12-2017

The Economic Benefits of the South African Agricultural Research Council's Wheat Breeding Program: 1992–2015

Matthew James Coale
University of Arkansas, Fayetteville

The Economic Benefits of the South African Agricultural Research Council's Wheat Breeding Program: 1992–2015

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Agricultural Economics

by

Matthew J. Coale
University of Arkansas
Bachelor of Science in Agricultural, Food and Life Sciences, 2015

December 2017
University of Arkansas

This thesis is approved for recommendation to the Graduate Council.

Dr. Lawton Lanier Nalley
Thesis Director

Dr. Bruce Dixon
Committee Member

Dr. Petronella Chaminuka
Committee Member

Dr. Katarina Melichova
Committee Member

Abstract

Although classified as an upper middle-income country by the World Bank, food insecurity is still a concern throughout South Africa, as was evident in 2014–2015 when a drought left 22% of households food insecure. As such, agricultural research in South Africa is needed specifically in plant breeding to increase yields and help mitigate future food insecurity. To fill this need, the South African government funds the Agricultural Research Council (ARC), which conducts holistic research on wheat and other crops. Wheat is important to South African food security; due to the significant drop in wheat area planted since the abolishment of the fixed price marketing system provided by the wheat board in 1997, South Africa has become a net wheat importer. Further, recent political uncertainty has resulted in the South African Rand devaluing (by 58% to the USD during 2012–2017), leaving South Africa exposed to risk in global wheat and exchange rate markets and increasing its food insecurity vulnerability. Thus, an assertive effort has been made to break South Africa's dependence on imported wheat by increasing wheat yields per hectare.

This study estimates the proportion of increases in yield of ARC's wheat cultivars which is attributable solely to genetic improvements. In total, 36,507 yield observations were analyzed from 125 country-wide test plots from 1998 to 2014. We found that South African farmers who adopted the ARC's wheat varieties during 1992–2015 experienced an annual yield gain of 0.86%, 0.58%, and 0.31% in winter, facultative, and irrigated spring wheat types, respectively. Using actual area sown to ARC varieties we estimated that wheat producers gained $94.56 million (2016 USD) during 1992–2015 via the adoption of ARC varieties.

We estimate that every dollar invested in the ARC wheat breeding program generated a return of $4.49. This study is relevant because South Africa only has limited funds allocated to agricultural research and development. Without reliable estimates of the return on investment by the South African government, the ARC runs the risk of decreased funding, and the South African populous could run the risk of increased food insecurity.

Acknowledgements

I would like to first thank each of the members of my thesis committee: Dr. Lawton Lanier Nalley, Dr. Bruce L. Dixon, Dr. Petronella Chaminuka, and Dr. Katarina Melichova. Their support and invaluable input are what made this study possible.

I would also like to acknowledge all of those who were so graciously willing to work with me during my time in South Africa. First, Dr. Ernest Dube for his incredible hospitality and eagerness to share his vast knowledge of the South African wheat sector with me. Next, John and Vicky Tolmay who gave me the hands-on experience I so greatly needed to put my results into a real-life context. Finally, to all of the fellow students and employees at the ARC in Pretoria and SGI in Bethlehem who were always willing to point me in the right direction, I sincerely thank you all.

Further, I would like to extend my appreciation to everyone that was involved from of the Agricultural Economics and Agricultural Business department at the University of Arkansas. To Dr. Daniel Rainey and Dr. Bruce Ahrendsen for seeing me through the Atlantis program from day one, to Diana Danforth for her incredible coding work, Ryan Ruiz for his top-shelf edits, and Alicia Minden for her outstanding organizational efforts throughout this entire process.

Finally, I would like to thank my parents and my brother. I will be forever grateful for their endless support and encouragement of my pursuit of higher education.

Table of Contents

Introduction ... 1

Research Objectives ... 4

Literature Review ... 6

The ARC Wheat Breeding Program ... 6

Previous Research ... 9

Data ... 10

ARC Wheat Dataset Overview ... 10

Experimental Design of ARC Wheat Trials ... 11

Conceptual Framework ... 13

The Just-Pope Production Function ... 13

Results ... 18

Impact of Release Year ... 18

Winter Wheat ... 18

Spring Dryland and Irrigated Wheat ... 19

Facultative Wheat ... 20

Cumulative Genetic Gain ... 20

Producer Benefits ... 22

Benefit Cost Analysis ... 24

Conclusions ... 25

Tables and Figures ... 32

Table 1. Descriptive Statistics of South Africa's Agricultural Research Council's Wheat Varieties Commercially Released between 1992 and 2012 ... 32

Table 2. Regression Results for RLYR Coefficients for All South African Agriculture Research Council Wheat Types ... 33

Table 3. Percent of Total South African Wheat Planted to ARC Cultivars: 1992–2015 ... 34

Table 4. Increased Producer Revenue from the Adoption of ARC Wheat Varieties: 1992–2015 ... 35

Table 5. Cost Benefit Analysis of the ARC Wheat Breeding Program: 1992–2015 ... 36

Table 6. Total Gains Attributable to Agricultural Research Council's Wheat Breeding Program: 1992–2015 ... 37

Figure 1. Agricultural Research Council Wheat Cultivar Trial Locations Used in the Dataset: 1998–2014. ... 38

Figure 2. Cumulative Genetic Gains Associated to the Agricultural Research Council Wheat Breeding Program: 1992–2015 38

References 39

Appendix 43

Table A1. Planting and Harvesting Rules Used by Agricultural Research Council's Test Plot Locations Across South Africa 43

Table A2. Percent of Agricultural Research Council's Total Wheat Area Planted by Wheat Type: 1992–2015 44

Table A3. Fixed Effects Regression Results from the OLS and Just-Pope Models for Spring Irrigated Wheat Varieties 45

Table A4. Fixed Effects Regression Results from OLS and Just-Pope Production Models for Spring Dryland Wheat Varieties 50

Table A5. Fixed Effects Regression Results from OLS and Just-Pope Models for Winter Wheat Varieties 54

Table A6. Fixed Effects Regression Results from OLS and Just-Pope Models for Facultative Wheat Varieties 57

Table A7. South African Agricultural Research Council Average Yield by Wheat Type: 1998–2014 60

Table A8. Yearly Average Yield for All ARC Test Plots 60

Table A9. Average Yield of ARC Varieties by the Year It Was Commercially Released (RLYR) 61

Table A10. Average ARC Test Plot Yields by Station and Location: 1998–2014 61

Figure A1. South African Actual Wheat Yields vs. Agricultural Research Council's Experimental Test Plot Wheat Yield Average Observations: 1998–2014 66

Figure A2. Yield (kg/ha) Observations by Normal and Late Planting: 1998–2014 67

Figure A3. Yield Observations by Irrigated and Dryland Production: 1998–2008 67

Figure A4. Yield Observations by Variety Type: 1998–2014 68

Figure A5. Yield Observations by Growing Year 68

Figure A6. Yield Observations by Release Year 69

Introduction

Since the end of Apartheid in 1991, South Africa has made substantial progress in reducing domestic food insecurity. In October 1994, five months after he was democratically elected to lead South Africa, Nelson Mandela said, "[South Africa's] principal goal is a better life for all South Africans: black and white, farmer and farm-worker. . . . I would like to give [South Africans] the assurance that the government regards a healthy agricultural sector as indispensable for the continued welfare of South Africa" (Mandela, 1994). For 1994, Altman, Hart, and Jacobs (2009) found that over 40% of South Africans surveyed with children in their household claimed their children were always or often hungry, compared to just 11% in 2007. Much of the decrease in food insecurity can be attributed to the South African government investing in agricultural research and development. That being said, in November 2015, South Africa experienced its worst drought in 23 years and food insecurity spiked. It was estimated that, between November 2014 and November 2015, 22% of South African households ran out of money to buy food (STATSSA, 2016). This number reached as high as 41% in the Northwest Territory and 32%, 31%, and 26% in the Eastern Cape, Northern Cape, and the Free State, respectively. This disparity was driven by the fact that cereal prices (mainly maize and wheat) rose by an estimated at 53.7% for the same time period (STATSSA). As such, continued agricultural research is needed, particularly in plant breeding, to both increase yields per hectare as well as breed for biotic and abiotic stresses, reduce yield variability, and help mitigate food insecurity in the future. This need for increased agricultural research is not unique to South Africa, since there is widespread consensus that agricultural research and development is pivotal to overall economic progress in sub-Saharan Africa's overall economic growth (Pardy et al., 2016; Alston and Pardy, 2014; World Bank, 2015; ADB, 2015).

In South Africa, wheat is the second most consumed grain crop behind maize and is a staple food for the majority of the population living in semi-rural and urban areas (DAFF, 2014). According to the Food and Agricultural Organization (FAO), from 2012–2014, an average of 497,690 hectares of wheat per year were grown domestically, which is a 69% decrease from the 1989–1991 yearly average area planted (1.61 million tons) at the end of Apartheid. Since 1990, South Africa has been a consistent wheat importer, mainly due to a decrease in total production area (USDA-FAS, 2014). In 1997, South Africa incurred a large decrease in wheat area planted when the South African government deregulated the market. The single channel fixed price marketing system run by the South African wheat board was abolished, and prices were determined by the free market (Cauvain, 2008). This transition led to a large shift out of wheat and into other grains such as maize. Given its dependence on imports and the fact that recently the value of the Rand has dropped significantly against the USD (by 58% in the last 5 years (Forex, 2017)), increasing yields per hectare could play a major role in breaking the dependency on imported wheat and help to alleviate food insecurity by lowering domestic prices. Altman, Hart, and Jacobs (2009) state that rising food prices, specifically maize and wheat which are the staple crops of South Africa, pose a serious problem for both urban and rural poor attempting to combat food insecurity in South Africa.

Increasing wheat yields per hectare could play a large part in eliminating food insecurity, as per capita wheat consumption in South Africa has been estimated to have increased by 1.8% and 8.9% between 1994–2009 and 1999–2012, respectively (Ronquest-Ross, Vink, and Sigge, 2015). However, previous studies (Brisson et al., 2010; Bell et al., 1995; Byerlee, 1992) have shown a deceleration in world wheat yield growth (per hectare) since the 1980s, specifically in irrigated areas, which cover approximately 21% of the total wheat production area in South

Africa (Sosibo et al., 2017). This observation suggests that the potential for genetic gains could be slowing. Traxler et al. (1995) reported that the yield increases in tall and Green Revolution semi-dwarf wheat cultivars released by the Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT) breeding program “reached a plateau” in the 1980s. This genetic gain plateau in wheat was also estimated by Peltonen-Sainio et al. (2009) and Finger (2010) to occur somewhere between 1992 and 1995. Other studies (Nalley et al., 2008; Nalley et al., 2010; Fischer, 2009; DePauw et al., 2007; Xiao et al., 2012; HGCA, 2011) found that wheat yields are increasing but in a linear fashion. If wheat breeding has truly hit a genetic plateau, this is not only a South African problem, but a global one as well with regards to food security.

The FAO estimated that to feed the growing global population, total wheat output (via increased areas planted or genetic gains) would need to increase by 38% (0.86% annually) or 24 kg/ha/year to meet the estimated demand in 2050. To put these needed gains in perspective, Fischer, Byerlee, and Edmeades (2014) conducted a meta-analysis of the genetic contributions of global wheat breeding programs. They analyzed twelve wheat growing environments distributed across the world and found that from 1970–2010 global wheat yield potential was only rising at 0.61% annually, less than the 0.86% growth necessary to match demand increases as estimated by FAO. They found the gains in spring wheat (the predominate wheat in South Africa) grew at 0.58% annually and winter wheat at 0.70. They also concluded that there were no differences in average proportionate gains between dry and irrigated wheat. While there are no empirical studies of genetic gains in South Africa specifically, CIMMYT classifies South Africa as part of Mega Environment 1 and

4 for spring and winter wheat production.[1] Average genetic gains in Mega Environments 1 and 4 are estimated to be 0.6% and 0.3% annually which is significantly less than the per capita increase of estimated wheat consumption in South Africa of 1.8 to 8.9%. From a global food security perspective, this observation is disturbing. All the studies analyzed by Fischer, Byerlee, and Edmeades were found to contain strong linear growth patterns indicating a constantly increasing (but not increasing at an increasing rate) growth in yields. They conclude that increases in farm yields for wheat will mainly be driven by increasing yield potential and not closing the yield gap. Furthermore, they state "in order to secure future food supplies, it is essential that the current low rates of progress in yield potential of wheat be accelerated." They found that of all the major food crops (wheat, rice, maize, soya, and cassava), wheat has shown the lowest rate of progress in yield potential despite its growth in demand as a food crop.

Research Objectives

The objective of this study was to estimate the proportion of the increases in yield in the South African Agricultural Research Council's Small Grain Institute's released spring, facultative, and winter wheat cultivars attributable to genetic improvements. A total of 36,507 yield observations were analyzed from 125 test plots across South Africa from 1998 to 2014 (Figure 1). The dataset included 26 ARC/SGI-released varieties (16 spring, 5 facultative, and 5 winter) commercially released to the public between 1992 and 2012. A second objective of this study was to determine if newer cultivars were associated with higher yield variance. Critics of modern varieties (MVs) have suggested that MV yields, although higher, vary more from season

[1] Mega Environment 1 is classified as autumn sown (spring-sown rare), largely white/amber grain, low rainfall, irrigated (>5% of 5 arc min grid cell equipped for irrigation). Average min. temperature for coolest quarter 11°C > T = 3°C. Mega Environment 4 is classified as autumn sown, winter drought or Southern Cone-type rainfall, pre-flowering moisture deficits low rainfall, wettest quarter precipitation = 100mm, < 400mm. Average min. temperature for coolest quarter 11°C > T = 3°C.

to season than traditional wheat varieties, thereby exposing consumers and producers to greater production/price volatility. Timmer (1998) found that global food security is a function of many short-run dimensions, including food price stability. Yield stability (or variance reduction) benefits wheat producers because it reduces the risks they face. Timmer also found that consumers benefit from stable food prices because they do not face the risk of sudden and (sometimes) sharp reductions in real income. Thus, the benefits to consumers from price stabilization via yield variance reduction have a significant equity dimension which can play an important role in poverty alleviation. Lastly, we calculate the economic benefits to wheat producers in South Africa from the adoption of ARC wheat cultivars. The literature is sparse on studies attempting to estimate the genetic gains in South African wheat breeding, (Stander, 2012) and to our knowledge, there is no existing study that uses empirical data. Furthermore, unlike any previous South African wheat study, we disaggregate improvements in genetic gains by wheat types (spring, facultative, winter) and production methods (irrigated vs. dryland and late plantings).

This study is relevant because agricultural research and development projects must compete with other projects that could increase the quality of life in South Africa. Further, the ARC 2015/2016 annual report shows that the total (real) investments in ARC wheat breeding have been declining since 2004. As such, without persuasive evidence measuring returns on the investment South Africa makes by funding the SGI's wheat breeding program, ARC risks the possibility of competitive funds flowing to other crops such as maize, soya, and dry beans. Increased information on the economic impact of wheat cultivar improvements would allow government and private donors to better gauge returns to investments. To insure future funding, the ARC, whose cultivars are released to help low income producers and consumers, will need to provide tangible economic benefits attributable to their modern lines. As South Africa continues to struggle with food insecurity, studies like this can give policymakers and scientists insight on the progress made and distance needed to go to eliminate food insecurity. This study is only one part of a larger effort to develop sustainable wheat production in South Africa. Achieving this goal in the face of climate change, reduced wheat area planted, decreased purchasing power, and population growth requires integrated approaches across economic, agronomic, biologic, hydrologic, and other scientific disciplines whose research can be aided by the results provided in this study.

Literature Review

The ARC wheat breeding program

The Agricultural Research Council's Small Grain Institute was founded in 1970 and conducts holistic research on wheat, oats, barley, and triticale. As a part of its founding objectives, the Small Grain Institute (SGI) has conducted research for the public good in areas including wheat breeding, soil cultivation, pest and disease control, quality improvement work, and farmer training since the 1970s. Like other global breeding programs, the ARC breeding program focuses on two major breeding components: yield enhancement and pest and disease resistance (maintenance breeding). Since its creation, the ARC has commercially released 43 wheat varieties at a rate of 1.2 cultivars per year (Stander, 2012). Moreover, SGI has continually bred for maintenance breeding for evolving diseases/fungi that plague South African wheat production like stripe rust, crown rot, and pests like the Russian wheat aphid.

In practice, plant-breeding programs generally have two objectives: high yields and resistance to biotic and abiotic stresses (maintenance breeding). While the former leads to observable outcomes such as increased production per hectare, the latter generally results in pathogen resistance for a crop, which is often less observable. For this reason, policymakers and economists tend to undervalue the opportunity cost of informative agricultural research, specifically concerning maintenance breeding. Accordingly, the economic impact of maintenance breeding, or maintaining yield at its genetic potential, can be as great if not greater than the impact of the genetic yield increases observed in breeding programs (Marasas, 2003). In addition, the literature has shown that a lack of maintenance breeding has caused a slower rate of rice yield increase in South Asia (Pan et al., 1999), which in turn reinforces the hypothesis that discontinuing or diminishing maintenance breeding programs would stifle the ability of the industry to meet increasing demand for rice on a global level. While this study does not specifically quantify the value of maintenance breeding like previous studies do (i.e., Nalley et al., 2016 and Nalley et al., 2017), we do account for yield variability that may arise from a lack of maintenance breeding by estimating yield variance, which can often times be a function of disease/fungi/pest pressure. Specifically, the ARC wheat breeding program has set goals to breed wheat lines that are resistant to stem rust Ug99 and the Russian wheat aphid (ARC, 2012). The ARC also has a dedicated karnal bunt (fungal disease) laboratory to combat the disease in wheat. This is important not only in a food security sense, but from a producer revenue standpoint as well. The disease, which first appeared in the Northern Cape in 2000, can result in intra-national movement barriers for maize and wheat in South Africa. Although not one of their stated goals, the ARC, which breeds for both pest and disease pressures, has an implicit goal of reducing yield variance.

