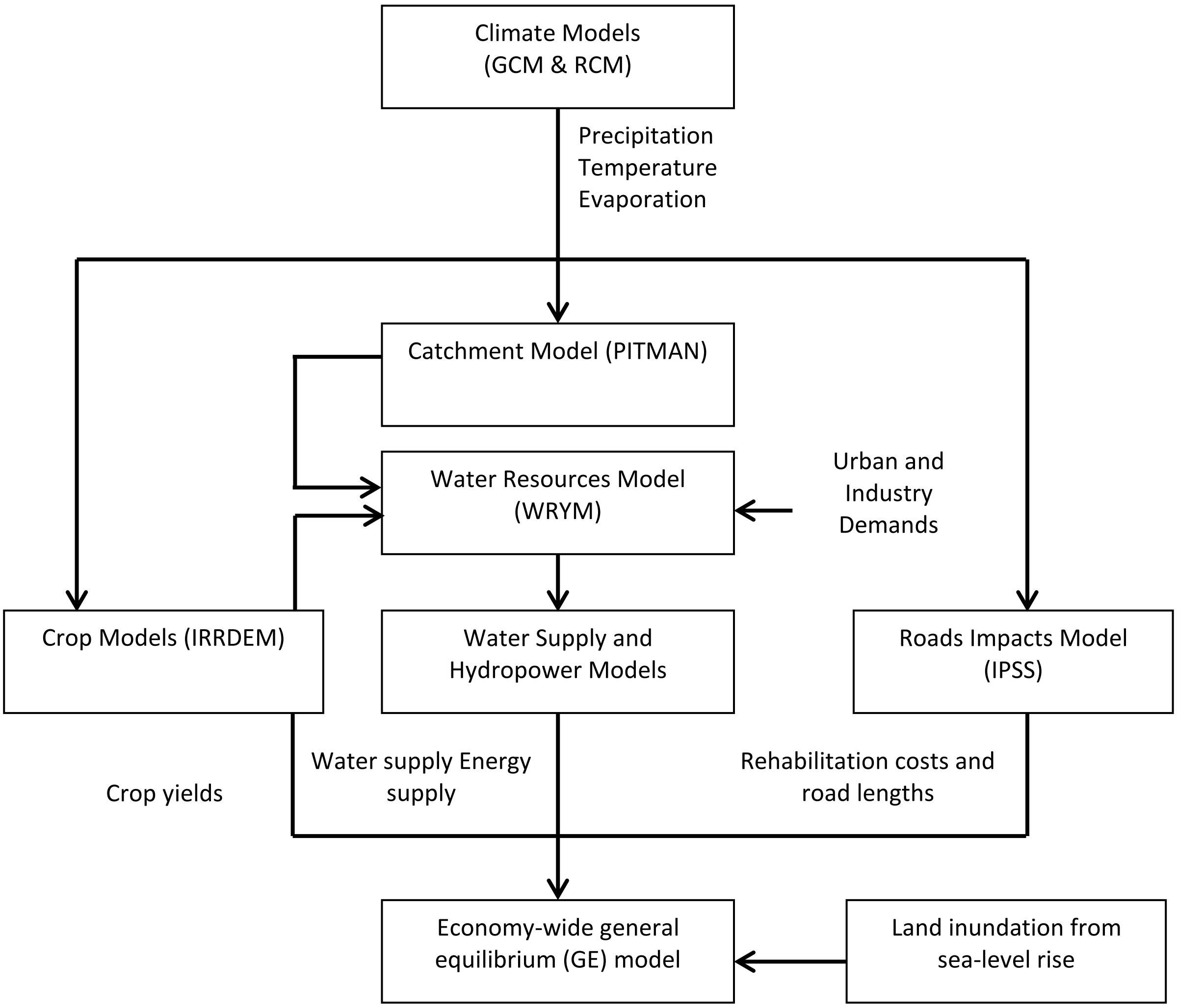

Figure 1: SACRED Framework
Source: Cullis et al. (2015)

Table 1: Climate models modelled in SACRED for South Africa

Scenario name	Description
Baseline	This presents the business as usual path for South Africa without annual weather or climate shocks or changes in world prices. No climate change is assumed.
World prices	World prices changes to 2050 as projected by Paltsev (2012) are imposed as derived from the unconstrained global emissions scenario.
Roads	World prices plus additional costs for rehabilitating and maintaining existing road infrastructure networks. Increased road infrastructure spending negatively impacts productivity. This result is captured by reducing the growth in TFP in accordance with existing literature on the links between transport and economywide productivity growth.
Irrigation	Roads plus the impact of climate change on the availability of water by water management area.
Dry agriculture/Total	Irrigation plus climate change temperature and precipitation impacts on the productivity of dryland agriculture.

Source: Cullis et al. (2015)

3 AGRICULTURE IN SOUTH AFRICA

Agricultural GDP in South Africa depends on three key crops, namely sugarcane, summer cereals such as maize, and deciduous fruits such as grapes, pome fruits, and stone fruits. These crops account for roughly two thirds of total agricultural value added. They are primarily produced in specific regions of South Africa. Sugarcane is largely produced in water management area (WMA) 11 (Mvoti to Umzimkulu), but also in WMAs 5, 6 and 7 (KwaZulu Natal and Mpumalanga). Summer cereals are primarily produced in WMAs 8, 9 and 10 (Free State and North West), with WMA 4 (Mpumalanga) also producing a significant portion. Deciduous fruits are largely produced in WMAs 17, 18 and 19 (Western Cape), although WMA 14 (Northern Cape) also produces significant amounts. This geographical landscape of production therefore identifies KwaZulu-Natal, Free State, North West, Mpumalanga, and Western Cape as key regions for agriculture production. Approximately 80% of South African crop production is rainfed, with irrigated crops accounting for only 20%. For key crops and regions, rainfed agriculture is the primary activity. Negative climate impacts in these areas would therefore have a significant impact on total agricultural production.

While the agricultural sector accounts for a relatively small direct share of GVA (~2%) and employment (~5%), the sector's contribution to value added and employment is larger when considering links to food processing. This is particularly true for agriculture and food processing exports, which together account for 6% of total exports. South Africa is a net agriculture and food exporter. Agriculture plays a different role in people's livelihoods depending on where they are situated. Figure 2 illustrates the importance of agriculture and food processing in different parts of South Africa for three key crops. In 10 of the 19 WMAs presented, agriculture and food processing accounts for more than 10% of regional GDP. These regions are also key growers of summer cereals, sugarcane and deciduous fruits.