Funding for the ARC is derived primarily from three sources: the South Africa Parliamentary Grant, external income (revenue derived from project contracts, research and development contracts, and the sale of farm products), and other income such as interest received from short-term investments. In 2014, ARC funding was allocated from the three sources above at a rate of 68%, 30%, and 2%, respectively. Like all public agricultural research centers, the ARC continuously lobbies for funding. According to the ARC annual report (2015/2016), total revenue declined by 8% due to reduced allocations of Parliamentary Grant from the government from 2014 to 2016 and a lack of growth in private sector investments in agricultural research and development over the last decade. This reduction in research funding is not unique to South Africa. Pardy et al. (2016) found that after adjusting for the rising costs of research, 39% of Sub-Saharan African countries spent less on public food and agricultural research and development in 2011 than in 1980.

The total wheat area sown in South Africa has decreased by 67% from 1991 to 2014 (FAO); this transition is attributable to several factors. First, the deregulation of the market in 1997 and the abolishment of a fixed price marketing system provided by the South African wheat board instigated a sharp drop in total wheat area sown. Second, wheat prices have been historically low on the world markets in part due to high production in high-income countries (Peacemaker-Arrand B., 2004). Further, the cost of fertilizer, seed, and other inputs have increased from 2010 to 2017 because of the depreciating Rand. As a result, producers in South Africa are switching away from wheat and towards more profitable crops, such as maize and soybeans. The current economic and environmental climate, which is characterized by increasing water scarcity, drought and rising average temperatures (Sosibo et al., 2017; Jury, 2013) contributes to these crop substitutions. As an example of producers adjusting to the economic and environmental climate, maize uses approximately the same amount of fertilizer and pesticide inputs as irrigation wheat. Further, summer maize in South Africa is mostly rain-fed which normally makes irrigated spring wheat production more expensive than maize. As a result, producers are moving towards the more lucrative investment. Finally, the adoption of conservation agriculture practices has placed wheat production in direct competition with other winter cash crops such as barley, canola, lupine, and oats. As a result, there has been a 36% decrease in the total area of wheat harvested domestically from 750,000 hectares in 1992 to 476,570 hectares in 2014 (FAOSTAT).

Previous Research

Numerous studies show that investments in agricultural R&D have enhanced agricultural productivity globally over the past 50 years, reducing poverty, and increasing food security (Alston, Pardey, and Piggott, 2006; Evenson and Gollin, 2003; Pardey et al., 2007). In Sub-Saharan Africa, economic analysis finds strong and consistent evidence that investment in agricultural research yields high returns per dollar spent (Goyal, Aparajita, and Nash, 2017.) The literature is also rich in research on the relationship between public expenditure in agriculture and economic growth, and several articles look specifically at this relationship in the context of agriculture (Goyal and Nash, 2017; Fan, Hazell, and Thorat, 2000; Fan, Zhang, and Zhang 2000; Dixon et al., 2006). The articles demonstrate positive growth in GDP and poverty reduction effects, with particularly high returns associated with investment in agricultural research and development. Furthermore, Fan and Saurkar (2006) found that investment in agriculture can be important for promoting economic growth and alleviating poverty in rural areas.

With so much evidence available to support the claim that investment in agricultural research and development is worthwhile, it is counterintuitive to find that public funding for it is decreasing, particularly in the low- and middle-income world. A study conducted by Fan and Saurkar in 2006 compared total public expenditure on agriculture R&D to total agricultural GDP in 44 low-income countries from 1980 to 2002. The results showed that in 2000, the share of agricultural R&D expenditures in agricultural GDP in Africa and Asia was between 0.5% and 0.9%, and Latin America's share was at 0.98%. These rates are relatively low compared to 2%–3% in high-income countries. Further, their evidence shows that, in real terms, public expenditure towards agriculture had increased over the period analyzed; however, agricultural expenditures as a proportion of total government spending showed a declining trend.

Literature evaluating genetic gains amongst wheat breeders in South Africa is sparse. Stander (2012) estimated a technological k-shift[2] parameter using indexes of varietal improvements to determine the benefits associated with research conducted by the ARC in the South African wheat industry. The author found that the ARC's total benefit was $633.44 million USD ($22.6 million/year) from 1980 to 2008. While Stander (2012), the seminal piece of research on South African wheat breeding, states that one of the largest drawbacks to their methodological approach was the fact they did not look at empirical test plot yields, only country wide macro level yields, Stander (2012) does specify that "using a regression model to estimate yield indexes, given the required information is available, is definitely a possibility for future studies." As such, this study builds on Stander's study by utilizing a large, robust dataset (36,507 individual test plot yields) to estimate the genetic benefits attributed to the ARC wheat breeding program in terms of both yield and yield variance (risk) between 1992 and 2015.

Data

ARC Wheat Dataset Overview

In South Africa, wheat is grown in three production regions: winter/spring-planted wheat in the summer rainfall region (Free State province), winter-planted wheat types under dryland

[2] The k-shift calculates the growth in yield levels due to varietal improvement brought upon by research after accounting for other factors contributing to the growth in output over time. By multiplying this value with price and quantity data, total benefits brought about by a cultivar development can be calculated. (Alston, et al., 1998)

conditions within the Mediterranean climate of the Western Cape Province, and spring wheat types grown under irrigation in the Free State's summer rainfall region (Hatting, Poprawski, and Miller, 2000). Wheat test plot data were collected from ARC test plots (1.5m x 5m) throughout 125 stations across South Africa from 1998 to 2014 (Figure 1). A total of 36,507 yield observations were deemed usable from 125 test plots, which included wheat grown under both irrigated and dryland conditions. The dataset included 26 ARC/SGI-released varieties (see Table 1), of which 59% were spring wheat (21,643 observations), 29% facultative wheat (10,577 observations), and 12% winter wheat (4,287 observations) varieties grown under both irrigated and dryland conditions (55% and 45%, respectively). Spring wheat refers to wheat that does not require extreme cold for vernalization, whereas winter wheat is more tolerant to low temperatures. Facultative varieties are usually characterized by strong photosensitivity and partial sensitivity to vernalization (Stelmakh, 1998). Facultative wheats can be sown in winter or spring wheat conditions and generally have less cold tolerance, a shorter but distinct period required for vernalization and start growing and initiate flowering earlier compared to true winter wheats. The planting dates for spring, winter, and facultative wheat varieties are the same, because the diverse geography of South Africa allows for both winter and spring wheat production simultaneously in various parts of the country. Average yields for each wheat type, year, release year, and location are reported in Tables A7–A10 and Figures A3–A6.

Experimental Design of ARC Wheat Trials

Under the National Wheat Cultivar Evaluation Program (NWCEP) set forth by ARC-Small Grains Institute, the wheat test plots were planted in winter each year (May–July) on producers' fields across South Africa (within the main production regions in South Africa: irrigation and dryland in the Free State's summer rainfall region and dryland production in the

Western Cape) according to a randomized block design with 4 replicates at each location each year. The trials were planted in one of two periods, normal or late, depending on their location (see Table A1.) Late planting is typically for dryland wheat production as dryland wheat production typically precedes a fallow period to conserve moisture in the soil. Cooper et al. (1987) showed that pre-planting moisture is one of the most important determinates in dryland (rain fed) wheat production, and, as such, wheat production after a fallow period can increase soil moisture, which is highly desirable amongst dryland producers, specifically in the relatively dry Free State. Under irrigated production, there are years when producers harvest maize and then sow wheat. Climatic conditions dictate when the maize crop will be harvested; thus, the wheat that follows the maize may be past the optimal planting date. As such, the dataset includes 10,949 late-planting observations to mimic these production conditions/constraints. Average yield observations by normal and late planting dates are shown in Figure A2.

Seeding rates of each cultivar were calculated according to recommendations by ARC breeders. Fertilizer was applied according to recommendations for the area and, in most cases, by the farmer together with the rest of their wheat crop. Weed control was performed whenever necessary using both mechanical and chemical means, and plant, pest, and disease control was also performed when necessary, in line with farmer practices in the area. Although cultural practices vary somewhat across participant and production locations, each wheat trial was produced under typical farming practices for each given region, and all trials were visited by ARC staff to monitor growth and production practices. Appendix (Figure A1) shows how yields recorded in ARC field trials correlate with actual yields reported in South Africa for the same time period.

Although a gap between experimental and actual yields exists, Brennan (1984) concluded that the most reliable sources of relative yields are cultivar trials outside actual farm observations. Although yields are often greater in experimental test plots, as compared with producers' fields, the relative yield differences between varieties are assumed to be comparable. Figure A1 illustrates the difference between the average on-farm yields in South Africa and the experimental plots used in this study from 1998 to 2014.

Conceptual Framework

The Just-Pope Production Function

The Just-Pope (1979) production function offers flexibility in describing a stochastic technological process that might exhibit changes in the mean and variance of output. This method provides a straightforward procedure for testing the effects of increased yield on yield stability. Specifically, the Just-Pope production function allows the inputs to affect both the mean and variance of the outputs. The production function is as follows:

(1) $$Y_{ilt} = f(\boldsymbol{X}_{ilt}, \beta) + h(\boldsymbol{X}_{ilt}, \alpha)\varepsilon_{ilt},$$

where Y_{ilt} is yield of the i^{th} varietal test at location l and in time t, $\mathbf{X}_{ilt}$ are explanatory variables, β and α are parameter vectors, and ε_{ilt} is the customary error term with a mean of zero. The first term—$f(\boldsymbol{X}_{ilt}, \beta)$—on the right-hand side of Equation (1) captures other factors affecting the mean output, while the second term—$h(\boldsymbol{X}_{ilt}, \alpha)\varepsilon_{ilt}$—captures factors affecting the output variance (σ^2_{ilt}).

An advantage of the Just-Pope production function is its flexibility that allows multiplicative heteroscedasticity to be explicitly incorporated in the model. This is important for varietal traits because of the variations in the traits due to breeding (yield, disease resistance, etc.) across varieties. Because of these stated differences in the breeding program across time, the error terms across varieties may be heteroscedastic in nature. Wheat is grown throughout heterogeneous areas across South Africa and varieties are specifically bred for resistance to different pathogens and insects and adaptation to various agronomic conditions. This implies a strong likelihood that the stochastic errors, ε_{ilt}, could be heteroscedastic. Assuming the variance of ε_{ilt} (σ^2_{ilt}) is an exponential function of the *K* explanatory variables, the general model with heteroscedastic errors can be written as

(2) $Y_{ilt} = X'_{ilt}\beta + e_{ilt}$,

(3) $E(e_{ijt})^2 = \sigma^2_{ilt} = exp[X'_{ilt}\alpha]$,

where $X'_{ilt} = (x_{1ilt}, x_{2ilt}, \ldots, x_{kilt})$ is a row vector of observations on the *K* independent variables. The vector $\alpha = (\alpha_1, \alpha_2, \ldots, \alpha_k)$ is $K \times 1$. $E(e_{ilt}) = 0$ and $E\left(e_{ilt} \cdot e_{jlt}\right) = 0$ for all off-diagonal elements of the covariance matrix of the error terms. Equation (3) is rewritten as

(4) $\ln \sigma^2_{ilt} = X'_{ilt}\alpha$,

where σ^2_{ilt} is unknown, but the marginal effects of the explanatory variables on the variance of production, using the ordinary least squares (OLS) residuals from Equation (2), can be estimated such that:

(5) $\ln(\hat{e}_{ilt})^2 = X'_{ilt}\alpha + \mu_{ilt}$,

where $\hat{e}_{ilt}$ are residuals from the least squares estimates of Equation (2). The μ_{ilt} are error terms for the variance equation. The estimates of the output variance ($\hat{\sigma}_{ijt}$) are calculated from the estimation of Equation (5):

(6) $\ln(\hat{e}_{ilt})^2 = X'_{ilt}\hat{\alpha}$

The predicted values from Equation (6) are used as weights for estimating generalized least squares coefficients for the mean output in Equation (2). That is, the estimates of α from Equation (5), α, can be viewed as the effects of the independent variables on yield variability

(σ_{ilt}^2). The $\ln \hat{e}_{ilt}^2$ are exponentiated and these exponentiated values are then used as weights when re-estimating Equation (2). Using these weights, the estimated GLS coefficients of α are obtained to provide the efficient, estimated effects of the independent variables on yield.

The main statistical challenge in using field trial data is that typically the same varieties are not included in every trial year, due to entry and exit of varieties across time. Genetic improvement is captured by identifying the mean yield for each variety and then plotting these estimates against each variety's release year (RLYR). The RLYR of each variety can be interpreted as the "vintage" of a breeding technology (Arrow, 1962; Traxler et al., 1995; Nalley et al., 2016). The coefficient on the RLYR captures the progression of the wheat breeding technology across time and is the main parameter for measuring the impact (yield and yield variance) of the ARC wheat breeding program. However, a distinction exists between RLYR, which varies from 1992 to 2012, and the field plot trial dates, which vary from 1998 to 2014. Each variety has a single RLYR, the date that the wheat variety was released commercially to the public, and each one embodies the breeding technology that was readily available for that given year. In the estimated multiple regression model, the coefficient on RLYR only captures the effect of wheat seed technology at the specific year of release. A typical life cycle of a variety is one of relatively higher yields than previously released varieties in the early years of adoption, then the eventual replacement with yet higher-yielding releases (Nalley et al. 2008b). Average yield by RLYR is shown in Table A9 and Figure A6.

RLYR is not a time-trend variable but is modeled similarly to the way in which Arrow's (1962) growth model showed the embodied technology (Traxler et al., 1995). Specifically, Arrow (1962) assigned "serial numbers" of ordinal magnitude to the embodied technology in capital. In this model, the variable RLYR represents the embodied technology for a given year of release for a wheat variety by the ARC breeding program. This method is standard procedure for measuring the impact of technological change on output (Nalley et al., 2008b). Independent regressions were run for each wheat type (spring, facultative. and winter), as each was bred for different growing environments and, as such, would have different mean yields and yield variances by location and year.

Although a balanced panel dataset is preferred, it is often not available in test plot data. As an example, let y_{it} define the yield (kg/ha) for variety i =1, . . . ,N in trial year t =1, . . . ,T. For each variety i, further define the total number of trial-years that it was grown by Ti. In ideal data, each variety would appear in every trial year so that Ti =T for all i (i.e. a balanced panel), and mean yields could be estimated using the variety specific sample averages. However, for small T, the estimates could be unreliable in settings where exogenous weather shocks can induce large changes in observed yields (Lobell et al., 2005; Lobell, Schlenker and Costa-Roberts, 2011; Maltais-Landry and Lobell, 2012). Specifically, when T is small, the sample may incidentally coincide with a period of abnormal (good or bad) weather, a point emphasized in Lobell, Cassman, and Field (2009). Given the unbalanced panel nature of the test plot dataset, a regression-based approach that controls for exogenous impacts is used to estimate mean yields. We also attempt to mitigate the issues raised by Lobell et al. (2005) with a large and robust dataset, with the minimum variety having 235 observations over multiple growing seasons.

Importantly, management practices vary by location (irrigated or non-irrigated) and year, as many of the test plots are on actual wheat producers fields. Results from a single year or single site could be misleading, due to the possibility of extreme weather events (particularly for dryland wheat production) or pest pressure. Production methods are considered "best management practices" for each location-year-production type combination. Annual and location fixed effects are included in the regression model to account for differences in management and production practices across years and locations. The annual fixed effects hold constant all non-weather annual changes in growing conditions and practices and, therefore, empirically separate genetic gains attributed to the ARC breeding program from environmental conditions and management decisions. Changes in management practices have occurred during the period under investigation, including the introduction and adoption of reduced tillage, improved chemical and machinery as well as different crop rotations to enhance pre-planting soil moisture. One potential source of bias in yield data and its subsequent modeling is the possibility that new varieties respond more to enhancements in the production environment, defined as the Genetic x Environment (GxE) interaction. These interactions are captured in the fixed effect variables.