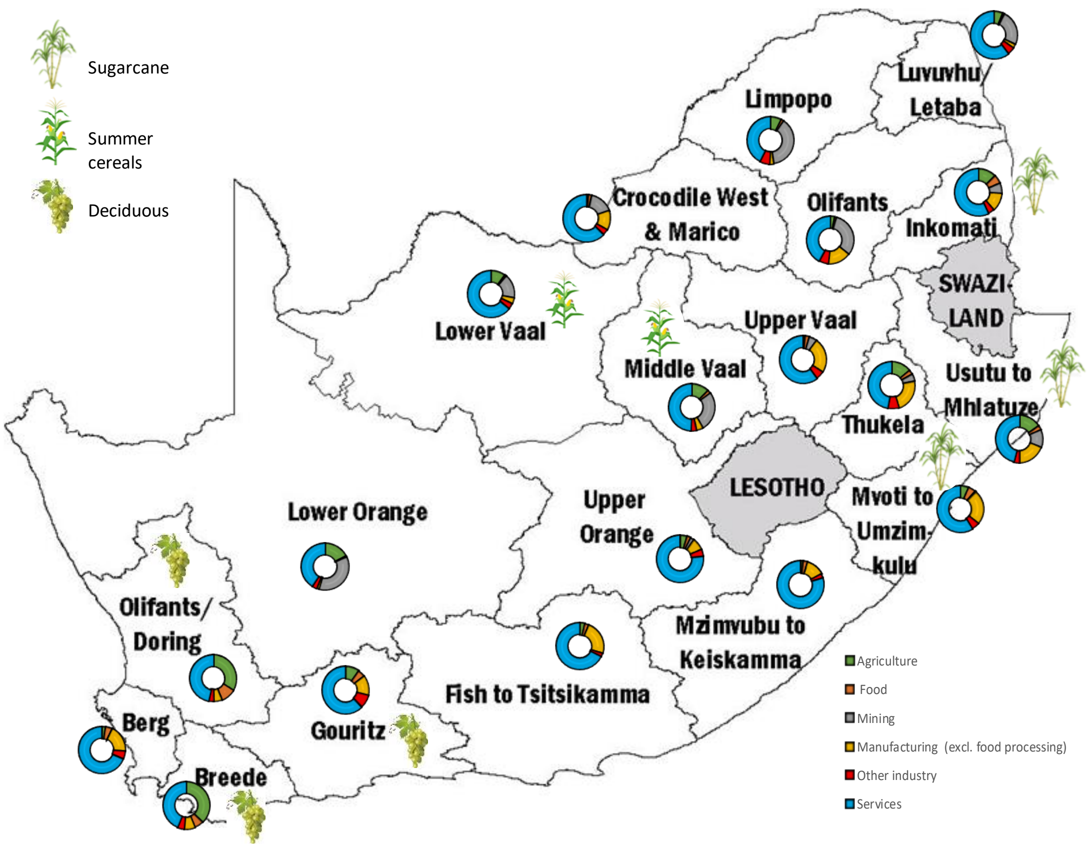

Figure 2: Regional GVA by sector

4 RESULTS

4.1 Total gross domestic product

Figure 3 presents the range of average GDP impacts for the 17 climate models considered by region and for the whole of South Africa. The results show that, at a national level, all climate model scenarios result in a negative impact on real GDP, ranging between -0.1% and -2.3%, with a median impact of -1.5%. For most regions, the impacts on GDP are consistently negative. However, there are climate scenarios in which there are positive effects on regional GDP – the provinces of Mpumalanga (specifically WMA 5), KwaZulu-Natal (WMAs 6, 7 and 11), Free State (WMA 9) and North West (WMA 10) are these exceptions – but these occur in fewer than a quarter of the climate models considered. The variations in GDP impact in these regions, particularly in Mpumalanga and KwaZulu-Natal (areas with high poverty and food insecurity rates), are also broad, as indicated by the whiskers of the box plot, with larger than mean national GDP declines a possibility. The Western Cape region (WMAs 16, 17, 18 and 19) is likely to experience one of the largest declines in GDP, with most climate models showing a decrease in GDP larger than the median national impact. The province is responsible for 15% of total GDP (StatsSA 2019).

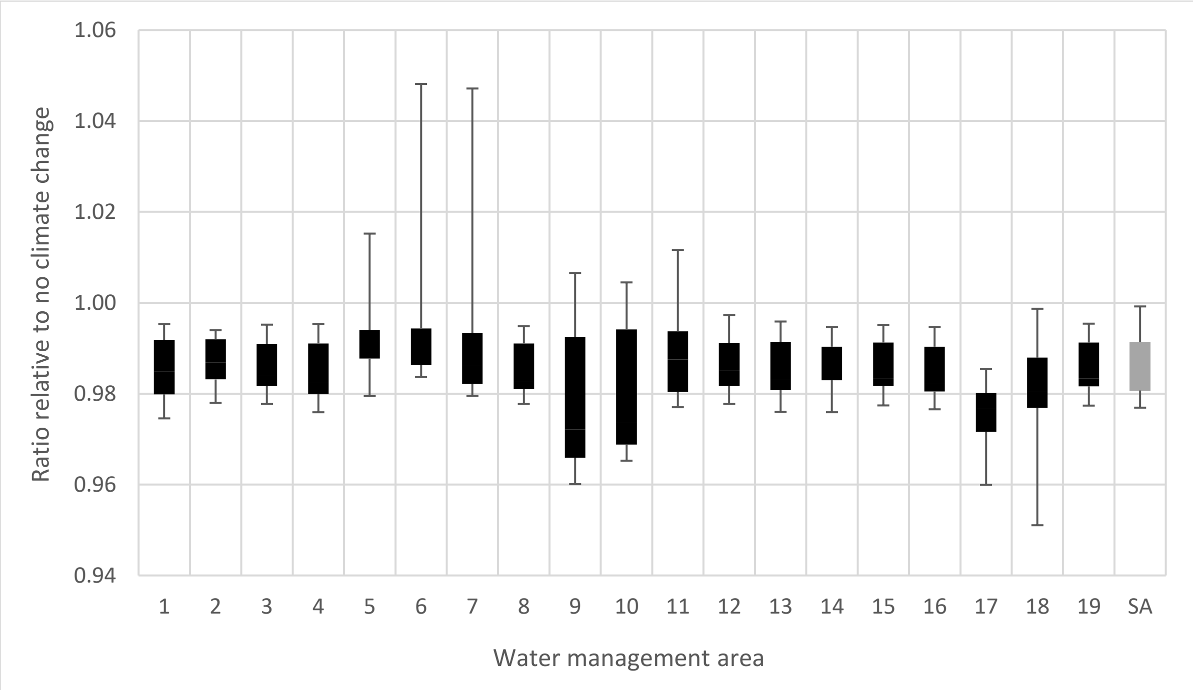

Figure 3: Regional real GDP estimates (2045-2050), deviation from no climate change scenario

4.2 Agriculture crop value added

The mean impacts of climate change on crop production by climate model is presented in Figure 4. As discussed in Cullis et al. (2015), the switch from dryland to irrigated agriculture is a key endogenous adaptation channel that takes place to mitigate the negative impact of climate change. This is clearly illustrated by the increase in irrigated crop production across most climate models. The increase in irrigated crop production partly compensates for the decline in rainfed yields but is not, in most cases, able to fully offset the declines experienced in rainfed agriculture. As a result, net agricultural production declines across most climate models.

For some crops, such as citrus, deciduous fruits, vegetables and other horticulture, the impacts of climate change are highly likely to be negative, with very little variability seen across the climate models. Other crops, such as sugarcane, oilseeds and summer cereals, illustrate large ranges of variability. Sugarcane is highly sensitive and shows the largest variation. Rainfed summer cereal production, the largest agricultural activity in South Africa and a major food staple, is highly likely to decrease with a median decline of -13.6%.

In climates where favourable precipitation offsets negative effects of higher temperatures, dryland crop yields rise, leading to an increase in dryland production of these crops. The decrease in substitution of irrigation for rainfed crops frees up irrigated water to be used by crops for which rainfed agriculture is not an option in South Africa, i.e. deciduous and citrus fruits, vegetables and other horticulture. Under such climate models, production of these crops continues to grow. This occurs, however, in fewer climate models, as indicated by the small positive whiskers in Figure 4.

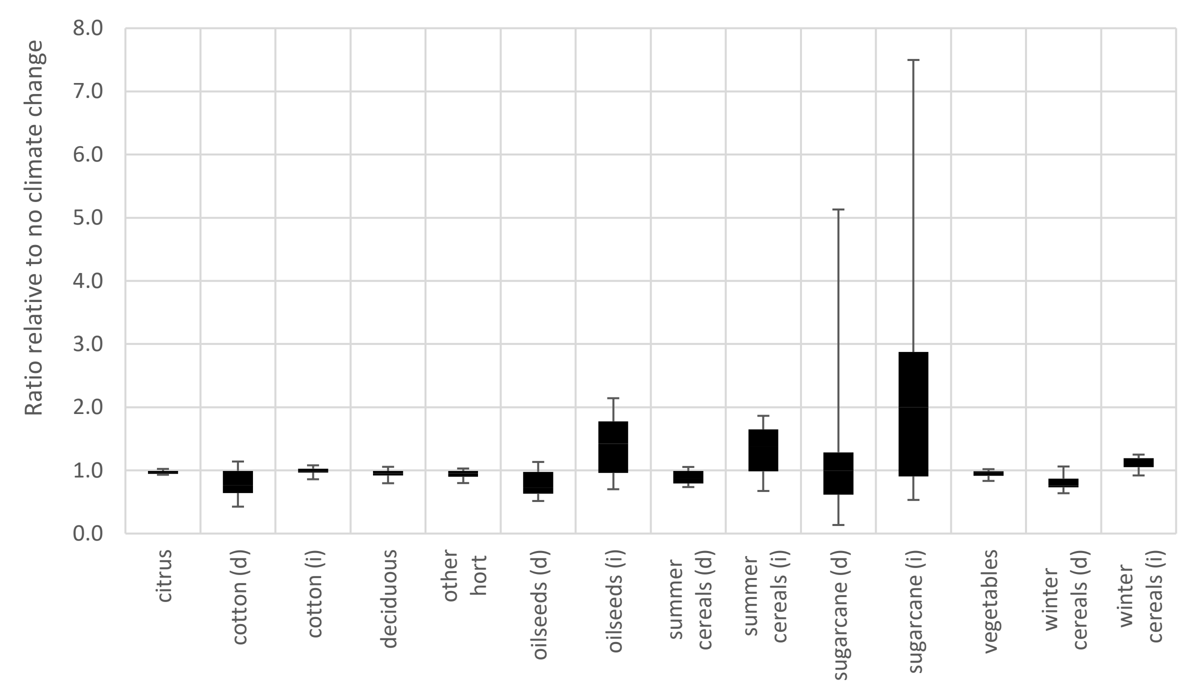

Figure 4: Crop gross value added

For most climate models, lower agricultural production results in a decline in exports of agriculture commodities and food (see Figure 5), and an increase in imported crops, particularly winter and summer cereals, and oil seeds. Key export crops, namely deciduous and citrus fruits and oilseeds, decrease. Consequently, the combination of higher imports and lower exports of agriculture and food commodities leads to a deterioration in South Africa's food trade balance, making the country a net food importer (it is currently a net food exporter).

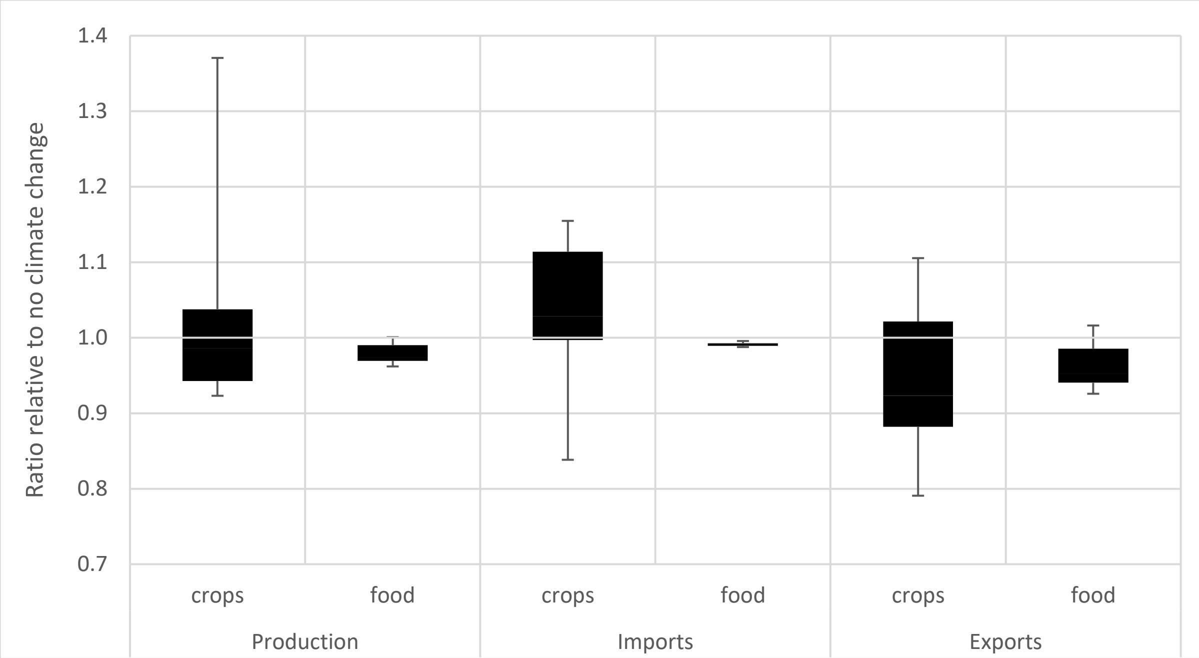

Figure 5: Agricultural crop and processed food production, imports and exports

4.3 Agriculture crop value added by region

As in many parts of the world, different crops are primarily produced in different regions of the country, where the climate best suits them. As a result, climate change impacts on regional agricultural production within South Africa differs. Figure 6 presents the impact on total crop GVA (both field crops and horticulture) by region and for the whole of South Africa. Nationally the impact of climate change on GVA by crop ranges between -7.7% and 37.1%, with a median impact of -1.4%. The variation in impacts across regions and climate model scenarios is larger than for total GDP, with the potential for more regions to experience a positive crop GVA impact, although the likely impact remains negative for most regions.