Location fixed effects are included in the model to account for location-specific factors, including time-invariant factors such as soil quality and biotic stress (such as karnal bunt, rust, and other foliar disease presence as well as pest pressure such as the Russian wheat aphid). Potential yield trends over time are accounted for by including test plot-year fixed effects. Including these fixed effects, the regression model for yield and yield variance, respectively, becomes

(7) $Y_{ijt} = \beta_0 + \beta_1 LNRLYR_{ijt} + \beta_2\ PLANTING_{ijt} + \delta_t + \varphi_i + \varepsilon_{ijt},$

(8) $\ln(e_{ijt})^2 = \alpha_0 + \alpha_1 LNRYLR_{ijt} + \alpha_2 PLANTING_{ijt} + \delta_t{}^* + \varphi_{i^*} + \varepsilon_{ijt},$

where Y_{ijt} is the yield in kg/ha for variety i, at station j, in time period t for wheat type (spring, winter, and facultative). Planting variables are qualitative (0–1) for variety I, indicating if variety i was planted late or during its optimal planting period. $LNRLYR_i$ is the log of release year for variety i. The term $\boldsymbol{\delta_t}$ represents a vector of qualitative variables for each year (t), from t= 1998 to t = 2014, with t = 1998 being omitted as the base (default) year.[3] The term φ_i is a vector of qualitative variables for each of the 125 locations, or experiment stations, where the variety test performance experiments were conducted. Independent regressions were run for all wheat types (spring, facultative and winter) as the breeding goals (drought tolerance, quality, and heat stress tolerance) are different for each. All dryland and facultative wheat in the study were produced under dryland conditions; however, spring wheat was produced under both dryland and irrigated practices which resulted in the yield and yield variance modeled as:

(9) $Y_{ijt} = \beta_0 + \beta_1 LNRLYR_{ijt} + \beta_2 PLANTING_{ijt} + \beta_3 IRR_{ijt} + \delta_t + \varphi_i + \varepsilon_{ijt}$

(10) $\ln(e_{ijt})^2 = \lambda_0 + \lambda_1 LNRYLR_{ijt} + \lambda_2 PLANTING_{ijt} + \lambda_3 IRR_{ijt} + \delta t^* + \varphi_i^* + \varepsilon_{ijt}$

where IRR_i represented if spring variety i was produced under irrigated conditions. The asterisks are appended to account for the fact that the fixed effects have different values in equation (9) than equation (10). Since wheat yields are a function of climatic data such as precipitation (in the case of dryland wheat), solar radiation and temperature would ideally enter into the equations estimating yield and yield variance. However, like the majority of large panel datasets from low-/middle-income countries, weather data were not available in its entirety. As such, year (δ) and location (φ) fixed effects were used to account for weather as well as clustered standard errors by year.

Results

Impact of release year

Winter Wheat

The coefficient of RLYR is the main variable of focus in this study since it captures the "vintage" of each cultivar, or the level of technology that characterizes each wheat cultivar.

[3] A $RLYR^2$ term was initially modeled to capture curvature in genetic gain, but due to perfect collinearity between RLYR and $RLYR^2$ the LNRLYR was used to capture curvature.

Using the Just-Pope results from the model (Table A5) and using β_1LNRLYR for each year to calculate annual average gains, it was found that on average, from 1992 (with the release of Tugela-DN) to 2014, the ARC wheat breeding program added 16.91 kg/ha ($P<0.05$) annually[4] in their winter wheat varietal releases. The model explains 55% of the yield variation and both Year and Station fixed effects were highly ($P<0.01$) significant. With regard to yield variance, this study shows that from 1992 to 2014, the varieties released by the ARC Breeding Program experienced some ($P<0.05$) increase in annual yield variance (Table A5). This observation would imply that yield risk (as measured by the second moment of the Just-Pope model) is slightly increasing over the sample period, indicating that ARC-released winter wheat variety yields have increased with a tradeoff with increased yield variance.

Spring Dryland and Irrigated Wheat

Using the Just-Pope results from the model (Tables A3 and A4) and transforming the LNRLYR into annual average gains, it was found that, on the average, from 1994 (with the release of Marico) to 2014, the ARC wheat breeding program added 6.68 kg/ha ($P<0.05$) annually with the release of their irrigated spring wheat varieties. The model explains 49% of the yield variation and both Year and Station fixed effects were ($P<0.10$) significant. Unlike the findings in the winter wheat varieties, the associated yield gain attributed to the ARC irrigated spring wheat breeding program is not accompanied by an increase in yield variance ($P>0.10$). This would imply producers of irrigated spring wheat released by ARC experienced a yield gain

[4] $(\beta_1 \sum_{i=1}^{t} lnRLYR_i)$ / # of years
Technically, a per year percentage growth rate implies compounding. However, it is the convention in the yield gains attributable to genetic improvements literature to take the percentage gain. To make our percentages comparable to others found in this literature, we compute using the averaging formula above knowing that it does not adhere to the conventional notion of compounding.

with no associated increase in yield risk. The insignificance of the RLYR coefficient on spring dryland wheat (Table A4) could be attributed to the fact that three of the four ARC dryland spring wheat varieties were released in the same year (2012) and the other was released shortly before (2009), resulting in a short window for progression in breeding technology.

Facultative Wheat

The Just-Pope RLYR estimates associated with facultative wheat (Table A6) suggest that the ARC breeding program has added 5.27 kg/ha ($P<0.05$) annually, on average, from the release of Limpopo in 1994. Again, both the fixed effects for station and year were highly statistically significant ($P<0.01$) model explains 53% of the yield variation and both Year and Station fixed effects. Like spring irrigated wheat, the yield gains associated with facultative wheat did not come at the expense of yield variance. Additionally, from 1994 to 2015, there was no increase in yield risk associated with newer facultative release varieties with respect to older ones.

Cumulative Genetic Gain

An important feature of the calculation of genetic gains associated with a breeding program is to take into account the cumulative effects of the program over the entire period. That is, the yield gains attributable to the breeding program in 1993 are those observed in 1993 plus those observed in 1992. So, the genetic gains for 2014 would be the sum of the year-specific genetic gains from 1992 to 2014 for winter wheat and 1994 to 2014 for spring and facultative wheat, corresponding to the first release of each variety in the study. Figure 2 illustrates the cumulative genetic gains (as derived from the RLYR coefficients on Tables A3 and A6) associated with the ARC/SGI wheat breeding program by year and wheat type. The largest gain by wheat type was winter wheat which experienced a yield gain of 518.03 kg/ha from the initial release of Tugela-DN in 1992. The average winter wheat yield in the dataset was 2,719.72 kg/ha (Table A10), which would equate to a 19.05% increase over the initial release of Tugela-DN through 2014 and is solely attributed to the ARC breeding program. This difference would equate to an annual increase of 0.86%. This relatively large increase would match the Food and Agricultural Organization's (FAO) estimate that to feed the growing global population that total wheat output (via increased area planted or genetic gains) would need to increase by 38% (0.86% annually) to meet the demand in 2050.

Gains through the ARC breeding program for irrigated spring wheat were estimated at 206.11 kg/ha from the initial release of Marico in 1994 and the 2014 growing season. The average yield for irrigated spring wheat in the dataset was 6,686.59 kg/ha resulting in a 0.31% total increase. The regression coefficient on facultative wheat from Table A6 resulted in a cumulative gain of 162.49 kg/ha from the initial release of Gariep in 1994 and the 2014 growing season. The average facultative yield in the dataset was 2,825 kg/ha resulting in a genetic gain of 5.75% across the entire time period or 0.575% annually.

These results suggest that the largest gains in the ARC are from dryland wheat breeding as all winter wheat observations were under dryland conditions and less than 1% of facultative wheat was irrigated. The average annual gain of dryland (facultative and winter wheats) was 0.72%, which is larger than the results in the meta-analysis conducted by Fischer, Byerlee, and Edmeades (2014), who found that global wheat yield potential was only rising at 0.61% annually. Our winter/dryland results are in line with Fischer, Byerlee, and Edmeades (2014), who found that global winter wheat annual yield increases to be 0.70%, compared to our 0.72%. However, the gains estimated in this study are still below the 0.86% growth necessary to match demand increases as estimated by FAO. Like the Fischer, Byerlee, and Edmeades study, we find that the average annual genetic gains for spring wheat are less than those for winter wheat. With the exception of dryland spring wheat, we find that wheat breeding conducted by ARC in South Africa has not reached a genetic plateau.[5] Furthermore, Table 3 indicates that the majority (99.74%) of spring wheat planted in South Africa is not sown to ARC varieties; whereas, 19.54% of South Africa is sown to ARC winter wheat varieties. While the ARC does not disaggregate its wheat breeding budget by wheat type, it could be that a larger portion of the breeding budget is allocated to winter wheat improvements.

Producer Benefits

Producer benefits, measured as revenue gains, attributable to the ARC's wheat breeding program from 1992 to 2015 are presented in Table 4. Using the cumulative estimated yearly genetic gain increases, actual area sown to ARC varieties by type (spring, winter, and facultative) and price data from 1992 to 2015, we can roughly estimate the total revenue gain to South African wheat producers. Table 6 indicates that the total gains attributable to the ARC's wheat breeding program were estimated to be $94,653,815 (2016 USD) or $3,943,909 (2016 USD) annually. These results are less than those observed by Stander (2012), who found the ARC wheat breeding program added $22.6 million (2016 USD) annually from 1980 to 2008. The higher results estimated by Stander could be attributed to the time period; after 1997, there was a significant drop in South African wheat area planted as the marketing board was liberalized. As such, the Stander study captured the benefits of many more wheat hectares and substantially higher wheat prices. So, the genetic gain could be the same, but due to exogenous factors like hectares sown to ARC lines and wheat price, the estimated gains would be higher. Second, the

[5] Results from dryland spring wheat need to be viewed with caution, given the relatively few commercially-released varieties in the dataset.

Stander estimates were not derived from empirical yield data but rather by analyzing macro-level data.

Another way of interpreting these results is the counterfactual case. That is, what would have happened if the ARC had not invested in wheat breeding from 1992 to 2014? The implicit counterfactual is that South Africa and producers would have continued to grow varieties of the vintage and yield of Tugela-DN and would have forfeited the benefits estimated above. However, it is more likely that South Africa producers would have adopted wheat varieties developed by other breeding programs (CIMMYT, Pannar, and Sensako, for example). In that sense, the estimates derived above would overestimate the total benefits of the ARC breeding program. Conversely, this study likely underestimates the true benefits of the ARC wheat breeding program in that it does not estimate the benefits made by ARC in terms of pathogen/disease/pest resistance. Globally, producers tend to focus on yield potential (ceilings) of varieties instead of variability (floors) and, thus, may often undervalue the genetic resistance to a disease that does not raise yield potential but raises the yield floor. In other words, when ARC breeds for Russian wheat aphid resistance, for example, it does not raise the yield potential of a given variety because Russian wheat aphids are not present every growing season, and yield potential is derived from a best-case scenario. However, disease/pest/pathogen resistance does, in fact, reduce the yield variability (floor) of a variety. Economists and policymakers tend to undervalue the opportunity cost of this type of informative agricultural research, specifically with regard to maintenance (pathogen/disease/pest resistance) breeding. The opportunity cost of maintenance breeding can be viewed as the productivity losses that can be evaded by breeding for resistance against diseases such Russian wheat aphids, strip rust, and other biotic stressors. Accordingly, the substantial economic benefit that accrues from avoided yield losses through resistance to pathogens is often omitted in the cost-benefit analysis of such breeding programs because the producers do not experience the losses, but breeding programs incur the costs to prevent them. While we do not explicitly estimate these benefits, we implicitly acknowledge their important contribution.

Benefit Cost Analysis

ARC provided breeding costs for their wheat breeding program (Table 5). These costs include all breeding, pre-breeding, laboratory, salaries, and other expenses associated with the program. Ideally, benefits would be lagged for 10 years, representing the time it takes to initially cross a variety and its eventual commercial release. That being said, ARC wheat breeding cost data was only available from 2004 to 2015; as such, lagging was not an option. We linearly extrapolate costs from 2004 to 1992 and adjust for inflation. While this is less than ideal, it does give some context of what the return on investment is. A discount rate of 10.25% is used to calculate a benefit-cost ratio.[6] We estimate (Table 5) the benefit-cost ratio to be 4.49:1. That is, for every dollar invested in the ARC wheat breeding program, a return of $4.49 is generated. The benefit-cost ratio provides evidence that the economic rate of return to the ARC wheat breeding program is high, although assessing these measures further is difficult without comparable values for other public investments (the opportunity cost of funds).

To put this in context, Pardy et al. (2016) found that the mean benefit-cost ratio for agricultural investment in Sub-Saharan Africa is 30:1. The 4.49:1 ratio would be in the second

---

[6] The benefit-cost ratio (BCR) as defined by Tassey (2003) is calculated as a measure of gross research benefits: $\frac{\sum_t \frac{B_t}{(1+r)^t}}{\sum_t \frac{C_t}{(1+r)^t}}$, where B_t is the total economic benefit in year t, C_t represents annual program costs, and r is the assumed rate of discount of 10.25%.

quartile of 129 benefit-cost ratio studies analyzed in Africa. The relatively low results could be due to a litany of factors including the fact that ARC/SGI uses its funds for a multitude of activities besides wheat breeding. ARC conducts holistic research for the public good in areas including wheat breeding, soil cultivation, pest and disease control, quality improvement work, and farmer training, which are all incorporated in its wheat breeding budget. Furthermore, between 1997 and 1998 after the deregulation of the wheat market and abolishment of the fixed pricing system implemented by the wheat marketing board, wheat area in South Africa fell by 46%. As such, even with the significant estimated genetic gains associated with the ARC wheat breeding program, benefits would decline given the lower wheat price and the substantial area reduction. However, given the estimates in this research, the benefits of the ARC-SGI's wheat breeding program outweigh the costs $4.49 to $1, demonstrating that investments in the ARC breeding program have provided large and sustained economic benefits to wheat producers and consumers in South Africa.

Conclusions

Although classified as an upper middle-income country by the World Bank, food insecurity is still a concern throughout South Africa. Food insecurity was at the forefront of South African policy between November 2014 and 2015 when a severe drought left 22% of South African households food insecure (STATSSA, 2016). Food security is a function of many short-run dimensions, including increased and consistent yields of modern staple crop varieties. Yield stability benefits wheat producers, because it reduces the risks they incur, as well as consumers, in the form of stable food prices because they do not face the risk of sudden and (sometimes) sharp reductions in real income. South Africa has seen a large drop in cultivated wheat acreage since the deregulation of the wheat market in 1997 and the abolishment of the fixed price marketing system provided by the South African wheat board. Even before deregulation in 1997, South Africa had become a net wheat importer beginning in 1990. This, coupled with recent political uncertainty, resulted in the South African Rand dropping significantly against the USD (by 58% between 2012 and 2017 (Forex, 2017)) and has left South Africa exposed to risk in both the global wheat market as well as the global exchange rate market, increasing its food insecurity vulnerability.

The South African government has combated food insecurity by funding the South African Agricultural Research Council's (ARC) Small Grains Institute (SGI) to breed improved wheat varieties. The SGI has conducted research for the public good in areas including wheat breeding, soil cultivation, pest and disease control, quality improvement work, and farmer training since the 1970s. During this period, ARC released 26 varieties including five facultative, five winter, and sixteen spring wheat varieties. Given South Africa has several distinct growing regions, each wheat type as well as irrigated and dryland wheat genetic gains were estimated separately.

Using a robust dataset from 1998 to 2014 and a total of 36,507 yield observations from 125 test plots across South Africa, a multiple regression analysis was used to estimate the ARC/SGI wheat breeding program from 1992 to 2015 in terms of genetic yield enhancements, changes in yield variability (risk), and increased producer revenue. It was found that South African wheat farmers who adopted the ARC's wheat varieties during the 1992–2015 period experienced an annual yield gain of 0.86%, 0.58%, and 0.31% in winter, facultative, and irrigated spring wheat types, respectively. These estimates are within the range of previous wheat genetic gain meta-analyses from 12 global wheat breeding studies (Fischer, Byerlee, and Edmeades, 2014), which found that global wheat yield potential was rising at 0.61% annually.

They found that global gains in spring wheat (the predominant wheat in South Africa) grew at 0.58% annually and 0.70% in winter wheat. Our estimates suggest that facultative wheat genetic gains via the ARC breeding program are slightly (0.03%) less than the global average, with ARC winter wheat genetic gains estimated to be higher than the global average. Importantly, unlike some other studies (Traxler et al.,1995; Peltonen-Sainio et al., 2009; and Finger, 2010), we find that genetic gains in wheat, in the South African context, have not reached a plateau. This finding alone has large implications for the future of wheat breeding in South Africa.

Assuming that genetic gains are cumulative over time, we estimated that ARC winter wheat experienced a yield gain of 518.03 kg/ha from the initial release of Tugela-DN in 1992 until 2014. The average winter wheat yield in the dataset was 2,719.72 kg/ha, which would equate to a 19.05% increase over the initial release of Tugela-DN through 2014, and was solely attributed to the genetic gains associated with the ARC breeding program. Similarly, genetic gains through the ARC breeding program for irrigated spring wheat were estimated at 206.11 kg/ha from the initial release of Marico in 1994 and the 2014 growing season. The average yield for irrigated spring wheat in the dataset was 6,686.59 kg/ha, resulting in a 3.1% total increase or 0.31% annually. Facultative wheat was estimated to have a cumulative gain of 162.49 kg/ha from the initial release of Gariep in 1994 and the 2014 growing season. The average facultative yield in the dataset was 2,825 kg/ha, resulting in a genetic gain of 5.75% across the entire time period or 0.575% annually. These results suggest that the majority of the genetic gain increases from the ARC wheat breeding program are in dryland (winter and facultative) production, with only marginal gains associated with varieties bred for irrigated production.

The quality standards for potential new wheat cultivars in South Africa have been strict since the deregulation of the wheat market in 1997. The Research Technical Committee (RTC) for wheat in South Africa set strict criteria regarding the rheological and baking characteristics during the final stages of approval for new wheat cultivars in South Africa. The holistic goal of the RTC is to guide wheat-related research in South Africa and set guidelines for wheat quality. A total of 17 tests are conducted on potential new cultivars to determine whether or not silos are allowed to accept the specific cultivars from producers. These are not regulations but rather suggestions for the wheat industry to follow. That being said, these "suggestions" are actually enforced in South Africa, and as such may lead to the possibility that buyers will not be willing to accept producers' cultivars if they do not appear on the list of accepted varieties (Du Plessis et al. 2005). South Africa has historically produced high quality wheat (via its high standards for varietal release) specifically with regards to protein percentage, and imported lower quality wheat from abroad (van der Merwe, 2015). South African millers will then blend the high quality South African wheat with lower quality imported wheat to obtain the blend they need for baking goods.