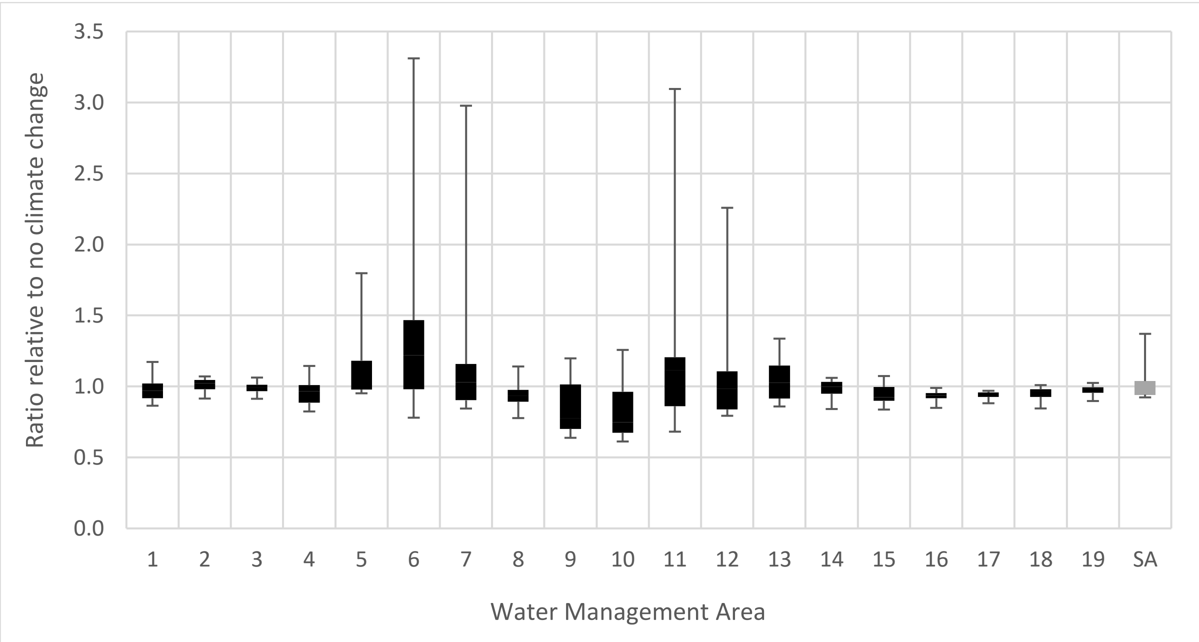

Figure 6: Regional real crop gross value added

Variations in impacts are particularly large in KwaZulu-Natal (WMAs 6, 7 and 11), which is a key sugarcane producer and key contributor to agricultural value added (~25% in 2018, according to StatsSA (2019)). Under favourable climates, rainfed sugarcane yield increases in KwaZulu-Natal are large, whilst under unfavourable conditions, the sharp rise in sugarcane prices (in response to decreasing yields) causes a shift to irrigated production as there is no substitute for the crop demand. This explains some of the variability seen in Mpumalanga (WMA 5) and the Eastern Cape (WMA 12) as these regions are key irrigated sugarcane producers. The change in sugarcane prices range between -11% and 23% (median: 9%) relative to the no climate change scenario. The rise in irrigated sugarcane production, however, causes a shift in resources away from other crops (see Appendix) and activities. Cullis et al. (2015) highlight a (small) decrease in non-agricultural activity because of the shift in resources toward agricultural production due to rising crop prices.

The Vaal region in the Free State and North West (WMAs 8, 9 and 10) is the primary producer of rainfed summer cereals and oilseeds and accounts for 18% of total agricultural GVA (StatsSA 2019). Whilst negative rainfed yield impacts on summer cereals and oilseeds also result in higher prices, shifting production from rainfed to irrigated, irrigated production volumes are quite small, and insufficient to compensate for the rainfed value loss. For nearly 80% of climate models, production within these regions decreases, with median declines of -6.7%, -22.3% and -25.1% experienced in WMAs 8, 9 and 10 respectively.

Figure 7 below presents the mean change in agricultural crop GVA by WMA (represented by dots) for each climate model. The shaded area indicates models under which national agricultural crop GVA is positive. When national agricultural outcomes are positive, this does not suggest a broadly favourable climatic profile for the country. Instead, positive agricultural GDP is concentrated in the highly variable WMAs shown in Figure 6 (i.e. WMAs 5, 6 ,7, 11, and 12).

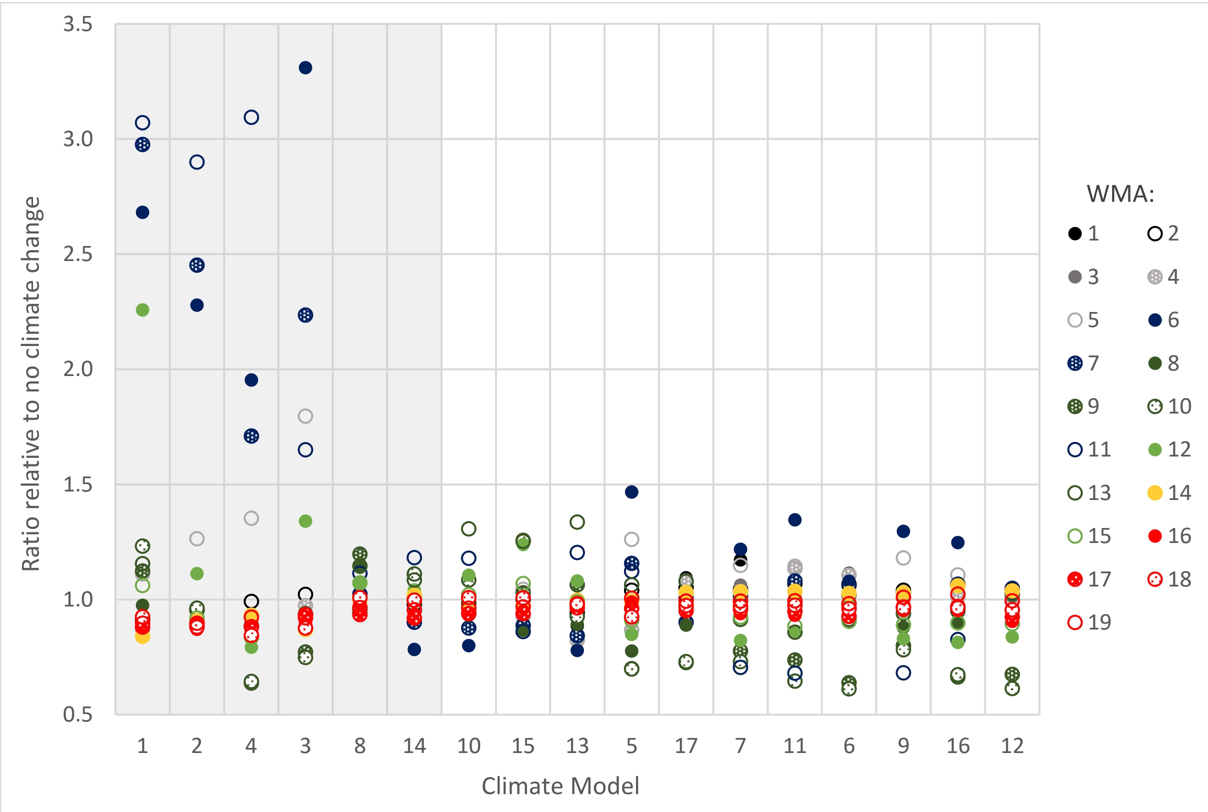

Figure 7: Agricultural crop value added by water management area and climate model (mean)

4.4 Regional welfare impacts

Whilst many studies have found South Africa to be a food secure nation, they have also highlighted the high levels of insecurity of food at the household level, with households in rural areas identified as particularly affected (Pereira et al. 2014; Altman et al. 2009; FAO 2008, Hart and Aliber 2009; Hendriks 2005; Knueppel et al. 2009; De Cock 2012). According to StatsSA (2019) more than 20% of households reported having inadequate or severely inadequate access to food in 2017. By province, the Northern Cape, North West, Eastern Cape and KwaZulu-Natal have the largest share of food-insecure households, whilst the Northern Cape, Mpumalanga and North West reported the most severe food access inadequacy rates – double that of the national rate. The country also experiences higher rates of hunger, including in children under the age of five. Food insecurity is linked to the high levels of inequality and high unemployment rates (Rudolph 2012). Food security is therefore more an issue of access than availability of food (Bonti-Ankomah 2001).

Figure 8 below presents the impacts of climate change on household welfare, which is represented by the change in real household consumption. As illustrated, total household welfare is lower under all climate models relative to the no climate case. This suggests that, in addition to food availability, households are challenged by lower income and purchasing power. This result is driven by the decrease in national activity, which affects wages and prices. Variation in consumption is largest for food (which here also includes agricultural crops), with most climate models indicating a decrease in household food consumption and hence potential increase in insecurity. Climate change threatens both the availability of food, through its impact on crop yields and the increased need for imports, and the ability to access food, through the rise in food prices.

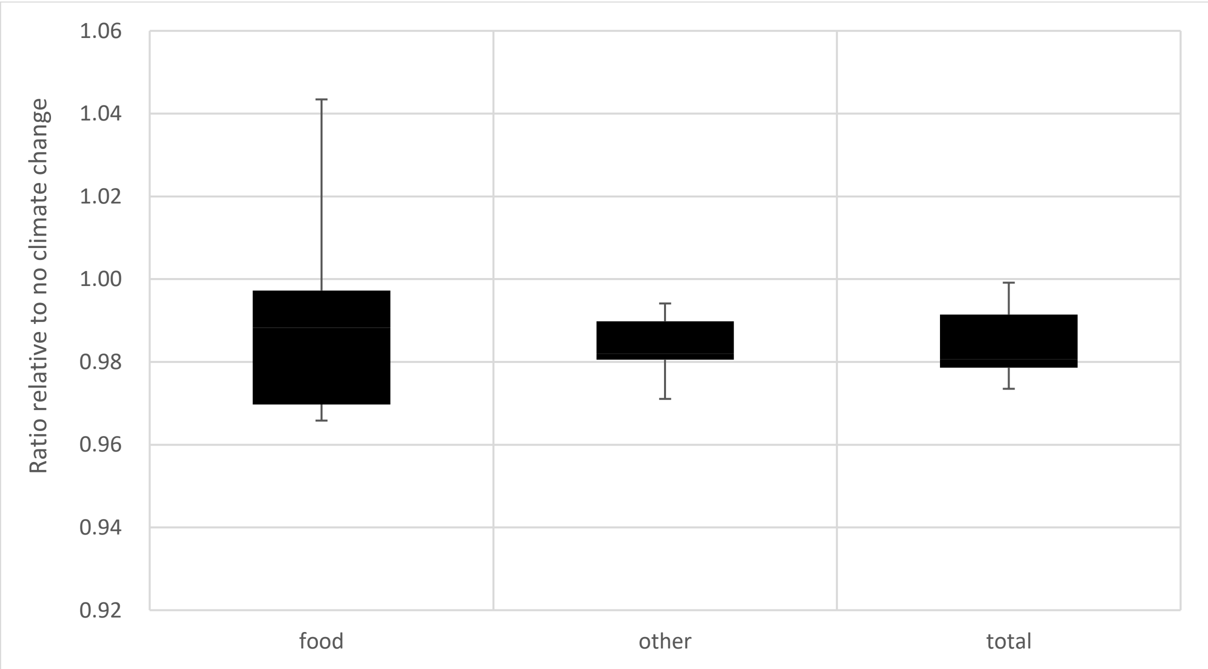

Figure 8: Real household consumption by commodity group

Figure 9 below presents the impact on household real food consumption by region. While the impacts on households differ between regions, most climate models negatively affect household food consumption. Households in KwaZulu-Natal (WMAs 6 and 7) experience higher variability in potential impacts, although some climate models do suggest an increase in food consumed. These climate models align to those in which sugarcane crop production increases under climate change. Households in the Western Cape (WMAs 17 and 18) could potentially be the hardest hit by climate change, with real food consumption declines of more than 3% experienced under the harshest climate models. In the Olifants-Doorn region (WMA 17), 22% of household income is derived from wages in agriculture. The negative results illustrate the vulnerability in agriculture-dependent households to changes in production.

Households in the Vaal region (WMAs 8, 9 and 10) are also some of the most negatively affected, with median impacts on par with those expected for the Western Cape. While all households are negatively affected by climate change, those in the poorest 20% of the population are vulnerable to larger negative impacts than those in the wealthiest 20% (see Figure 10).