Smith (2000) found that in South Africa wheat quality and wheat yields are highly correlated, although negatively, which makes wheat quality essential considerations when evaluating the profitability and performance of the industry as a whole. Van der Merwe (2015) estimated that wheat yields in South Africa could have increased by 12.81-19.03% if the focus of South African wheat breeders shifted toward yield gains instead of ensuring newer varieties met the strict quality standards imposed on new varieties. That is, the authors took the average yields of those cultivars which were slated for public release but did not meet the RTC criteria and compared them to cultivars planted in the same year in similar locations. They found if all the cultivars which were rejected for RTC quality reasons but still maintained an "acceptable quality standard" were released average South African wheat yields would have increased by up to 19.03%.

Thus, it would seem that the high quality standards set by the RTC could be undermining potential yield increases in South Africa. This is particularly true if millers simply import lower quality wheat from abroad. Given its recent struggle with food security it can be concluded that the standards put forth by the RTC for the South African wheat industry are negatively impacting the productivity and possibly jeopardizing food security. Quality attributes were not available for this study and as such causal relationships cannot be elicited for dampening ARC yield potential. That being said, presence of strict wheat quality standards combined with the fact that one of the general characteristics of wheat is the defect of conversion (yield declines as quality improves) may help to explain why the genetic gains elicited in this study have been increasing at a decreasing rate over time.

Yield variability (risk) was shown not to have increased for spring irrigated and facultative wheat but did increase with the release of newer varieties of winter wheat. Ideally, a breeding program would like to increase yield and reduce yield variability (risk) over time. This study found that yield was increasing with no significant (P>.10) increase in risk for both spring and facultative wheat; however, both yield and yield variability increased for ARC winter wheat varieties.

Yield variability (risk) was shown not to have increased for spring irrigated and facultative wheat but did increase with the release of newer varieties of winter wheat. Ideally, a breeding program would like to increase yield and reduce yield variability (risk) over time. This study found that yield was increasing with no significant (P>.10) increase in risk for both spring

and facultative wheat; however, both yield and yield variability increased for ARC winter wheat varieties.

Using the cumulative genetic gains with actual varietal sown area in South Africa by breeder (ARC, Pannar, and Sensako) and by type (spring, facultative and winter), we could estimate the increase in producer revenue through the adoption of ARC varieties. While ARC area has been decreasing due to both a reduction in wheat area and competition from private wheat breeding programs, namely Pannar and Sensako, producer gains via adoption of ARC varieties are estimated to be $3,943,909 (2016 USD) annually. Although the ARC wheat breeding program started in the 1970s, our study starts with the release of Tugela-DN in 1992 and runs through the 2015 growing season. Thus, in the time period of our analysis, ARC has attributed $94,565,816 in increased revenue to South Africa wheat producers.

We also considered a counterfactual scenario: what would the revenue implications be if the ARC wheat breeding program did not exist? While the loss is estimated at $94.57 million (2016 USD), this could be an overestimate as it is likely that South Africa wheat producers would have adopted wheat varieties developed by other breeding programs (CIMMYT, Pannar, and Sensako for example) in the absence of ARC. In that sense, the estimates derived above would overestimate the total benefits of the ARC breeding program.

Conversely, while the most tangible improvements of the ARC Breeding Program are the increased yields/ha, other substantial economic benefits are also evident in the yield losses avoided through resistance breeding, or "maintenance breeding." However, this study only valued yield increases derived from genetic gains and did not attempt to quantify the value of the maintenance breeding; therefore, the benefits estimated to producers in this study could also be considered conservative. That is, without the ARC breeding program, wheat yields could have remained at their lowest values in the early 1990s or could have deteriorated as pests and pathogens could have drastically reduced yield while increasing yield variation as they overcame earlier resistance genes. Previous studies (Marasas, 2003) have shown that the economic impact of maintenance breeding, or maintaining yield at its genetic potential, can be as great if not greater than the impact of the genetic yield increases observed in breeding programs. Further research is warranted to quantify the maintenance breeding efforts made at ARC to maintain yields from deteriorating to pests like the Russian wheat aphid and fungi like strip rust.

To provide a return on investment, the breeding costs for the ARC wheat breeding program were collected and estimated. Costs before 2004 were not available and, as such, were linearly extrapolated which is less than ideal. That being said, using a discount rate of 10.25%, the current interest rate in South Africa, it was found that every dollar invested in the ARC wheat breeding program generated a return of $4.49. This would indicate that the investment that the South African government is making in ARC has both positive and sustained returns to both increase producer revenue as well as increase the food supply to help combat food insecurity.

This study is only one part of a larger effort to develop sustainable wheat production to ensure global food security. Achieving this goal in the face of increased wheat demand and climate change requires integrated approaches across plant breeding, economic, agronomic, soil, biologic, hydrologic, and other scientific disciplines whose research can be guided by the results provided in this study. Similarly, the ARC wheat breeding program is one part of a holistic effort to ensure food security in South Africa. Continued funding for public plant breeding programs such as ARC-SGI ensures that genetic gains accomplished by wheat breeders avoid plateauing or raising the yield ceiling as well as ensures that maintenance breeding for disease and pest resistance simultaneously raises the yield floor.

Tables and Figures

Table 1. Descriptive Statistics of South Africa's Agricultural Research Council's Wheat Varieties Commercially Released between 1992 and 2012

Variety	Average Yield (kg/ha)	Yield Ratio*	Yield Difference (kg/ha)*	Coefficient of Variance (%)	Year Released to Public	Type	Observations	SD of Yield	Percentage Irrigated
BAVIAANS	5,527	1.77	2,403	39.85	2001	Spring	3,305	2,202.3	67.08
BETTADN	2,632	0.84	-491	49.38	1993	Winter	2,070	1,299.82	0.39
BIEDOU	4,671	1.5	1,548	41.67	2003	Spring	763	1,946.57	48.23
BUFFELS	7,276	2.33	4,153	29.62	2009	Spring	833	2,155.46	100
CALEDON	2,780	0.89	-344	46.7	1996	Facultative	2,176	1,298.22	0.37
DUZI	6,772	2.17	3,648	30.61	2006	Spring	1,893	2,072.59	94.51
ELANDS	2,873	0.92	-250	47.6	1999	Facultative	2,407	1,367.65	0.33
GARIEP	2,818	0.9	-306	47.78	1994	Facultative	2,420	1,346.4	0.33
KARIEGA	5,598	1.79	2,474	40.64	1994	Spring	3,733	2,274.98	66.33
KOMATI	2,762	0.88	-361	49.67	2003	Facultative	1,519	1,371.96	0.53
KOONAP	2,604	0.83	-520	47.67	2012	Spring	358	1,241.29	0
KROKODIL	7,059	2.26	3,935	30.95	2006	Spring	1,793	2,184.77	100
KWARTEL	3,715	1.19	591	26.65	2012	Spring	434	989.87	0
LIMPOPO	2,679	0.86	-445	50.66	1994	Facultative	2,055	1,357	0.39
MARICO	6,338	2.03	3,215	33.29	1994	Spring	1,510	2,110.16	99.27
MATLABAS	3,061	0.98	-62	49.6	2006	Winter	1,258	1,518.48	0
NOSSOB	1,732	0.55	-1,391	55.28	2006	Winter	281	957.7	0
OLIFANTS	6,565	2.1	3,442	30.47	2003	Spring	1,948	2,000.29	98.56
RATEL	4,016	1.29	892	26.94	2012	Spring	431	1,081.63	0
SABIE	7,475	2.39	4,351	26.96	2010	Spring	843	2,015.39	98.1
SENQU	2,891	0.93	-233	48.39	2012	Spring	235	1,398.66	0
STEENBRAS	6,102	1.95	2,979	32.07	2000	Spring	2,273	1,956.85	96.48
TANKWA	3,682	1.18	558	31.79	2009	Spring	841	1,170.38	0
TARKA	2,188	0.7	-935	49.44	2003	Winter	262	1,081.85	3.05
TUGELA DN	3,123	-	-	55.97	1992	Winter	416	1,748.23	0
UMLAZI	8,021	2.57	4,897	22.9	2012	Spring	450	1,837.05	100

* Yield ratios are relative to Tugela-DN which was the first variety released in the study in 1992

Table 2. Regression Results for RLYR Coefficients for All South African Agriculture Research Council Wheat Types

Wheat Type	OLS Yield	Just-Pope Variance	Just-Pope Yield	Nobs	Mean Yield (kg/ha)
Winter	160.99*** [0.5547]	0.12** [0.1276]	163.00** [0.5455]	4,287	2,760.2
Spring Irrigated	67.13** [0.4935]	0.02 [0.0625]	66.88* [0.4896]	8,678	6,696.4
Spring Dryland	20.82 [0.5513]	-0.12 [0.2063]	19.79 [0.521]	2,299	3,548.5
Facultative	51.90*** [0.5413]	-0.01 [0.115]	52.57** [0.5319]	10,577	2,825

*** (P<0.01), ** (P<0.05), *(P<0.10)

Brackets denote R^2

Table 2 summarizes the RLYR coefficients for all wheat types (Spring Irrigated, Spring Dryland, Winter and Facultative) modeled in the dataset. Full fixed effects regression results for all models run are found on Tables A3–A6.

Table 3. Percent of Total South African Wheat Planted to ARC Cultivars: 1992–2015

Year	% of Total Winter	% of Total Spring	% of Total Facultative	ARC Spring Wheat (Ha)	ARC Winter Wheat (Ha)	ARC Facultative Wheat (Ha)
1992	62.26	63.64	12.39	425,083	6,631	8,066
1993	96.35	60.85	72.53	468,428	20,612	200,382
1994	100.00	64.80	76.89	533,572	22,218	148,430
1995	100.00	52.10	72.25	508,235	56,428	238,609
1996	100.00	56.89	57.01	407,621	35,062	307,282
1997	90.21	33.75	35.01	230,790	37,713	229113
1998	80.42	10.60	37.56	34,566	20,091	149,071
1999	58.62	8.99	22.67	54,040	9,765	22,723
2000	69.70	1.84	2.91	12,846	2,148	6,779
2001	77.89	5.30	14.73	37,658	15,097	35,954
2002	74.22	3.20	20.84	22,936	15,714	42,731
2003	23.08	4.24	25.05	26,771	1,122	27,994
2004	49.06	5.55	30.65	38,257	2,158	41,746
2005	58.95	7.72	55.43	48,480	6,833	91,607
2006	59.45	15.64	43.66	106,282	5,776	33,099
2007	93.69	13.71	32.38	79,629	13,678	11,808
2008	54.07	12.28	51.78	77,277	11,203	49,421
2009	51.48	13.13	52.43	74,963	3,010	15,900
2010	36.45	11.90	49.16	56,100	3,845	37,396
2011	20.08	14.32	27.18	78,107	2,781	12,310
2012	28.61	10.43	36.24	50,942	2,149	5,482
2013	18.89	6.14	23.34	30,094	1,499	1,652
2014	36.32	2.23	23.00	10,450	1,541	844
2015	19.54	0.26	18.75	1,181	2,457	2,448

Source: South African Grain Laboratories Annual Wheat Reports (various years)

Table 4. Increased Producer Revenue from the Adoption of ARC Wheat Varieties: 1992–2015

Year	ARC Spring Wheat (Ha)*	Spring Wheat Cumulative Genetic Gain (kg/ha)**	ARC Winter Wheat (Ha)*	Winter Wheat Cumulative Genetic Gain (kg/ha)*	ARC Facultative Wheat (Ha)*	Facultative Wheat Cumulative Genetic Gain (kg/ha)**	Price USD/Ton	2016 USD Prices/Ton
1992	425,083	-	6,631	0.00	8,066	-	$250.00	$428.88
1993	468,428	-	20,612	112.98	200,382	-	$230.40	$382.12
1994	533,572	0.00	22,218	179.08	148,430	0.00	$212.60	$344.52
1995	508,235	27.44	56,428	225.97	238,609	36.44	$218.60	$344.58
1996	407,621	43.50	35,062	262.34	307,282	57.75	$210.50	$323.00
1997	230,790	54.89	37,713	292.06	229,113	72.88	$177.50	$264.32
1998	34,566	63.72	20,091	317.19	149,071	84.61	$146.20	$215.27
1999	54,040	70.94	9,765	338.95	22,723	94.19	$157.30	$226.61
2000	12,846	77.04	2,148	358.15	6,779	102.29	$167.90	$234.01
2001	37,658	82.33	15,097	375.33	35,954	109.31	$165.20	$223.88
2002	22,936	86.99	15,714	390.86	42,731	115.50	$149.10	$198.92
2003	26,771	91.16	1,122	405.05	27,994	121.04	$188.80	$246.27
2004	38,257	94.94	2,158	418.09	41,746	126.05	$168.90	$214.60
2005	48,480	98.38	6,833	430.17	91,607	130.63	$162.60	$199.82
2006	106,282	101.55	5,776	441.42	33,099	134.84	$225.10	$267.98
2007	79,629	104.48	13,678	451.94	11,808	138.73	$355.70	$411.74
2008	77,277	107.22	11,203	461.82	49,421	142.36	$279.30	$311.35
2009	74,963	109.77	3,010	471.14	15,900	145.75	$189.80	$212.33
2010	56,100	112.17	3,845	479.95	37,396	148.94	$316.10	$347.92
2011	78,107	114.43	2,781	488.31	12,310	151.94	$326.40	$348.26
2012	50,942	116.57	2,149	496.27	5,482	154.78	$354.90	$371.00
2013	30,094	118.61	1,499	503.85	1,652	157.48	$298.30	$307.33
2014	10,450	120.54	1,541	511.09	844	160.05	$281.30	$285.19
2015	1,181	122.38	2,457	518.03	2,448	162.49	$295.20	$298.92

*As derived from Table 3

**As derived from Table 2

Table 5. Cost Benefit Analysis of the ARC Wheat Breeding Program: 1992–2015

Year*	Costs 2016 USD	Benefits 2016 USD**	Discounted Costs 2016 USD***	Discounted Benefits 2016 USD***
1992	$1,204,967	$0	$1,092,941	$0
1993	$1,157,053	$889,883	$951,911	$732,109
1994	$1,107,952	$1,370,726	$826,771	$1,022,857
1995	$1,055,208	$12,195,623	$714,207	$8,254,478
1996	$1,031,498	$14,429,756	$633,250	$8,858,618
1997	$982,730	$10,672,734	$547,221	$5,942,978
1998	$981,071	$4,561,056	$495,508	$2,303,643
1999	$935,746	$2,103,739	$428,676	$963,747
2000	$941,295	$573,911	$391,128	$238,472
2001	$909,867	$2,842,576	$342,919	$1,071,337
2002	$894,494	$2,600,482	$305,783	$888,974
2003	$827,780	$1,547,427	$256,668	$479,807
2004	$756,428	$2,102,334	$212,738	$591,262
2005	$820,042	$3,931,559	$209,187	$1,002,916
2006	$844,848	$4,771,493	$195,479	$1,104,016
2007	$841,515	$6,645,343	$176,606	$1,394,633
2008	$863,566	$6,381,002	$164,384	$1,214,654
2009	$848,179	$2,540,356	$146,444	$438,611
2010	$690,641	$4,769,169	$108,158	$746,877
2011	$689,671	$4,237,050	$97,965	$601,855
2012	$605,516	$2,913,633	$78,015	$375,391
2013	$600,437	$1,409,048	$70,168	$164,663
2014	$658,406	$622,295	$69,789	$65,961
2015	$634,556	$542,621	$61,008	$52,169
			$8,576,922	**$38,510,029**
			BCR	**4.49**

*Actual costs provided by ARC were used from 2004 to 2015 and costs from 1992 to 2003 were linearly extrapolated.

**using data from Table 4 we calculate total benefits by the following equation: $\sum_{t=1}^{t} Ait\ \Upsilon it\ Pt$ where A_{it} is area of ARC wheat type i in year t (1992–2015), Υ_{it} is cumulative genetic gain for ARC wheat type i in year t, and P_t is wheat price in 2016 USD in year t.

*** Discounted at 10.25%

Table 6. Total Gains Attributable to Agricultural Research Council's Wheat Breeding Program: 1992–2015

Year	ARC Spring Wheat 2016 USD Gain*	ARC Winter Wheat 2016 USD Gain*	ARC Facultative Wheat 2016 USD Gain *	Total Gain 2016 USD
1992	-	$0	-	$0
1993	-	$889,883	-	$889,883
1994	$0	$1,370,726	$0	$1,370,726
1995	$4,805,969	$4,393,759	$2,995,895	$12,195,623
1996	$5,726,693	$2,971,035	$5,732,029	$14,429,756
1997	$3,348,141	$2,911,336	$4,413,257	$10,672,734
1998	$474,147	$1,371,870	$2,715,039	$4,561,056
1999	$868,706	$750,030	$485,003	$2,103,739
2000	$231,598	$180,052	$162,262	$573,911
2001	$694,102	$1,268,584	$879,891	$2,842,576
2002	$396,897	$1,221,789	$981,796	$2,600,482
2003	$601,021	$111,935	$834,471	$1,547,427
2004	$779,420	$193,635	$1,129,278	$2,102,334
2005	$953,045	$587,387	$2,391,127	$3,931,559
2006	$2,892,277	$683,236	$1,195,980	$4,771,493
2007	$3,425,648	$2,545,220	$674,475	$6,645,343
2008	$2,579,629	$1,610,870	$2,190,503	$6,381,002
2009	$1,747,197	$301,101	$492,057	$2,540,356
2010	$2,189,379	$642,019	$1,937,771	$4,769,169
2011	$3,112,775	$472,868	$651,407	$4,237,050
2012	$2,203,178	$395,680	$314,776	$2,913,633
2013	$1,096,960	$232,144	$79,943	$1,409,048
2014	$359,229	$224,542	$38,523	$622,295
2015	$43,197	$380,520	$118,904	$542,621
			Average	$3,943,909
			Total	$94,653,815

*As derived from 2016 prices from Table 4 and cumulative genetic gain used on Table 4

Figure 1. Agricultural Research Council Wheat Cultivar Trial Locations Used in the Dataset: 1998–2014.

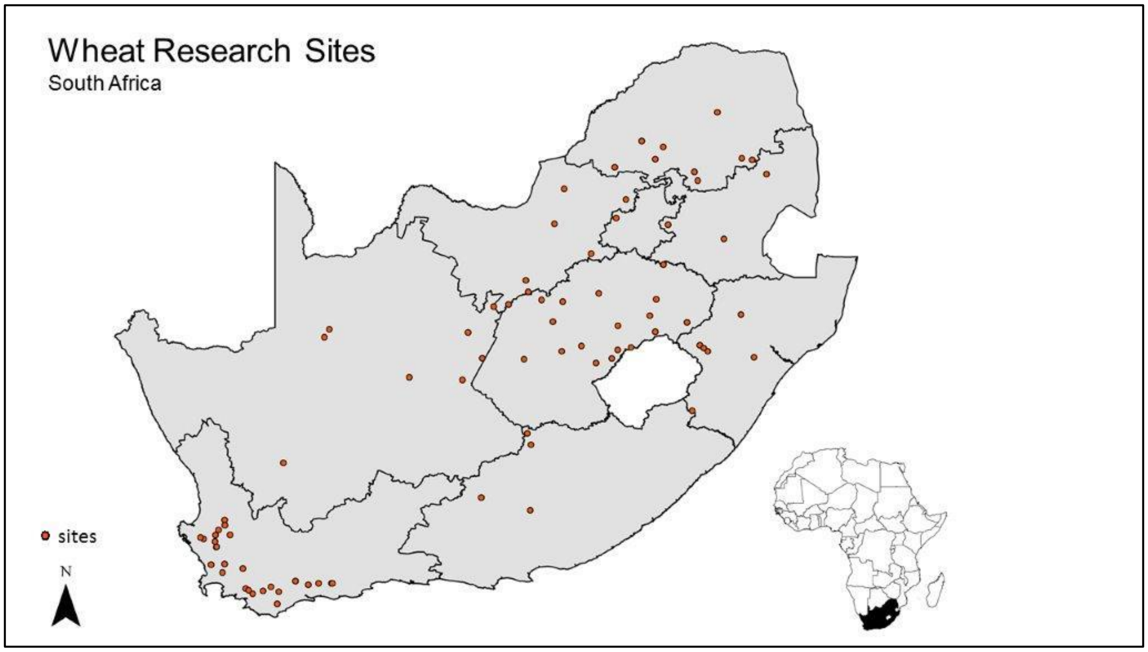
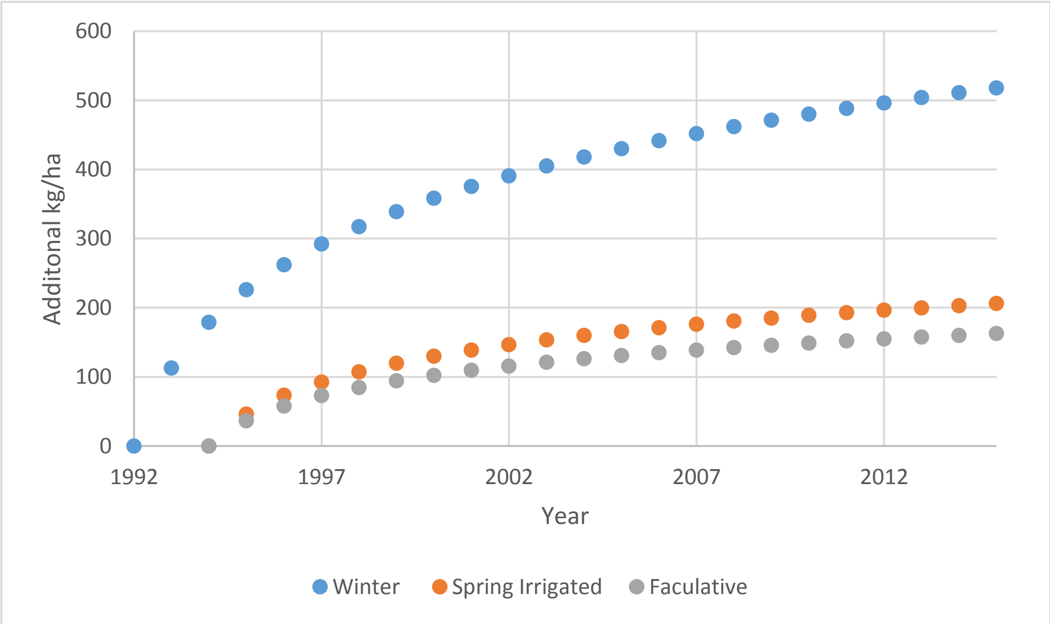


Figure 2. Cumulative Genetic Gains Associated to the Agricultural Research Council Wheat Breeding Program: 1992–2015



*Derived from Table 4

References

African Development Bank-African Economic Outlook (2015) "Special Theme: Regional Development and Spatial Inclusion". Available online at www.africaneconomicoutlook.org/sites/default/files/content-pdf/AEO2015_EN.pdf Accessed August 18, 2017.

Agricultural Research Council (ARC) Reports 2007-2015. Available online at http://www.arc.agric.za/Pages/ARC-Annual-Report-.aspx Accessed September 23, 2016.

Alston, J., Pardey P., and Piggott R., eds. (2006) "Agricultural R&D in the Developing World." Washington, DC: International Food Policy Research Institute.

Alston, J., Pardey, P. (2014) Agriculture in the Global Economy. Journal of Economic Perspectives. 28 (1), 121–146.

Altman, M., Hart, T., and Jacobs, P. (2009) "Household food security status in South Africa". Agrecon, 48(4):345-361.

Arrow, K. (1962) "The Economic Implications of Learning by Doing." Rev Econ Stud 29:155–173.

Bell, M., Fischer, R., Byerlee, D., & Sayre, K. (1995). "Genetic and agronomic contributions to yield gains, a case study for wheat." Field Crops Research, 44, 55-65. Retrieved May 12, 2017.

Brennan, J. (1984) "Measuring the Contribution of New Varieties to Increasing Wheat Yields." Review of Marketing and Agriculture Economics 52:175-195.

Brisson N., Gate, P., Gouache D., Charmet G., Oury F. and Huard F. (2010) "Why are wheat yields stagnating in Europe?" A comprehensive data analysis of France. Field Crop Research 119, 201-212.

Byerlee, D. (1992). Technical change, productivity, and sustainability in irrigated cropping systems of South Asia: emerging issues in the post-green revolution era. Journal of International Development 4, 477–496.

Cauvain, S. (2008) "Using cereal science and technology for the benefit of consumers": Proceedings of the 12th International ICC Cereal and Bread Congress, 23-26th May 2004, Harrogate, UK. Boca Raton: CRC Press.

Cooper, P., Gregory, P., Tully, D., and Harris, H. (1987) "Improving water-use efficiency in the rainfed farming systems of West Asia and North Africa" Exp. Agric., 23, 1987, 113-158.

Department of Agriculture, Forestry, and Fisheries of South Africa (DAFF) Available online at http://www.daff.gov.za/ Accessed August 24, 2016.

DePauw R., Knox R., Clarke F., Wang H., Fernandez M.., Clarke J. (2007) "Shifting Undesirable Correlations." Euphytica 157, 409−415.

Dixon, J., Nalley, L., Kosina, P., La Rovere, R., Hellin, J., & Aquino, P. (2006) Adoption and economic impact of improved wheat varieties in the developing world. The Journal of Agricultural Science, 144(6), 489-502.

Evenson, R., and Gollin, D. (2003) "Assessing the Impact of the Green Revolution, 1960 to 2000." Science 300 (5620): 758–62.

Fan, S. and Saurkar, A. (2006) "Public Spending in Developing Countries: Trends, Determination and Impact" (mimeo).

Fan, S., Hazell, P. and Thorat, S. (2000) "Government spending, agricultural growth and poverty in rural India." American Journal of Agricultural Economics 82(4).

Fan, S., Zhang, L. and Zhang, X. (2000) "Growth and Poverty in Rural China: The role of public investment." Environment and Production Technology Division Discussion Paper 66. IFPRI.

Finger, R., (2010) "Evidence of slowing yield growth – The Example of Swiss Cereal Yields. Food Policy" 35, 175–182.

Fischer, R. (2009) "Exploiting the synergy between genetic improvement and agronomy of crops in rainfed farming systems of Australia." 23–54 in 'Crop physiology: applications for genetic improvement and agronomy', ed. by V. Sadras and D. Calderini. Elsevier: Amsterdam.

Fischer, T., Byerlee, D., & Edmeades, G. (2014) "Crop yields and global food security: Will yield increase continue to feed the world?" Australia: Australian Centre for International Agricultural Research.

Food and Agricultural Organization of the United Nations (FAO) Available online at http://www.fao.org/faostat/en/#home Accessed August 20, 2016.

FOREX: Inflation and Currency Exchange Calculations: Available online at https://www.forex.com/en-us/markets/popular-markets/usd_zar Accessed September 18, 2017.

Goyal, Aparajita, and John Nash. (2017) "Reaping Richer Returns: Public Spending Priorities for African Agriculture Productivity Growth." Africa Development Forum series. Washington, DC: World Bank.

Hatting, J., Poprawski, T., & Miller, R. (2000) "Prevalences of fungal pathogens and other natural enemies of cereal aphids (Homoptera: Aphididae) in wheat under dryland and irrigated conditions in South Africa." BioControl, 45, 179-199.

Home Grown Cereal Authority (2011) "Recommended List Early Sown Winter Wheat Trials Protocol" Available online at https://ahdb.org.uk/about/documents/Protocol-EARLY12-17-earlysownwheattrialprotocol.pdf Accessed July 21, 2017.

Jury, M. "Climate trends in southern Africa." (2013) South African Journal of Science. 109(1/2), Art. #980.

Just, R., Pope, R. (1979) "Production function estimation and related risk considerations." American Journal of Agricultural Economics. 61, 2.

Lobell, D., Cassman, K., and Field, C. (2009) "Crop Yield Gaps: Their Importance, Magnitudes, and Causes." Annual Review of Environment and Resources 34 (1): 179–204.

Lobell, D., Ortiz-Monasterio, J.,Asner, G., Matson, P., Naylor, R., and Falcon, W. (2005) "Analysis of Wheat Yield and Climatic Trends in Mexico." Field Crops Research 94 (2): 250–56.

Lobell, D., Schlenker, W., and Costa- Roberts, J. (2011) "Climate Trends and Global Crop Production since 1980."

Maltais-Landry, G., and Lobell, D. (2012) "Evaluating the Contribution of Weather to Maize and Wheat Yield Trends in 12 US Counties." Agronomy Journal 104 (2): 301–11.

Mandela, N. (1994) Presidential address at the opening of the Congress of the South African Agricultural Union. Available online at http://www.mandela.gov.za/mandela_speeches/1994/941018_saau.htm Accessed October 8, 2017.

Marasas, C., Smale, M. and Singh, R. (2003), "The economic impact of productivity maintenance research: breeding for leaf rust resistance in modern wheat". Agricultural Economics, 29: 253–263

Nalley L., Barkley, A. and Featherstone, A. (2010) "The genetic and economic impact of CIMMYT wheat breeding program on local producers in the Yaqui Valley, Sonora Mexico." Agricultural Economics 41, 453–462.

Nalley L.L., A.P. Barkley, J.M. Crespi, and K.D. Sayre. (2008b) "The Impact of the CIMMYT Wheat Breeding Program: An Economic Welfare Analysis." J Int Agric Trade Dev 5:11–16.

Nalley, L., Barkley, A. and Chumley, F. (2008) "The impact of the Kansas wheat breeding program on wheat yields", 1911–2006. Journal of Agricultural and Applied Economics 40, 913–925.

Nalley, L., F. Tsiboe, A. Durand-Morat, A. Shew and G. Thoma. (2016) "Economic and Environmental Impact of Rice Blast Pathogen (Magnaporthe oryzae) Alleviation in the United States". Public Library of Science (PLoS ONE). 2016.

Pan, X., M. Rush, X. Sha, Q. Xie, S.Linscombe, S.Stetina and J. Oard. (1999) "Major gene, nonallelic sheath blight resistance from the rice cultivars Jasmine 85 and Teqing". Crop Science 39(1999): 338-346.

Pardey, P., J. James, J. Alston, S. Wood, B. Koo, E, Binenbaum, T. Hurley, and P. Glewwe. (2007) "Science, Technology, and Skills." Background Paper for World Development Report 2008, World Bank, Washington, DC.

Pardy, P., Andrade, R., Hurley, T., Rao, X. and Liebenberg, F. (2016) "Returns to food and agricultural R&D investments in Sub-Saharan Africa", 1975-2014. Food Policy 65: 1-8.

Peacemaker-Arrand, B. (2004) "The Impact of a New WTO Agricultural Agreement on Cereals Markets in Sub-Saharan Africa", Honors Thesis for the Department of Agricultural Economics, Tufts University.

Peltonen-Sainio, P., Jauhiainen, L., Laurila, I. (2009) "Cereal trends in northern European conditions: changes in yield potential and its realization." Field Crops Research 110, 85–90.

Ronquest-Ross L., Vink, N., Sigge G. (2015) “Food consumption changes in South Africa since 1994.” South African Journal of Science; 111(9/10), Art. #2014-0354.

Sosibo, N. & Muchaonyerwa, P., Visser, L., Barnard, A., Dube, E., and Tsilo, T. (2017) “Soil fertility constraints and yield gaps of irrigation wheat in South Africa.” South African Journal of Science. Volume 113.

South African Grain Laboratories (SAGL) Wheat reports 1998-2015. Available online at http://www.sagl.co.za/Wheat/Wheatreports.aspx Accessed August 3, 2017.

Stander, C. (2012) “The economics of cultivar improvement research in the South African wheat industry”, Department of Agricultural Economics, Extension, and Rural Development; Faculty of Natural and Agricultural Sciences; University of Pretoria.

Statistics South Africa (2016) Available online at http://www.statssa.gov.za/?p=9922 Accessed October 8, 2016

Stelmakh, A. (1998) “Genetic systems regulating flowering response in wheat.” Euphytica: 100:359–69.

Timmer P. (1998) “The Macroeconomics of Food and Agriculture.” International Agricultural Development. C. Eicher, ed. Baltimore, MD: Johns Hopkins Univ. Press, 1998.

Traxler G., J. Falck-Zepeda, J.I. Ortiz-Monasterio R, and K. Sayre. (1995) “Production Risk and the Evolution of Varietal Technology.” *Am J Agric Econ* 77:1–7.

Tsiboe, F., L. Nalley, A. Durand, G. Thoma and A. Shew. (2017) “The Economic and Environmental Benefits of Sheath Blight Resistance in Rice”. Journal of Agricultural and Resource Economics. 2017. 42(2):215–235.

USDA-Foreign Agricultural Service, (2013) “South Africa’s 2013/14 Wheat Area Remains Low, While Wheat Imports Continue to Rise” Available online at https://ipad.fas.usda.gov/highlights/2013/08/SouthAfricaWheat/ Accessed August 26, 2017.

World Bank, (2015) “Global Economic Prospects: Having Fiscal Space and Using It.” Available online at http://www.worldbank.org/content/dam/Worldbank/GEP/GEP2015a/pdfs/GEP15a_web_full.pdf Accessed September 14, 2017.

Xiao Y., Qian Z., Wu K., Liu J., Xia X.., Ji W. (2012) “Genetic gain in grain yield and physiological traits in winter wheat in Shandong Province, China, from 1969 to 2006.” Crop Science 52, 44–56.

Appendix

Table A1. Planting and Harvesting Rules used by Agricultural Research Council's Test Plot Locations Across South Africa

Production Type	Planting Period	Region	Planting	Emergence	Harvest
Irrigated	Early	All	Site Specific	7 days after planting	30 days after flowering
Irrigated	Late	All except Eastern Highveld	2 weeks after planting period 1	7 days after planting	30 days after flowering
Irrigated	Late	Eastern Highveld	2 weeks after planting period 1	7 days after planting	37 days after flowering
Dryland	Early	All	Site Specific	10 days after planting	30 days after flowering
Dryland	Late	Ruens and Swartland	2 weeks after planting period 1	10 days after planting	30 days after flowering
Dryland	Late	NWFS, SWFS, CFS	3 weeks after planting period 1	10 days after planting	30 days after flowering
Dryland	Late	Eastern Free State	4 weeks after planting period 1	10 days after planting	30 days after flowering

Table A2. Percent of Agricultural Research Council's Total Wheat Area Planted by Wheat Type: 1992–2015

	% of Area				% of Wheat Type		
Year	ARC	Winter	Spring	Facultative	ARC Spring Wheat	ARC Winter Wheat	ARC Facultative Wheat
1992	58.64	1.42	89.06	8.68	63.64	62.26	12.39
1993	64.21	1.99	71.61	25.70	60.85	96.35	72.53
1994	67.21	2.12	78.57	18.42	64.80	100.00	76.89
1995	59.00	4.14	71.57	24.23	52.10	100.00	72.25
1996	58.17	2.71	55.38	41.66	56.89	100.00	57.01
1997*	42.68	3.03	49.49	47.36	33.75	90.21	35.01
1998	27.18	3.34	43.60	53.06	10.60	80.42	37.56
1999	8.96	2.32	83.72	13.96	8.99	58.62	22.67
2000	2.27	0.33	74.75	24.94	1.84	69.70	2.91
2001	8.43	1.99	72.95	25.06	5.30	77.89	14.73
2002	8.65	2.25	76.17	21.79	3.20	74.22	20.84
2003	7.24	0.65	84.41	14.94	4.24	23.08	25.05
2004	9.90	0.53	83.05	16.41	5.55	49.06	30.65
2005	18.23	1.44	78.01	20.53	7.72	58.95	55.43
2006	18.98	1.27	88.83	9.91	15.64	59.45	43.66
2007	16.64	2.31	91.90	5.77	13.71	93.69	32.38
2008	18.44	2.77	84.13	12.76	12.28	54.07	51.78
2009	17.51	0.91	88.86	4.72	13.13	51.48	52.43
2010	17.44	1.89	84.47	13.63	11.90	36.45	49.16
2011	15.41	2.29	90.20	7.49	14.32	20.08	27.18
2012	11.46	1.47	98.58	2.96	10.43	28.61	36.24
2013	6.67	1.57	96.96	1.40	6.14	18.89	23.34
2014	2.69	0.89	98.33	0.77	2.23	36.32	23.00
2015	1.29	2.62	94.62	2.72	0.26	19.54	18.75

*1997 does not exist due to report transition from Wheat Board to South African Grain Laboratories. Values for 1997 were estimated by averaging 1996 and 1998 values.