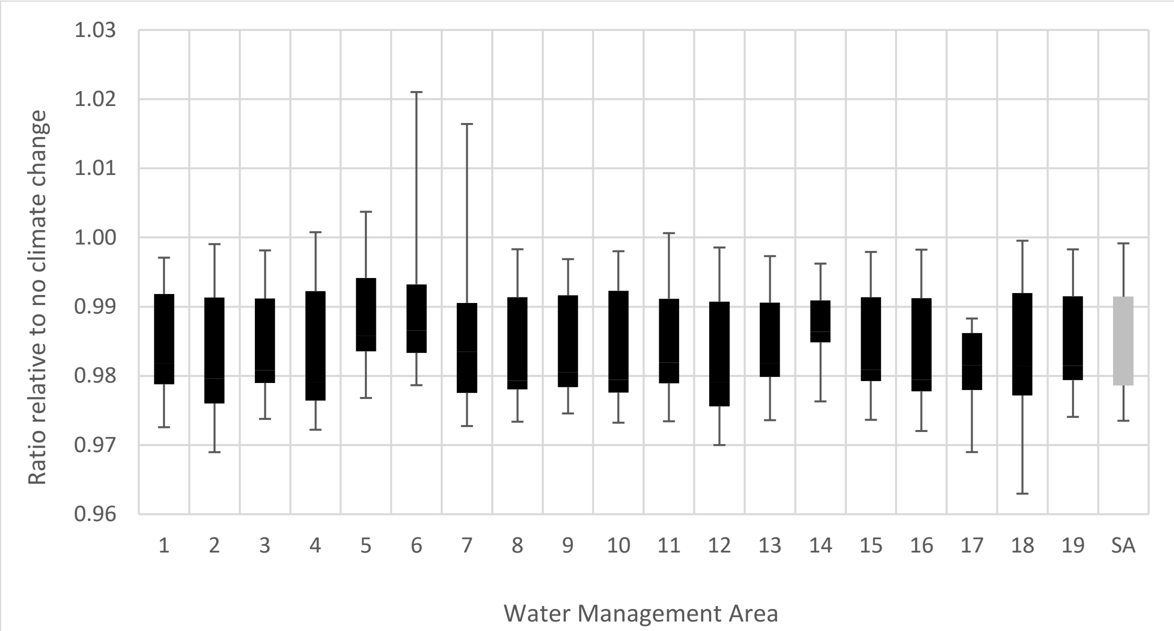

Figure 9: Real household food consumption by region

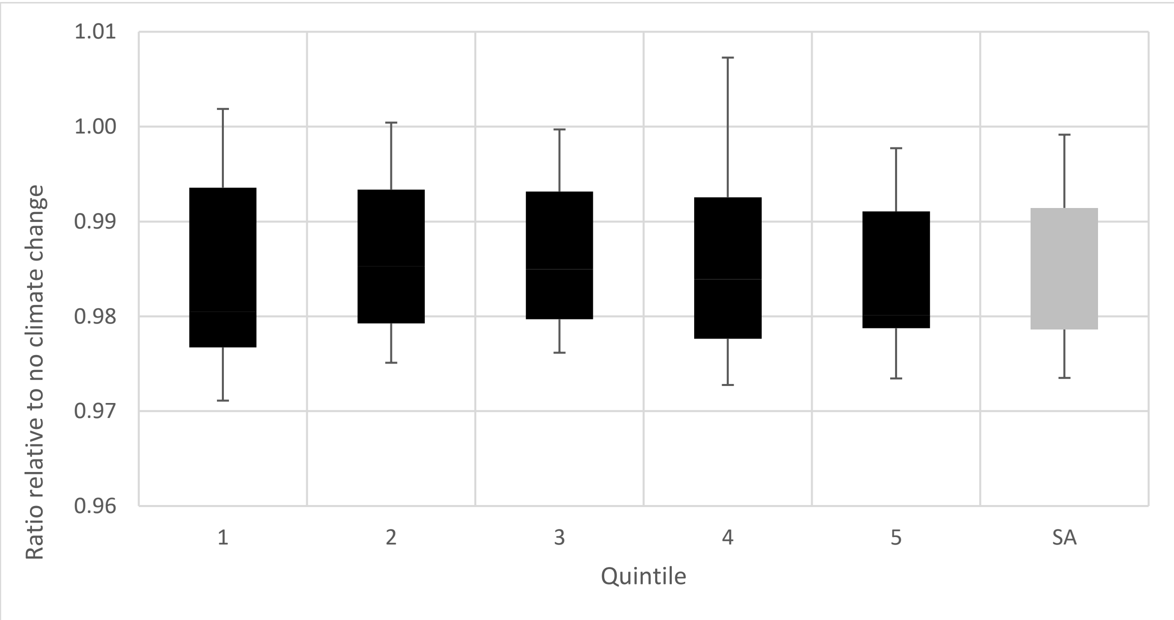

Figure 10: Real household food consumption by quintile

5 DISCUSSION

This paper extends the analysis of Cullis et al. (2015) by unpacking the impacts of climate change on crops and regions in South Africa. Furthermore, it looks at the impact of climate change on household food consumption and its implications for food security. The analysis suggests that, while the impacts of climate change are likely to be negative in South Africa, the size of impacts can be highly variable depending on the climate scenario that transpires. The largest range of vulnerability lies along the eastern coast, where there is substantial rainfed sugarcane production, which is highly vulnerable to rising temperatures and drying conditions. By headcount, regions along the eastern coast also have the highest poverty ratios (World Bank Group 2018). Whilst a shift to irrigated agriculture offsets some of the negative impacts on sugarcane production, it does so at the expense of other crops in the region and is also insufficient to fully offset the impacts. Climate-induced lower rainfed sugarcane yields also shift production to regions where irrigated production is possible. This is seen by the increase in irrigated production in WMAs 5, 6 and 7. The decline in key crops like summer and winter cereals as well as deciduous fruits has a negative impact on production in regions where these are produced, namely the Free State, North West and Western Cape provinces, but also negatively affects South Africa's agricultural trade balance, making the country more dependent on external sources of, particularly, summer and winter cereals.

The Western Cape shows a consistent negative impact across climate models, with all indicating significant drying. This is significant given that produce from the Western Cape is a significant contributor to export earnings. In this regard, consideration also needs to be given as to how climate change might impact other regions of production in the world - ones which may be even harder hit than South Africa, and with less potential for adaptation. Some of these climate change risks can be mitigated though effective investment in adaptation options, such as the raising of the Clanwilliam Dam and better management of existing systems such as the Western Cape water supply system. The benefits of investing in conservation agriculture techniques and new tools, such as Fruitlook, that assist in improving water use efficiency have also shown benefits, even during the recent drought.

A key finding from the analysis is the shift of resources into agriculture, particularly high-value crops. The rise in prices of certain crops pulls resources into producing them and away from other crops. This was particularly found in sugarcane regions – sugarcane experiences the largest price increases across most climate models. In adapting to climate change, a strategy must be developed to ensure that crops produced align with national policy goals that ensure food security as opposed to food sovereignty (i.e. producing own food as opposed to the ability to purchase it on the global or regional market). Easing conditions for imports is also necessary to ensure that deficits can be met with foreign products, including imports of sugar, which is currently a protected industry. Rising temperatures and limits on water available for irrigation (from drying conditions and increasing competition for water for urban and industrial needs) reduce the number of agriculture adaptation options available (Cullis and Phillips 2019). Increased trade therefore becomes a key adaptation tool to ensure food sovereignty (Engelbrecht et al. 2019).

Whilst the results show an endogenous adaptation to irrigated agriculture, that shift is insufficient to offset declines in production. Calzadilla et al. (2014) find a similar result from their modelling, and report that a doubling in irrigated agriculture in South Africa would not offset the losses to GDP experienced. A shift to irrigated agriculture alone is therefore not an effective strategy to cope fully with the impacts of climate change. It also puts agriculture into conflict with other water-dependent sectors, including both municipalities and industry, which have higher returns.