Table A3. Fixed Effects Regression Results from the OLS and Just-Pope Models for Spring Irrigated Wheat Varieties

Parameter	OLS Yield	Just-Pope Variance	Just-Pope Yield
Intercept	6643.89 [147.06]***	14.45 [0.22]***	6671.36 [433.97]***
AMERSFOORT	169.86 [241.52]	-1.00 [0.36]**	174.52 [565.07]
ATLANTA	287.51 [130.79]*	0.01 [0.19]	294.03 [668.18]
BARKLEY_WEST	1417.21 [93.91]***	0.19 [0.14]	1419.96 [520.21]**
BEDFORD	1447.03 [374.68]***	-2.02 [0.55]**	1449.96 [349.32]***
BERGVILLE	-65.50 [114.67]	-0.39 [0.17]*	-56.41 [432.81]
BLOEMHOF	1877.52 [209.83]***	0.19 [0.31]	1908.41 [789.97]*
BLOUDRIFT	639.32 [378.98]	-1.17 [0.56]*	649.50 [389.44]
BRITS	355.36 [98.01]**	-0.61 [0.15]***	354.66 [395.61]
BULLHILL	1981.48 [94.74]***	-0.07 [0.14]	1983.23 [395.04]***
BULTFONTEIN	796.35 [284.64]**	1.57 [0.42]**	782.68 [1255.06]
BURGERSFORT	183.61 [201.05]	-0.67 [0.30]*	192.95 [578.22]
CHRISTIANA	2318.69 [125.17]***	-0.59 [0.19]**	2323.47 [419.81]***
CLARENS	2524.65 [528.84]***	-3.61 [0.78]***	2533.66 [478.85]***
DANIELSRUS	1377.29 [437.40]**	-3.05 [0.65]***	1395.94 [414.69]**
DELMAS	2695.57 [430.33]***	-1.44 [0.64]*	2697.41 [347.44]***
DOUGLAS	2244.40 [111.40]***	-0.21 [0.16]	2255.58 [422.23]***
DUNDEE	-530.65 [158.41]**	-0.22 [0.23]	-515.93 [614.08]

Table A3 (continued)

FRANKFORT	1816.69 [215.59]***	-0.73 [0.32]*	1834.46 [598.33]**
GREYTOWN	-912.97 [374.68]*	-1.75 [0.55]**	-910.12 [349.32]*
GROBLERSDAL	604.75 [134.91]***	-0.85 [0.20]***	615.22 [440.53]
HARRISMITH	927.12 [528.84]	-5.37 [0.78]***	936.07 [478.85]
HARTSWATER	3822.48 [129.96]***	-0.77 [0.19]***	3823.59 [489.30]***
HOOPSTAD	2201.27 [159.95]***	0.10 [0.24]	2200.75 [573.92]**
HOPETOWN	2631.71 [102.93]***	-0.23 [0.15]	2637.78 [492.99]***
KANONEILAND	3496.62 [206.69]***	-0.48 [0.31]	3496.93 [371.49]***
KOEDOESKOP	1000.18 [120.94]***	-1.15 [0.18]***	997.55 [393.67]*
LADYBRAND	1319.87 [149.16]***	-0.13 [0.22]	1326.33 [501.18]*
LICHTENBURG	1450.21 [117.20]***	-0.63 [0.17]**	1450.36 [472.35]**
LOSKOP	1754.25 [139.07]***	-0.79 [0.21]***	1757.81 [419.30]***
MAGALIESBURG	478.53 [186.12]*	-0.35 [0.28]	457.92 [715.74]
MAKOPPA	1175.39 [340.13]**	-0.95 [0.50]	1208.46 [666.28]
MARBLEHALL	-149.90 [160.68]	-1.19 [0.24]***	-140.20 [405.38]
MODDERFONTEIN	2345.60 [268.79]***	-1.44 [0.40]**	2345.91 [437.15]***
MODDERIVIER	-493.04 [146.78]**	-0.01 [0.22]	-489.74 [522.46]
NABOOMSPRUIT	719.85 [125.66]***	-0.48 [0.19]**	726.44 [450.70]
NEWCASTLE	-786.23 [243.01]**	-1.49 [0.36]***	-782.47 [422.97]
NYLSTROOM	-495.09 [308.68]	-1.61 [0.46]**	-489.41 [317.91]

Table A3 (continued)

OHRIGSTAD	646.91 [154.85]***	-0.19 [0.23]	654.76 [564.95]
ORANJEVILLE	2350.08 [285.77]***	-2.49 [0.42]***	2366.53 [524.65]***
PLOOYSBURG	1817.69 [430.87]***	-3.26 [0.64]***	1807.50 [332.18]***
POTCHEFSTROOM	364.52 [157.39]*	-0.15 [0.23]	364.47 [581.79]
PRIESKA	2174.06 [99.21]***	-0.10 [0.15]	2181.21 [417.29]***
RAMA	2364.42 [92.94]***	-0.41 [0.14]**	2364.23 [344.19]***
REITZ	2342.06 [386.39]***	-0.79 [0.57]	2330.64 [575.85]**
REMHOOGTE	2562.62 [99.72]***	0.18 [0.15]	2573.33 [411.27]***
RIETRIVER	2409.41 [98.33]***	0.55 [0.15]**	2415.11 [594.16]**
SANDVET	2166.40 [430.33]***	-2.06 [0.64]**	2167.99 [347.44]***
SKUINDRIFT	1365.65 [166.51]***	0.21 [0.25]	1378.33 [796.41]
STANDERTON	699.39 [201.44]**	-0.88 [0.30]**	694.97 [726.60]
TAUNG	-915.91 [254.69]**	-0.55 [0.38]	-915.80 [447.22]*
THEUNISSEN	831.19 [145.62]***	-0.99 [0.22]***	842.63 [273.54]**
UPINGTON	1949.77 [99.82]***	-0.56 [0.15]***	1949.57 [499.47]**
VAALHARTS	2296.93 [83.27]***	-0.34 [0.12]**	2301.01 [492.88]***
VAALWATER	-44.75 [164.00]	-0.07 [0.24]	-33.68 [478.73]
VERENA	2187.24 [430.33]***	-1.17 [0.64]	2188.30 [347.44]***
VILLIERS	1018.81 [153.03]***	-0.73 [0.23]**	1034.31 [472.71]*
VRYHEID	-1463.78 [307.66]***	-1.57 [0.46]**	-1465.92 [450.91]**

Table A3 (continued)

WINTERTON	-503.62 [135.72]**	-0.50 [0.20]*	-492.69 [513.88]
1999	-434.56 [175.18]*	0.07 [0.26]	-473.06 [400.64]
2000	-2029.68 [155.81]***	-0.63 [0.23]**	-2067.42 [262.75]***
2001	-3132.53 [163.27]***	-0.68 [0.24]**	-3160.88 [327.46]***
2002	-2007.25 [157.08]***	-1.20 [0.23]***	-2034.39 [267.49]***
2003	-2172.03 [146.18]***	-0.60 [0.22]**	-2200.32 [231.98]***
2004	-2499.19 [146.53]***	-0.80 [0.22]**	-2546.24 [404.08]***
2005	-1268.21 [153.71]***	-0.76 [0.23]**	-1284.81 [265.50]***
2006	-1335.89 [146.23]***	-0.90 [0.22]***	-1365.78 [307.07]***
2007	-1558.18 [147.89]***	-0.87 [0.22]***	-1581.88 [271.15]***
2008	-1622.01 [155.32]***	-0.88 [0.23]***	-1658.88 [288.68]***
2009	-2369.62 [162.42]***	-1.12 [0.24]***	-2406.55 [296.19]***
2010	-1329.54 [155.40]***	-1.21 [0.23]***	-1363.06 [258.63]***
2011	-269.65 [150.27]	-0.90 [0.22]***	-297.31 [258.96]
2012	-323.52 [156.37]*	-0.91 [0.23]***	-355.50 [257.78]
2013	-931.86 [175.05]***	-0.90 [0.26]**	-977.26 [324.47]**
2014	-699.37 [173.12]***	-0.31 [0.26]	-735.09 [419.56]
Late planting	-482.01 [48.93]***	-0.26 [0.07]**	-483.40 [168.98]**
logrlyr	67.13 [22.02]**	0.02 [0.03]	66.88 [29.37]*
R^2	0.4935	0.0625	0.4896
P value for Year	<0.0001	<0.0001	<0.0001
P value for Station	<0.0001	<0.0001	<0.0001

Table A3 (continued)

Number of Clusters	-	-	51
Mean Yield (kg/ha)	6686.59	-	6696.4
Nobs	8,678	8,678	8,678

*** (P<0.01), ** (P<0.05), *(P<0.10)

Table A4. Fixed Effects Regression Results from OLS and Just-Pope Production Models for Spring Dryland Wheat Varieties

Parameter	OLS Yield	Just-Pope Variance	Just-Pope Yield
Intercept	2756.02 [174.58]***	12.25 [0.43]***	2725.48 [346.00]***
ADOWA	-836.00 [455.61]	-3.76 [1.13]**	-818.87 [318.34]*
ALPHA	1355.25 [167.97]***	0.09 [0.42]	1380.40 [433.17]**
ARLINGTON	-1052.02 [182.88]***	-2.09 [0.45]***	-1040.85 [322.41]**
BOONTJIESKRAAL	1946.48 [460.88]***	-1.26 [1.14]	1977.02 [346.00]***
BOTHAVILLE	920.96 [184.11]***	0.22 [0.46]	928.67 [344.73]*
BREDASDORP	271.37 [172.82]	-1.00 [0.43]*	295.99 [335.76]
BULTFONTEIN	575.86 [176.02]**	0.30 [0.44]	591.11 [521.60]
CALEDON	814.79 [282.38]**	-0.44 [0.70]	827.44 [264.12]**
CLARENS	1212.56 [185.40]***	2.70 [0.46]***	1206.18 [850.02]
CLOCOLAN	-861.51 [217.22]***	-1.37 [0.54]*	-849.30 [209.30]**
DEVLEI	534.00 [455.61]	-2.52 [1.13]*	551.13 [318.34]
EENDEKUIL	1388.35 [183.01]***	-0.32 [0.45]	1415.99 [417.15]**
ELSENBURG	3703.61 [336.74]***	-0.68 [0.84]	3727.50 [401.33]***
EXCELSIOR	-1747.72 [260.80]***	-3.57 [0.65]***	-1725.13 [268.94]***
FICKSBURG	466.92 [178.12]**	-0.02 [0.44]	472.52 [352.99]
GELUKSFONTEIN	-1340.98 [329.31]***	-3.68 [0.82]***	-1336.90 [225.78]***
HALFMANSHOF	625.09 [161.59]***	0.47 [0.40]	631.40 [403.59]
HARRISMITH	1189.79 [188.59]***	2.08 [0.47]***	1175.98 [619.67]

Table A4 (continued)

HEBRON	-1304.95 [220.62]***	-3.04 [0.55]***	-1286.96 [326.80]**
HEIDELBERG	752.87 [253.01]**	-0.23 [0.63]	763.69 [372.04]
HOPEFIELD	643.48 [159.40]***	-0.46 [0.40]	660.73 [358.86]
KLEINFONTEIN	-278.19 [183.01]	0.28 [0.45]	-268.38 [459.26]
KLIPDALE	976.71 [164.58]***	-1.21 [0.41]**	995.52 [343.36]**
KOPERFONTEIN	257.94 [188.55]	-0.68 [0.47]	270.20 [311.57]
KORINGBERG	738.95 [187.35]***	-0.11 [0.46]	768.27 [406.99]
LADYBRAND	-625.84 [174.13]**	-0.75 [0.43]	-621.23 [142.71]**
LANGGEWENS	1503.51 [159.44]***	0.25 [0.40]	1532.17 [394.24]**
LANGRUG	2163.20 [186.39]***	0.15 [0.46]	2184.90 [444.39]***
MALMESBURY	2111.28 [170.38]***	-0.06 [0.42]	2133.55 [401.09]***
MEADOWS	-1473.90 [195.21]***	-2.34 [0.48]***	-1468.84 [292.55]***
MOORREESBURG	1965.48 [161.75]***	-0.22 [0.40]	1990.24 [337.10]***
NAPIER	442.27 [172.79]*	0.58 [0.43]	454.99 [468.97]
PHILADELPHIA	2437.09 [168.83]***	0.03 [0.42]	2461.50 [356.96]***
PIKETBERG	996.41 [170.38]***	-0.71 [0.42]	1023.72 [363.43]*
POOLS	1000.21 [160.67]***	1.02 [0.40]*	1021.07 [665.76]
PORTERVILLE	1089.01 [168.67]***	-0.36 [0.42]	1111.66 [418.64]*
PROTEM	830.61 [164.76]***	-0.41 [0.41]	838.25 [418.72]
REITZ	104.31 [185.50]	1.25 [0.46]**	104.38 [267.05]

Table A4 (continued)

RIETPOEL	2533.98 [460.88]***	-2.02 [1.14]	2564.52 [346.00]***
RIVERSDAL	1464.07 [168.44]***	0.11 [0.42]	1475.82 [402.62]**
RIVIERSONDEREND	1843.51 [282.38]***	-1.51 [0.70]*	1852.10 [264.12]***
RONNEPLEEGTE	-1294.32 [188.39]***	-2.49 [0.47]***	-1285.81 [277.76]***
ROODEBLOEM	1840.46 [166.60]***	0.03 [0.41]	1852.13 [249.02]***
SAMESUING	-682.40 [348.19]	-1.52 [0.86]	-650.69 [308.32]*
SERJANTSRIVIER	2443.98 [460.88]***	-0.34 [1.14]	2474.52 [346.00]***
SWELLENDAM	1076.64 [162.68]***	0.11 [0.40]	1088.08 [537.86]
TWEESPRUIT	-1100.87 [197.10]***	-0.98 [0.49]*	-1097.53 [454.36]*
TYGERHOEK	1433.42 [171.05]***	-0.21 [0.42]	1454.09 [406.92]**
UITVLUG	1875.19 [180.31]***	0.50 [0.45]	1910.29 [484.87]**
VELDDRIFT	1320.78 [218.23]***	-1.10 [0.54]*	1322.32 [300.18]**
VOORSTEKOP	678.56 [179.34]**	-1.16 [0.45]**	691.98 [383.62]
VREDENBURG	141.57 [245.71]	-1.48 [0.61]*	162.26 [415.16]
WESSELSBRON	198.40 [189.99]	-0.03 [0.47]	207.99 [547.00]
WINBURG	-1373.67 [329.00]***	-3.23 [0.82]***	-1341.96 [308.32]**
WITSAND	437.40 [192.55]*	0.07 [0.48]	447.16 [580.84]
2008	-272.52 [143.84]	0.48 [0.36]	-259.12 [123.47]*
2009	-380.64 [138.82]**	0.49 [0.34]	-368.96 [118.29]**
2010	-1158.26 [137.29]***	-0.24 [0.34]	-1138.12 [112.04]***

Table A4 (continued)

2011	-114.54 [125.40]	0.09 [0.31]	-114.29 [168.95]
2012	256.52 [126.09]*	-0.05 [0.31]	293.16 [358.40]
2013	29.35 [127.57]	0.54 [0.32]	29.58 [252.30]
2014	-456.05 [131.38]**	0.00 [0.33]	-434.90 [226.64]
late_planting 1	293.19 [71.77]***	-0.37 [0.18]*	309.84 [104.17]**
logrlyr	20.82 [36.23]	-0.12 [0.09]	19.79 [44.73]
R^2	0.5513	0.206301	0.521
P value for Year	<0.0001	<0.0001	<0.0001
P value for Station	<0.0001	<0.0001	<0.0001
Number of Clusters	-	-	22
Mean Yield (kg/ha)	3501.9	-	3548.5
Nobs	2,299	2,299	2,299

*** (P<0.01), ** (P<0.05), *(P<0.10)

Table A5. Fixed Effects Regression Results from OLS and Just-Pope Models for Winter Wheat Varieties

Parameter	OLS	JP VAR	JP Yield
Intercept	3765.50 [82.43]***	12.65 [0.19]***	3821.29 [251.55]***
AMERSFOORT	339.19 [254.24]	0.15 [0.57]	338.35 [129.25]*
ARLINGTON	-928.62 [82.93]***	-0.88 [0.19]***	-917.07 [110.09]***
BLOEMFONTEIN	-1604.02 [154.88]***	0.27 [0.35]	-1610.97 [372.18]**
BOTHAVILLE	-100.24 [104.69]	0.23 [0.24]	-121.45 [297.81]
BULTFONTEIN	694.42 [71.30]***	0.78 [0.16]***	677.15 [377.23]
CLARENS	928.30 [80.73]***	0.01 [0.18]	925.27 [132.34]***
CLOCOLAN	71.46 [93.27]	0.94 [0.21]***	68.14 [340.51]
EXCELSIOR	-630.61 [86.43]***	0.42 [0.19]*	-624.57 [489.32]
FICKSBURG	778.38 [85.73]***	1.11 [0.19]***	792.40 [251.66]**
FRANKFORT	538.99 [146.87]**	2.64 [0.33]***	600.38 [967.59]
GELUKSFONTEIN	-1778.28 [267.52]***	-1.36 [0.60]*	-1766.29 [179.89]***
HARRISMITH	485.89 [90.29]***	-0.09 [0.20]	485.86 [217.58]*
HEBRON	-1226.93 [76.91]***	0.25 [0.17]	-1244.93 [273.78]***
HENNENMAN	-679.77 [98.26]***	-0.58 [0.22]**	-696.54 [230.34]**
KROONSTAD	-2186.29 [349.70]***	-3.52 [0.79]***	-2242.07 [252.75]***
LADYBRAND	90.59 [75.77]	0.45 [0.17]**	94.66 [197.55]
MEADOWS	-1484.73 [178.29]***	-1.50 [0.40]**	-1483.94 [173.36]***
PETRUSBURG	-1289.93 [80.10]***	-0.44 [0.18]*	-1304.87 [267.91]***
PETRUSSTEYN	-744.75 [129.09]***	0.01 [0.29]	-800.77 [438.61]

Table A5 (continued)

REITZ	-278.26 [86.32]**	0.34 [0.19]	-305.56 [268.86]
RONNEPLEEGTE	-1545.55 [212.33]***	-1.27 [0.48]**	-1549.98 [272.51]***
SAMESUING	-575.76 [156.78]**	-0.17 [0.35]	-586.02 [167.54]**
SENEKAL	-962.04 [113.20]***	-0.53 [0.26]*	-998.11 [314.84]**
TWEESPRUIT	-910.23 [85.57]***	-0.28 [0.19]	-937.95 [336.92]**
WESSELSBRON	419.77 [78.80]***	0.45 [0.18]*	423.78 [191.90]*
WINBURG	-1482.40 [495.13]**	-3.20 [1.12]**	-1487.82 [234.43]***
1999	-1476.15 [87.87]***	-1.10 [0.20]***	-1522.34 [230.96]***
2000	-776.86 [98.25]***	-1.26 [0.22]***	-828.07 [264.68]**
2001	-482.30 [103.51]***	-1.32 [0.23]***	-551.17 [306.79]
2002	-1360.95 [88.63]***	-2.08 [0.20]***	-1420.19 [261.28]***
2003	-2211.72 [91.46]***	-1.15 [0.21]***	-2263.28 [238.72]***
2004	-2131.18 [84.53]***	-1.15 [0.19]***	-2199.39 [268.40]***
2005	-1898.94 [81.54]***	-1.38 [0.18]***	-1952.84 [218.94]***
2006	-398.11 [78.14]***	-1.22 [0.18]***	-438.41 [227.53]
2007	-39.99 [83.07]	0.16 [0.19]	-88.26 [221.57]
2008	-1849.35 [108.13]***	-0.65 [0.24]**	-1912.47 [257.15]***
2009	-653.08 [84.38]***	-1.05 [0.19]***	-694.51 [258.79]*
2010	-1705.19 [106.19]***	-0.76 [0.24]**	-1771.27 [279.49]***
2011	-1339.06 [129.93]***	-1.18 [0.29]***	-1394.88 [327.86]**

Table A5 (continued)

2012	-235.58 [115.56]*	-0.72 [0.26]**	-287.24 [270.31]
2013	-899.68 [128.90]***	-0.38 [0.29]	-926.98 [240.46]**
2014	-1127.13 [125.34]***	-1.16 [0.28]***	-1196.92 [292.20]**
late_planting	8.68 [30.34]	0.23 [0.07]**	2.84 [64.35]
logrlyr	160.99 [16.35]***	0.12 [0.04]**	163.00 [50.39]**
R^2	0.5547	0.127566	0.5455
P value for Year	0.0001	0.0001	0.0001
P value for Station	0.0001	0.0001	0.0001
Number of Clusters	-	-	29
Mean Yield (kg/ha)	2719.72	-	2760.2
Nobs	4287	4287	4287

*** (P<0.01), ** (P<0.05), *(P<0.10)

Table A6. Fixed Effects Regression Results from OLS and Just-Pope Models for Facultative Wheat Varieties

Parameter	OLS	JP VAR	JP Yield
Intercept	3749.42 [52.39]***	12.98 [0.12]***	3801.98 [306.65]***
AMERSFOORT	483.52 [152.67]**	-0.40 [0.36]	484.99 [106.59]***
ARLINGTON	-1135.60 [49.29]***	-0.90 [0.12]***	-1119.85 [138.99]***
BLOEMFONTEIN	-1419.73 [91.88]***	-0.15 [0.22]	-1417.49 [217.59]***
BOTHAVILLE	-100.65 [63.35]	-0.11 [0.15]	-99.90 [212.39]
BULTFONTEIN	505.04 [42.32]***	0.53 [0.10]***	478.31 [357.62]
CLARENS	795.88 [45.51]***	-0.03 [0.11]	793.86 [151.12]***
CLOCOLAN	-276.47 [52.95]***	0.30 [0.12]*	-275.59 [296.36]
EXCELSIOR	-800.85 [52.56]***	-0.05 [0.12]	-797.22 [461.92]
FICKSBURG	771.45 [47.87]***	0.60 [0.11]***	784.04 [222.33]**
FRANKFORT	425.89 [85.60]***	2.25 [0.20]***	486.75 [901.92]
GELUKSFONTEIN	-1360.89 [244.59]***	-2.55 [0.58]***	-1343.30 [150.00]***
HARRISMITH	401.67 [51.45]***	0.35 [0.12]**	412.52 [245.52]
HEBRON	-1292.11 [45.39]***	-0.14 [0.11]	-1307.53 [228.40]***
HENNENMAN	-753.69 [59.30]***	-0.79 [0.14]***	-769.06 [192.99]**
KROONSTAD	-1900.04 [234.62]***	-2.42 [0.55]***	-1953.03 [308.55]***
LADYBRAND	-209.67 [44.74]***	0.08 [0.11]	-209.21 [220.36]
MEADOWS	-1428.73 [122.41]***	-1.88 [0.29]***	-1429.23 [224.73]***
PETRUSBURG	-1333.66 [47.25]***	-0.45 [0.11]***	-1348.00 [259.69]***
PETRUSSTEYN	-849.55 [79.14]***	-0.34 [0.19]	-895.17 [303.79]**

Table A6 (continued)

REITZ	-421.31 [49.92]***	0.14 [0.12]	-446.36 [213.32]*
RONNEPLEEGTE	-1334.00 [140.12]***	-1.13 [0.33]**	-1343.78 [269.51]***
SAMESUING	-941.76 [90.52]***	-0.50 [0.21]*	-940.99 [217.31]**
SENEKAL	-1046.45 [67.63]***	-0.49 [0.16]**	-1072.37 [263.41]**
TWEESPRUIT	-1061.75 [50.85]***	-0.22 [0.12]	-1085.32 [292.74]**
WESSELSBRON	169.09 [46.72]**	0.36 [0.11]**	170.54 [175.04]
WINBURG	-1363.61 [270.66]***	-2.78 [0.64]***	-1365.05 [162.40]***
1999	-1334.24 [58.90]***	-1.28 [0.14]***	-1375.30 [291.13]***
2000	-537.80 [55.00]***	-0.71 [0.13]***	-582.64 [317.84]
2001	-237.05 [57.45]***	-1.02 [0.14]***	-305.37 [350.06]
2002	-1044.78 [55.13]***	-2.11 [0.13]***	-1097.61 [291.31]**
2003	-1911.87 [56.58]***	-1.20 [0.13]***	-1965.88 [284.49]***
2004	-1716.46 [55.01]***	-0.81 [0.13]***	-1782.49 [304.78]***
2005	-1369.09 [51.66]***	-1.12 [0.12]***	-1414.14 [258.25]***
2006	-259.63 [48.72]***	-1.02 [0.11]***	-301.18 [271.21]
2007	101.89 [51.50]*	0.37 [0.12]**	55.82 [263.08]
2008	-1818.24 [65.07]***	-0.64 [0.15]***	-1872.56 [288.66]***
2009	-494.11 [51.74]***	-1.19 [0.12]***	-534.94 [296.60]
2010	-1404.51 [62.95]***	-0.74 [0.15]***	-1467.83 [296.73]***
2011	-1063.83 [65.86]***	-0.91 [0.16]***	-1115.56 [296.49]**

Table A6 (continued)

2012	-123.05 [76.52]	-0.33 [0.18]	-158.14 [291.23]
2013	-1251.70 [96.81]***	-0.30 [0.23]	-1299.41 [290.90]***
2014	-1427.49 [92.69]***	-0.57 [0.22]**	-1496.68 [312.35]***
late_planting	172.58 [18.07]***	-0.09 [0.04]*	170.29 [57.13]**
logrlyr	51.90 [9.99]***	-0.01 [0.02]	52.57 [17.95]**
R^2	0.5413	0.115	0.5319
P value for Year	0.0001	0.0001	0.0001
P value for Station	0.0001	0.0001	0.0001
Number of Clusters	-	-	29
Mean Yield (kg/ha)	2787.6	-	2825
Nobs	10,577	10,577	10,577

*** (P<0.01), ** (P<0.05), *(P<0.10)

Table A7. South African Agricultural Research Council Average Yield by Wheat Type: 1998–2014

Type	Observations	Yield (kg/ha)	Standard Deviation of Yield (kg/ha)
Winter	4,287	2,719.72	1,433.15
Spring	21,643	5,935.23	2,319.87
Facultative	10,577	2,787.58	1,348.64

Table A8. Yearly Average Yield for All ARC Test Plots

Year	Observations	Average Yield (kg/ha)	Standard Deviation of Yield (kg/ha)
1998	1,117	4,589.01	2,970.04
1999	1,092	3,853.68	2,946.00
2000	1,595	4,374.24	2,228.87
2001	1,180	4,024.95	1,665.92
2002	2,016	4,099.29	1,891.12
2003	2,500	4,267.24	2,606.85
2004	2,472	3,823.46	2,172.64
2005	3,018	3,976.78	2,550.67
2006	3,759	4,597.61	2,212.16
2007	2,941	4,933.92	2,014.76
2008	1,986	4,581.02	2,397.60
2009	2,824	3,895.67	1,715.75
2010	2,173	4,878.19	2,583.16
2011	3,493	6,197.23	3,001.12
2012	2,225	5,842.62	2,702.00
2013	976	5,360.08	2,627.47
2014	1,140	5,072.55	2,726.39

Table A9. Average Yield of ARC Varieties by the Year it Was Commercially Released (RLYR)

Release ear	Observations	Average Yield (kg/ha)	Standard Deviation of Yield (kg/ha)
1992	416	3,123.48	1,748.23
1993	2,070	2,632.29	1,299.82
1994	9,718	4,403.33	2,429.97
1996	2,176	2,779.71	1,298.22
1999	2,407	2,873.14	1,367.65
2000	2,273	6,102.36	1,956.85
2001	3,305	5,526.89	2,202.30
2003	4,492	4,702.34	2,495.83
2006	5,225	5,705.96	2,714.89
2009	1,674	5,470.31	2,495.98
2010	843	7,474.59	2,015.39
2012	1,908	4,488.40	2,433.52

Table A10. Average ARC Test Plot Yields by Station and Location: 1998–2014

Station	Province	Observations	Average Yield (Kg/Ha)	Standard Deviation of Yield (kg/ha)	Irrigated	Lat	Long	Altitude (meters)
ADOWA	Western Cape	16	1,375.00	245.76	no	-34.083	20.967	84
ALPHA	Western Cape	220	3,669.86	1,047.09	no	-34.269	20.081	283
AMERSFOORT	Free State	132	3,670.38	1,443.72	both	-27.033	28.600	1493
ARLINGTON	Free State	829	1,863.67	959.78	no	-28.163	28.295	1631
ATLANTA	Western Cape	300	5,297.56	1,419.60	yes	-33.665	18.582	71
AURORA	Western Cape	24	3,315.00	1,234.07	no	-33.665	18.582	71
BARKLEY WEST	Northern Cape	760	6,782.38	2,283.51	both	-28.534	24.272	1004
BEDFORD	North-West	28	6,903.93	710.85	yes	-25.591	27.769	1085
BERGVILLE	Kwazulu-Natal	424	5,320.47	1,856.79	yes	-28.819	29.402	1244

Table A10 (continued)

BETHLEHEM	Free State	2,635	3,933.89	1,484.62	both	-28.163	28.295	1631
BLOEMFONTEIN	Free State	168	1,604.74	517.69	both	-28.950	26.350	1304
BLOEMHOF	North-West	108	7,322.86	1,589.84	yes	-27.633	25.600	1231
BLOUDRIFT	North-West	32	4,960.63	731.40	yes	-27.383	25.550	1309
BOLAND	Western Cape	24	4,666.67	1,619.89	no	-33.654	18.883	151
BOONTJIESKRAAL	Western Cape	48	2,767.08	1,035.28	no	-34.200	19.350	128
BOTHAVILLE	North-West	452	3,138.66	1,078.02	both	-27.383	25.550	1309
BREDASDORP	Western Cape	196	3,365.90	977.52	no	-34.533	20.050	44
BRITS	North-West	732	5,816.86	1,211.69	yes	-25.591	27.769	1085
BULLHILL	Northern Cape	739	7,383.21	1,835.68	yes	-27.958	24.840	1180
BULTFONTEIN	Free State	1,476	3,699.90	1,343.53	both	-28.300	26.150	1326
BURGERSFORT	Limpopo	112	5,797.64	1,026.87	yes	-24.683	30.333	793
CALEDON	Western Cape	12	3,134.00	565.24	no	-34.233	19.417	244
CHRISTIANA	North-West	342	8,096.77	1,446.00	yes	-27.917	25.167	1207
CLARENS	Free State	1,027	3,836.50	1,313.83	both	-28.517	28.417	1809
CLOCOLAN	Free State	628	2,766.87	1,014.65	both	-28.921	27.584	1602
DANIELSRUS	Free State	20	7,165.53	502.81	yes	-27.800	28.433	1615
DELMAS	Mpumalanga	24	7,274.58	783.83	yes	-26.149	28.701	1532
DEVLEI	Free State	16	3,340.00	484.13	no	-28.833	26.783	1454
DOUGLAS	Mpumalanga	451	7,473.62	1,634.84	yes	-26.467	29.933	1675
DUNDEE	Kwazulu-Natal	184	4,119.58	1,144.50	yes	-28.137	30.315	1219
DUNHYEPARK	Western Cape	8	4,377.50	780.73	no	-34.315	19.503	189
EENDEKUIL	Western Cape	124	3,516.13	929.11	no	-32.683	18.883	150
ELSENBURG	Western Cape	24	5,636.82	883.95	no	-33.842	18.839	227
EXCELSIOR	Eastern Cape	676	2,259.03	1,860.22	no	-31.017	25.667	1606
FAIRFIELD	Western Cape	24	3,666.67	614.14	no	-34.233	19.417	244
FICKSBURG	Free State	852	3,762.66	1,518.14	no	-28.867	27.883	1585
FRANKFORT	Mpumalanga	286	5,037.15	3,301.67	both	-25.033	30.883	1005
GELUKSFONTEIN	Free State	40	1,097.38	173.78	no	-28.950	26.350	1304
GREYTOWN	Kwazulu-Natal	28	4,368.21	804.99	yes	-29.083	30.604	1043

Table A10 (continued)