Climate change negatively affects household welfare both nationally and sub-nationally, with some parts of the country more affected than others. The impacts of climate change are through both the effect on household incomes and higher food prices, which negatively affect household food consumption. The analysis shows that, while all households are negatively affected by climate change, households in the first quartile are more vulnerable to larger shocks. Given South Africa's significant rate of food insecurity, particularly in rural areas, strategies must be developed to help protect these households from the negative impacts of climate change. These will involve not only physical interventions to improve agriculture production though, for example, introducing more conservation agriculture techniques and support, but also means for alternative income-generating activities that are less climate-dependent but provide money to buy food. While not covered in this paper, an additional key concern of climate change, particularly for poor households, is the increased risk of floods and droughts as well as infectious diseases and migration. Engelbrecht et al. (2019) expect an increase in extreme rainfall days (20 mm of rain within 24 hours over a 64 square kilometre area) as well as a rise in more hot days (temperatures greater than 34 ^{o}C). The latter raises the risk of heat stress, affecting health, with more than 27% of settlements in the country described as being at extreme or high risk to heat stress. Engelbrecht et al. propose adaptation responses such as improved access to water and the provision of cooling options to reduce the impact of heat stress on highly vulnerable rural communities.

REFERENCES

Abidoye, B.O. and Odusola, A.F. 2015. Climate change and economic growth in Africa: An econometric analysis. *Journal of African Economies* 24(2): 277–301. DOI: http://dx.doi.org/10.1093/jae/eju033

Bohensky, E. 2014. Learning dilemmas in a social-ecological system: An agent-based modeling exploration. *Journal of Artificial Societies and Social Simulation* 17(1) 2. DOI: http://dx.doi.org/10.18564/jasss.2448.

Bonti-Ankomah, S. 2001. Addressing food insecurity in South Africa. The National Institute for Economic Policy, Pretoria.

Calzadilla, A., Zhu, T., Rehdanz, K., Tol, R.S.J. and Ringler, C. 2015. Climate change and agriculture: Impacts and adaptation options in South Africa. *Water Resources and Economics* 5: 24-48. https://doi.org/10.1016/j.wre.2014.03.001 [Accessed: 01/10/2020].

Cullis, J., Alton, T., Arndt, C., Cartwright, A., Chang, A., Gabriel, S., Gebretsadik, Y., Hartley, F., de Jager, G., Makrelov, K., Robertson, G., Schlosser, A.C., Strzepek, K. and Thurlow, J. 2015. An uncertainty approach to modelling climate change risk In South Africa. WIDER Working Paper 2015/045. Helsinki: UNU-WIDER.

Cullis, J. & Phillips, M. 2019. Green book. Surface water supply. Water supply climate risk narrative for South Africa. Pretoria: Aurecon & CSIR. Available https://pta-gis-2-web1.csir.co.za/portal2/apps/GBCascade/index.html?appid=60437bfd1bc947d48f9b00c9a0990c3f. [Accessed 12/01/2021].

De Cock, N. 2012. A comparative overview of commonly used food security indicators in Limpopo province, South Africa. Ghent University, Ghent, Belgium, Netherlands.

Dube, S., Scholes, R.J., Nelson, G.C., Mason-D'Croz, D. and Palazzo, A. 2013. South African food security and climate change: Agriculture futures. *Economics: The Open-Access, Open-Assessment E-Journal*, 7: 2013-35. DOI: http://dx.doi.org/10.5018/economics-ejournal.ja.

Engelbrecht, F., Le Roux, A., Arnold, K. and Malherbe, J. 2019. Green book. Detailed projections of future climate change over South Africa. Pretoria: CSIR. Available at: https://pta-gis-2-web1.csir.co.za/portal/apps/GBCascade/index.html?appid=b161b2f892194ed5938374fe2192e537.

FAO [Food and Agriculture Organization]. 2008. *Climate change and food security: A framework document*. Food and Agriculture Organization of the United Nations, Rome.

Hart, T. & Aliber, M. 2009. Food security definitions, measurements and recent initiatives in South Africa and Southern Africa. Unpublished report, Centre for Poverty Employment and Growth, Human Sciences Research Council, Pretoria.

Hendriks, S.L. 2005. The challenges facing empirical estimation of food (in) security in South Africa, *Development Southern Africa* 22(1): 103–123. DOI: https://doi. org/10.1080/03768350500044651.

Knueppel, D., Demment, M. & Kaisser, L. 2009. Validation of household food insecurity access scale in rural Tanzania. *Public Health Nutrition* 13(3): 360–367. DOI: https://doi.org/10.1017/S1368980009991121.

Meehl, G.A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J.F.B., Stouffer, R.J. and Taylor, K.E. 2007. The WCRP CMIP3 multi-model dataset: A new era in climate change research. *Bulletin of the American Meteorological Society* 88: 1383-94.

Mnisi, M.S. and Dlamini, C.S. 2012. The concept of sustainable sugar production: Global, African, South African perceptions. *African Journal of Agriculture Research* 7(31): 4337-4343.

Mugambiwa, S.S. and Tirivangasi, H.M. 2017. Climate change: A threat towards achieving "Sustainable Development Goal number two" (end hunger, achieve food security and improved nutrition and promote sustainable agriculture) in South Africa. *Jàmbá: Journal of Disaster Risk Studies* 9(1): a350. DOI: https://doi.org/10.4102/ jamba.v9i1.350.

Paltsev, S. 2012. Implications of alternative mitigation policies on world prices for fossil fuels and agricultural products. Working Paper 2012/065. Helsinki: UNU-WIDER.

Rudolph, M., 2012. The state of food insecurity in Johannesburg. Urban Food Security Series No. 12, Queen's University, Kingston.

Schlosser, C.A., Gao, X., Strzepek, K., Sokolov, A., Forest, C.E., Awadalla, S. and Farmer, W. 2012. Quantifying the likelihood of regional climate change: A hybridized approach. Journal of Climate 26(10): 3394-3414. DOI: https://doi.org/10.1175/JCLI-D-11-00730.1.

Shisanya, S. and Mafongoya, P. 2016. Adaptation to climate change and the impacts on household food security among rural farmers in uMzinyathi District of Kwazulu-Natal, South Africa. *Food Security* 8: 597-608. DOI: https://doi.org/10.1007/s12571-016-0569-7.

Schulze R.E. 2011. A 2011 perspective on climate change and the South African water sector. Water Research Commission, Pretoria, RSA. WRC Report TT 518/12.

StatsSA [Statistics South Africa]. 2019. P0441 - gross domestic product (GDP), 4th Quarter 2019. Available: http://www.statssa.gov.za/?page_id=1854&PPN=P0441&SCH=7695 [Accessed: 23/09/2020].

Webster, M., Sokolov, A.P., Reilly, J.M., Forest, C.E., Paltsev, S., Schlosser, C.A., Wang, C., Kicklighter, D., Sarofim, M., Melillo, J., Prinn, R.G., and Jacoby, H. D. 2012. Analysis of climate policy targets under uncertainty. *Climatic Change* 112(3-4): 569-83.

World Bank Group. 2018. *Overcoming poverty and inequality in South Africa: An assessment of drivers, constraints and opportunities*. World Bank, Washington, DC.

Ziervogel, G., New, M., van Garderen, E.A., Midgley, G., Taylor, A., Hamann, R., Stuart-Hill, S., Myers, J. and Warburton, M. 2014. Climate change impacts and adaptation in South Africa. *WIREs Climate Change*, 5(5):605–620. DOI: https://doi.org/10.1002/wcc.295.

Appendix: Impact on agriculture crop production by crop and region (ratio relative to no climate change), median and *standard deviation*

Agriculture crop	Water Management Area 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Citrus fruits	1.03	1.04	0.91	0.98	0.85	0.73	0.76	0.99	1.05	1.11	0.81	0.89		0.99	0.91	0.97	1.07	1.11	1.12
	0.09	*0.06*	*0.15*	*0.09*	*0.14*	*0.27*	*0.18*	*0.04*	*0.08*	*0.15*	*0.17*	*0.13*		*0.07*	*0.14*	*0.05*	*0.05*	*0.09*	*0.09*
Cotton (dry)	0.75	0.85	0.74	0.84	1.25	1.19	1.13		0.68	0.58			0.74	0.47	0.85	0.47		0.61	1.02
	0.35	*0.33*	*0.23*	*0.18*	*0.31*	*0.46*	*0.41*		*0.29*	*0.55*			*0.52*	*0.61*	*0.74*	*0.17*		*0.12*	*0.06*
Cotton (irrigated)	1.02	0.99	1.00	0.99	0.91	0.79	0.80	0.95	0.95	1.05			0.92	0.97	0.95	1.00	1.08	1.10	
	0.10	*0.07*	*0.08*	*0.06*	*0.10*	*0.22*	*0.16*	*0.05*	*0.06*	*0.16*			*0.11*	*0.07*	*0.06*	*0.09*	*0.08*	*0.06*	
Deciduous fruits	0.92	0.89	0.87	0.90	0.93	0.73		0.88	0.95	0.81	0.73		0.84	0.90	0.83	0.86	0.88	0.98	0.96
	0.11	*0.08*	*0.09*	*0.09*	*0.15*	*0.23*		*0.09*	*0.12*	*0.11*	*0.23*		*0.08*	*0.09*	*0.09*	*0.12*	*0.08*	*0.08*	*0.06*
Other horticultu	0.99	0.97	1.00	0.99	0.83	0.78	0.83	1.00	1.09	1.14	0.80	0.85	1.01	0.99	0.94	1.05	1.07	1.09	1.10
	0.07	*0.03*	*0.06*	*0.06*	*0.15*	*0.21*	*0.12*	*0.08*	*0.17*	*0.23*	*0.18*	*0.11*	*0.15*	*0.06*	*0.04*	*0.08*	*0.05*	*0.07*	*0.07*
Oilseeds (dry)	0.87	0.99	0.74	0.86	1.64	1.33	1.52	0.83	0.66	0.59	1.44		0.88	0.64	0.91	0.57	0.46	0.71	1.33
	0.56	*0.61*	*0.36*	*0.29*	*0.78*	*0.49*	*0.63*	*0.15*	*0.37*	*0.53*	*0.89*		*0.73*	*0.31*	*0.72*	*0.28*	*0.28*	*0.33*	*0.46*
Oilseeds (irrigated)	1.49	1.56	1.35	1.43	1.48	1.06	1.11	1.49	1.54	1.59	1.18		1.47	1.43	1.44	1.62	1.74	1.63	
	0.51	*0.61*	*0.36*	*0.44*	*0.68*	*0.37*	*0.32*	*0.54*	*0.58*	*0.66*	*0.43*		*0.55*	*0.45*	*0.50*	*0.62*	*0.70*	*0.53*	
Summer cereals	1.05	1.06	0.90	0.94	1.16	1.04	1.08	0.94	0.86	0.73	1.20	1.27	0.94	0.47	0.88	0.60	0.55	0.88	1.06
	0.42	*0.53*	*0.18*	*0.20*	*0.43*	*0.24*	*0.22*	*0.10*	*0.17*	*0.37*	*0.36*	*0.34*	*0.44*	*0.53*	*0.48*	*0.25*	*0.29*	*0.34*	*0.38*
Summer cereals	1.37	1.51	1.28	1.30	1.22	1.03	1.09	1.28	1.37	1.46	1.13	1.34	1.31	1.33	1.29	1.36	1.54	1.63	1.67
	0.40	*0.56*	*0.29*	*0.31*	*0.55*	*0.39*	*0.31*	*0.33*	*0.41*	*0.54*	*0.42*	*0.38*	*0.39*	*0.35*	*0.34*	*0.34*	*0.50*	*0.57*	*0.65*
Sugarcane (dry)				0.81	0.89	1.39	1.34				1.45	1.41							
				0.91	*1.08*	*2.14*	*2.04*				*1.35*	*1.73*							
Sugarcane (irrigated)	3.49			2.94	2.46	2.18	2.30				2.13								
	3.80			*2.90*	*1.94*	*1.59*	*1.90*				*1.67*								
Vegetables	0.96	1.02	0.93	0.88	0.86	0.70	0.73	0.95	0.94	0.96	0.82	0.93	0.87	0.83	0.95	1.00	0.96	1.06	1.12
	0.05	*0.07*	*0.08*	*0.14*	*0.18*	*0.33*	*0.23*	*0.05*	*0.04*	*0.04*	*0.20*	*0.08*	*0.11*	*0.17*	*0.05*	*0.07*	*0.03*	*0.05*	*0.05*
Winter cereals	0.96		0.84	0.82		0.87	0.90	0.83	0.87	0.91		1.21	0.97	0.86	0.92	0.70	0.80	0.69	0.72
	0.29		*0.29*	*0.25*		*0.34*	*0.36*	*0.33*	*0.32*	*0.27*		*0.51*	*0.44*	*0.17*	*0.40*	*0.14*	*0.12*	*0.11*	*0.12*
Winter cereals	1.13	1.24	1.12	1.13	0.98	0.93	0.99	1.12	1.15	1.11		1.07	1.08	1.14	1.11	1.13	1.21	1.32	1.32
	0.13	*0.20*	*0.09*	*0.07*	*0.24*	*0.31*	*0.21*	*0.09*	*0.11*	*0.09*		*0.08*	*0.08*	*0.10*	*0.10*	*0.09*	*0.12*	*0.18*	*0.18*

About the authors

Faaiqa Hartley is a senior researcher at the Southern Africa Labour and Development Research Unit at the University of Cape Town. Sherwin Gabriel is scientist at the International Food Policy Research Institute. James Cullis is a technical director and water resources engineer at Zutari with over 20 years of experience and expertise in hydrology and hydrological analysis, environmental flow requirements and hydro-economics. Channing Arndt is the Director of the Environment and Production Technology Division at the International Food Policy Research Institute, and the Academic lead of Work Stream 5 of SA-TIED.

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE
A world free of hunger and malnutrition
1201 Eye Street, NW | Washington, DC 20005-3915 USA
T: +1.202.862.5600 | F: +1.202.862.5606
Email: ifpri@cgiar.org | www.ifpri.org

This paper was prepared as an output for the Towards Inclusive Economic Development in Southern Africa (SA-TIED) project and has not been peer reviewed. Any opinions stated herein are those of the authors and not necessarily representative of or endorsed by IFPRI. The boundaries, names, and designations used in this publication do not imply official endorsement or acceptance by the authors, the International Food Policy Research Institute (IFPRI), or its partners and donors.

Copyright © 2018. Remains with author(s). All rights reserved.