GROBLERSDAL	Limpopo	287	6,131.12	1,386.79	yes	-25.174	29.355	948
HALFMANSHOF	Western Cape	139	3,175.53	1,067.94	no	-33.154	18.673	199
HARRISMITH	Free State	715	3,795.99	1,467.29	both	-28.313	29.116	1723
HARTSWATER	Northern Cape	316	9,473.14	1,531.49	yes	-28.534	24.272	1004
HEBRON	Free State	1,082	1,760.24	662.24	no	-28.950	26.350	1304
HEIDELBERG	Western Cape	24	2,355.91	1,091.08	no	-34.083	20.967	84
HENNENMAN	Free State	466	2,254.74	662.20	no	-28.389	27.587	1587
HEUNINGKLOOF	Western Cape	12	3,659.17	625.80	no	-34.083	20.967	84
HOOPSTAD	Free State	184	8,089.34	1,393.45	yes	-27.817	25.900	1262
HOPEFIELD	Western Cape	208	3,184.03	580.46	no	-33.067	18.350	30
HOPETOWN	Northern Cape	565	7,866.39	1,853.02	yes	-29.581	24.149	1135
KANONEILAND	Northern Cape	102	9,844.27	1,046.41	yes	-28.635	21.095	766
KLEINFONTEIN	Limpopo	76	2,282.99	685.27	no	-23.666	29.790	1210
KLIPDALE	Western Cape	116	3,333.64	771.57	no	-34.269	20.081	283
KOEDOESKOP	Limpopo	383	6,055.21	1,455.49	yes	-24.882	27.521	939
KOPERFONTEIN	Western Cape	62	2,719.55	648.79	no	-33.100	18.417	45
KORINGBERG	Western Cape	76	3,288.51	757.14	no	-33.017	18.683	130
KROONSTAD	Free State	24	1,802.92	382.08	no	-27.667	27.167	1338
LADYBRAND	Free State	1,363	3,486.66	1,816.18	both	-29.112	27.453	1581
LANGGEWENS	Western Cape	295	3,877.38	1,041.04	no	-33.283	18.700	177
LANGRUG	Western Cape	71	4,589.95	762.40	no	-33.154	18.673	199
LICHTENBURG	North-West	410	7,006.87	1,885.77	yes	-26.133	26.183	1491
LOSKOP	Kwazulu-Natal	272	6,570.37	1,426.28	yes	-28.950	29.583	1167
MAGALIESBURG	Gauteng	144	4,580.97	1,539.11	yes	-26.000	27.550	1480
MAKOPPA	Gauteng	36	7,128.01	955.15	yes	-26.000	27.550	1480
MALMESBURY	Western Cape	104	4,484.48	1,150.65	no	-33.276	18.706	191
MARBLEHALL	Limpopo	188	4,748.69	1,043.36	yes	-24.983	29.283	915
MATJIESKLOOF	Western Cape	32	5,207.19	963.18	no	-32.683	18.883	150
MEADOWS	Kwazulu-Natal	132	1,424.24	337.57	no	-30.267	29.233	1460
MODDERFONTEIN	Western Cape	56	8,005.50	899.05	yes	-32.683	18.883	150

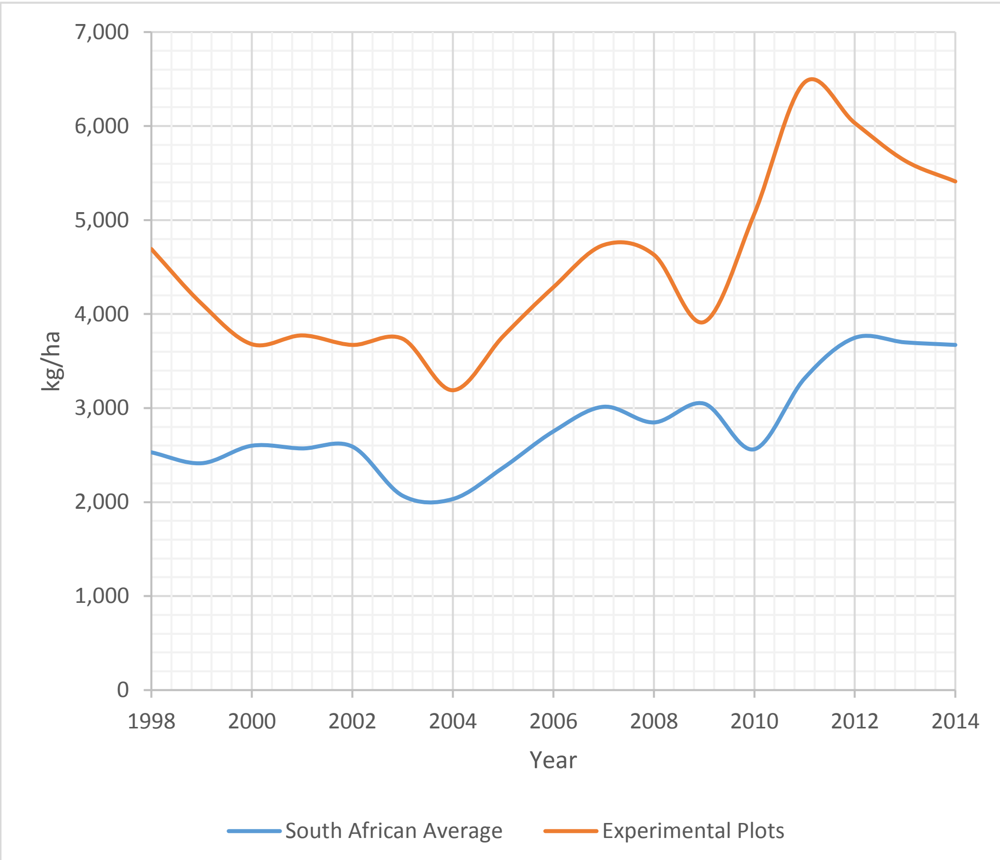
Table A10 (continued)

MODDERIVIER	Western Cape	232	5,535.56	1,250.76	yes	-32.683	18.883	150
MOORREESBURG	Western Cape	188	4,225.64	958.51	no	-33.154	18.673	199
NABOOMSPRUIT	Limpopo	339	6,181.27	1,274.95	yes	-24.427	28.594	820
NAPIER	Western Cape	100	2,982.79	907.04	no	-34.269	20.081	283
NEWCASTLE	Kwazulu-Natal	80	4,105.20	867.41	yes	-28.137	30.315	1219
NYLSTROOM	Kwazulu-Natal	48	3,510.21	1,024.69	yes	-24.700	28.417	1173
OHRIGSTAD	Limpopo	197	6,426.16	1,462.26	yes	-24.719	30.562	1079
ORANJEVILLE	Mpumalanga	52	6,712.31	994.64	yes	-25.033	30.883	1005
PETRUSBURG	Free State	911	1,599.36	616.64	no	-29.124	25.512	1282
PETRUSSTEYN	Free State	240	2,218.75	899.76	no	-28.163	28.295	1631
PHILADELPHIA	Western Cape	147	4,678.66	1,090.02	no	-33.665	18.582	71
PIKETBERG	Western Cape	164	3,512.60	1,074.08	no	-32.900	18.750	274
PLOOYSBURG	Mpumalanga	24	7,348.75	860.53	yes	-26.467	29.933	1675
POOLS	Western Cape	196	3,396.90	1,151.34	no	-32.797	18.888	161
PORTERVILLE	Western Cape	144	3,958.54	833.28	no	-33.012	18.999	149
POTCHEFSTROOM	North-West	192	6,322.94	1,171.73	yes	-26.790	26.996	1377
PRIESKA	Northern Cape	636	7,332.93	1,887.32	yes	-29.525	22.973	944
PROTEM	Western Cape	148	3,211.39	1,019.88	no	-34.269	20.081	283
RAMA	Northern Cape	791	7,784.91	1,648.09	yes	-29.525	22.973	944
RATELFONTEIN	Northern Cape	4	1,127.50	353.40	no	-31.417	20.183	1047
REITZ	Free State	870	2,939.00	1,351.32	both	-27.800	28.433	1615
REMHOOGTE	Western Cape	626	7,801.36	2,293.65	yes	-34.269	20.081	283
RIEBEEKWES	Western Cape	32	3,406.56	1,214.40	no	-33.154	18.673	199
RIETPOEL	Western Cape	36	3,196.94	1,442.76	no	-34.252	19.735	323
RIETRIVER	Northern Cape	764	7,340.28	2,277.32	yes	-29.104	24.584	1131
RIVERSDAL	Western Cape	144	3,929.75	1,091.19	no	-34.083	21.250	114
RIVIERSONDEREND	Western Cape	12	4,162.72	454.21	no	-34.162	19.907	183
RONNEPLEEGTE	Free State	108	1,685.54	313.82	no	-28.950	26.350	1304
ROODEBLOEM	Eastern Cape	192	4,583.07	1,092.39	no	-32.183	24.567	808
SAMESUING	Free State	176	2,236.35	539.25	no	-28.950	26.350	1304

Table A10 (continued)

SANDVELD	North-West	21	3,501.90	1,137.26	no	-27.633	25.600	1231
SANDVET	Northern Cape	24	6,685.83	798.82	yes	-29.104	24.584	1131
SENEKAL	Free State	332	2,091.72	884.60	no	-28.389	27.587	1587
SERJANTSRIVIER	Eastern Cape	72	4,271.11	1,581.32	no	-32.183	24.567	808
SKIETPAD	Eastern Cape	8	4,403.75	863.73	no	-32.183	24.567	808
SKUINDRIFT	North-West	161	6,837.50	2,508.25	yes	-25.359	26.398	1000
STANDERTON	Free State	116	5,933.19	1,666.60	yes	-28.163	28.295	1631
SWELLENDAM	Western Cape	188	3,907.23	987.60	no	-34.033	20.450	125
TAUNG	Eastern Cape	72	3,538.06	1,332.53	yes	-32.467	25.650	1198
THEUNISSEN	Eastern Cape	239	6,148.56	1,109.70	yes	-32.467	25.650	1198
TWEESPRUIT	Free State	737	2,175.98	751.44	no	-29.212	27.108	1583
TYGERHOEK	Western Cape	355	3,794.51	1,131.73	no	-34.162	19.907	183
UITKOMS	Eastern Cape	4	2,007.50	154.14	no	-30.767	25.583	1280
UITVLUG	Western Cape	139	4,530.65	1,043.86	no	-34.083	21.267	122
UPINGTON	Northern Cape	624	6,998.44	1,673.40	yes	-28.464	21.205	798
VAALHARTS	Northern Cape	1,410	7,723.55	1,977.85	yes	-27.958	24.840	1180
VAALWATER	Limpopo	180	5,014.63	1,765.21	yes	-24.300	28.117	1215
VELDDRIFT	Western Cape	32	4,088.08	483.24	no	-34.083	21.267	122
VERENA	Limpopo	24	6,645.00	1,017.63	yes	-24.300	28.117	1215
VILLIERS	Western Cape	209	6,925.45	1,559.37	yes	-33.750	19.283	670
VOORSTEKOP	Western Cape	160	3,255.67	987.55	no	-34.117	20.733	250
VREDENBURG	Western Cape	77	2,747.43	716.34	no	-33.067	18.350	30
VRYHEID	Limpopo	48	3,576.88	899.66	yes	-28.137	30.315	1219
WESSELSBRON	Free State	963	3,379.83	1,312.36	no	-27.850	26.367	1325
WINBURG	Eastern Cape	24	1,348.21	166.67	no	-32.467	25.650	1198
WINTERTON	Kwazulu-Natal	283	4,836.18	1,589.01	yes	-28.883	29.489	1100
WITSAND	Western Cape	51	3,481.86	904.55	no	-34.083	21.267	122

Figure A1. South African Actual Wheat Yields vs Agricultural Research Council's Experimental Test Plot Wheat Yield Average Observations: 1998–2014



Source: FAOSTAT, 2017

Figure A2. Yield (kg/ha) Observations by Normal and Late Planting: 1998–2014

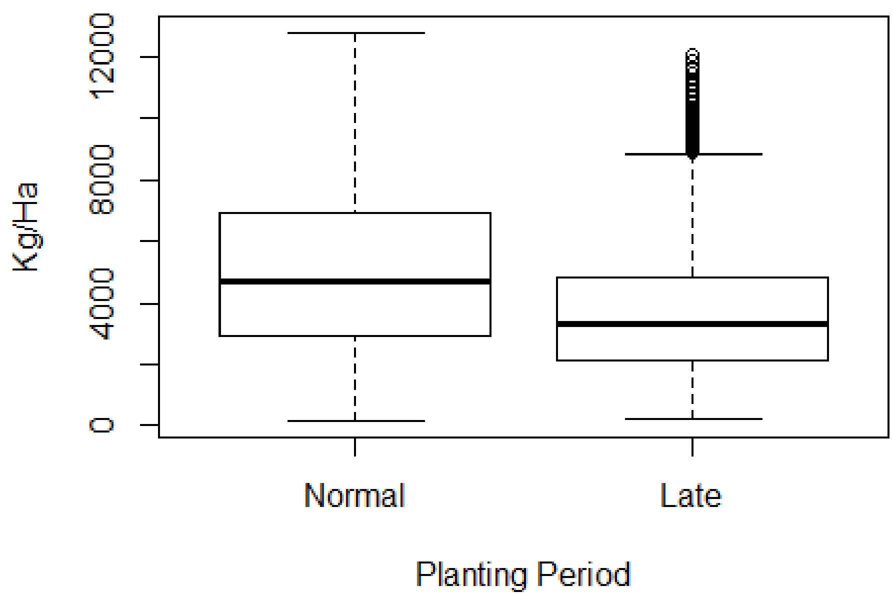


Figure A3. Yield Observations by Irrigated and Dryland Production: 1998–2008

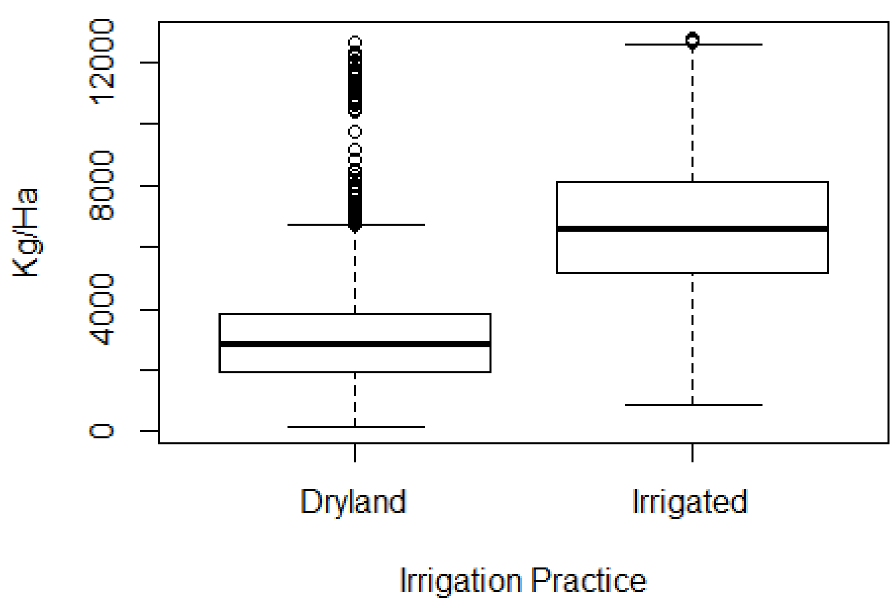


Figure A4. Yield Observations by Variety Type: 1998–2014

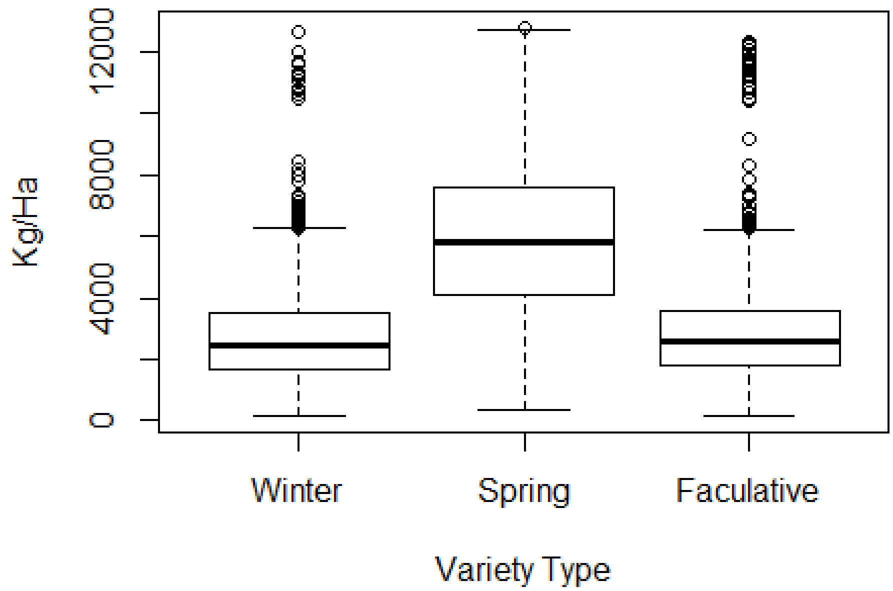


Figure A5. Yield Observations by Growing Year

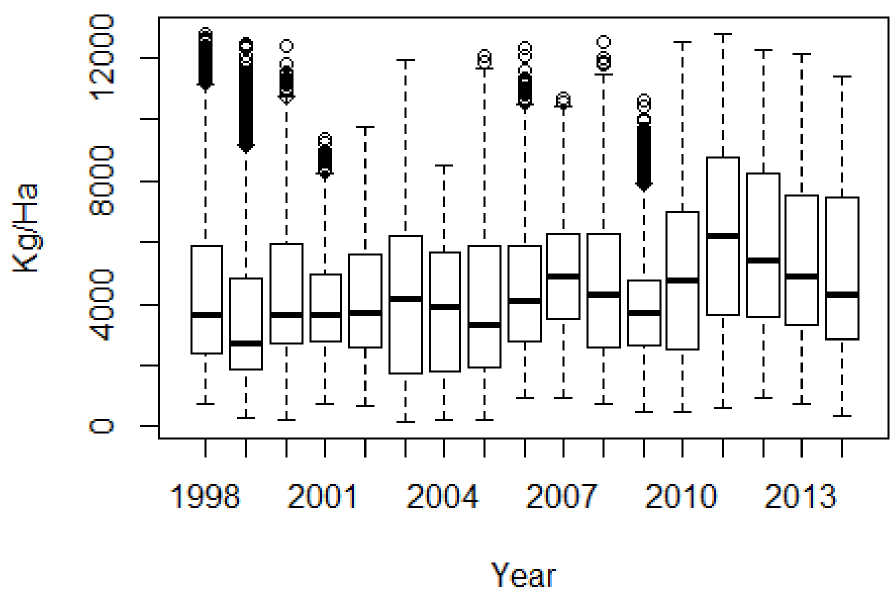


Figure A6. Yield Observations by Release Year