Estimating and attributing benefits from wheat varietal innovations in South African agriculture

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Significance of the work: This paper presents a comprehensive analysis of the estimates the benefits from wheat varietal innovations and attributes them to the different institutional sources (public, private and others) that have contributed to varietal changes in South Africa. The empirical analyses used data on market shares of wheat varieties planted by farmers and annual quantities of wheat produced across different wheat-production areas in South Africa (summer dryland, winter dryland winter, and irrigation).

Abstract

It is well accepted that biological innovations, particularly varietal improvements, have greatly contributed to agricultural yield and output growth in the past. At the same time, public funding for breeding programmes such as at the Agricultural Research Council in South Africa has dwindled. In an effort to confirm the importance of continued funding of varietal improvement programmes, this paper estimates the benefits from wheat varietal innovations and attributes them to the different institutional sources (public, private and others) that have contributed to varietal changes in South Africa. The empirical analyses used data on market shares of wheat varieties planted by farmers and annual quantities of wheat produced across different wheat-production areas in South Africa (summer dryland, dryland winter, and irrigation). A vintage regression model was estimated to calculate the proportional yield gain from wheat varietal improvements. The results indicated that the rate of gain in yield as a result of releases of new wheat varieties (variety research) was 0.8% per year (equivalent to 19.84 kg/ha/year) for dryland summer varieties, and 0.5% for both irrigation (equivalent to 32.20 kg/ha/year) and dryland winter varieties (equivalent to 16.65 kg/ha/year). The attribution of benefits among different institutional sources confirms that not accounting for attribution of benefits by source and time period results is overestimation of benefits to any specific research programme. Attribution of benefits by institutional source showed that Sensako dominated, while the share of the ARC-SGI substantially declined, after deregulation of the wheat sub-sector. The results highlight the impact of the decline in public funding for wheat variety improvement research after deregulation and provide a strong argument for continued public funding for variety improvement in South Africa.

Key words: Wheat, variety research, economic, attribution, South Africa

1. Introduction

Biological innovations, particularly varietal improvements, have greatly contributed to agricultural yield and output growth in the past (Alston et al., 2000; Pardey et al., 2016a; Pardey et al., 2016b; Fan et al., 2005; Lantican et al., 2016; Pingali, 2010; Rao et al., 2016). Varietal improvements are beneficial to farmers through improving yield potential, increasing resistance to biotic and abiotic stresses, and improving other qualities of crops such as nutrition and processing (Atack et al., 2009; Lantican et al., 2005; Lantican et al., 2016). As a result, improved wheat varieties contribute to increased productivity, better quality grain and end products, reduced food prices for consumers, and reduced negative impacts on the environment (Lantican et al., 2005; Lantican et al., 2016; Pal, 2011).

Given the competing needs for public resources and a trend of decreased public funding for research and development (Pardey et al., 2016a; Pardey et al., 2016b; Pal, 2011; Maredia and Byerlee, 2000), further support for wheat varietal research depends on highlighting and confirming the benefits derived from these investments. For example, despite the contribution of the Agricultural Research Council (ARC) in improving the performance of the agricultural sector in South Africa (Liebenberg, 2013), public funding (through the Parliamentary Grant) to the ARC has been declining in real terms over the recent years (Dlamini et al., 2015). This impacts the ability of the ARC to effectively implement and support its various research programmes, including crop breeding programmes (Dlamini and Liebenberg, 2015; Dlamini et al., 2015). The reality of declining public funding emphasises the need for the different research programmes to demonstrate their returns to public investments to prove their worth for continued funding. An estimation of the benefits derivable from wheat varietal improvement research could provide important arguments to decision makers in the prioritisation and allocation of public funding for wheat varietal research and other research needs.

Agricultural research and development, by its nature, involves collaboration among different institutions, and a failure to properly attribute benefits arising from research investments made by various players (public and private sector) leads to an overestimation of economic benefits received from research (Alston and Pardey, 2001; Pardey et al., 2006; Alston et al., 2009; Fuglie and Heisey, 2007; Lantican et al., 2016). South African wheat farmers use seeds produced as a result of research efforts from different sources (public and private), including international breeding programmes. The challenge is to ascertain how to attribute the aggregate benefits to a specific institution or breeding programme in a scenario where the benefits generated were derived from research investments received from other research institutions (public and private) (Maredia et al., 2010; Alston and Pardey, 2001; Alston et al., 2009; Pardey et al., 2006; Fuglie and Heisey, 2007).

A number of studies (Brennan and Quade, 2004; Heisey et al., 2002; Lantican et al., 2016; Lantican et al., 2005; Maredia et al., 2010; Pardey et al., 2006) have made efforts to estimate economic benefits from crop varietal improvement and attribute the benefits to the different institutions that were actively involved. This paper applies econometric methodology similar to that used by Maredia et al. (2010) and Pardey et al. (2006) to estimate benefits of the ARC Small Grains Institute (ARC-SGI) wheat varietal improvement research programme. We estimated vintage regression models to generate estimates of wheat yield gains from the release of new varieties. Using the estimates of the wheat yield gain from wheat varietal research and data on wheat production and producer prices, the aggregate benefits derived from investments in wheat varietal research in South Africa were estimated for the period 1978 – 2015. The approach applied estimated benefits credited to ARC-SGI wheat varietal research investments and other sources, as well as across different time periods.

Following earlier research on the economic impacts of wheat and other crop breeding research (such as Heisey et al., 2002; Lantican et al., 2016; Lantican et al., 2005; Maredia et al., 2010; Reyes et al., 2016), the process of estimating benefits arising from the wheat varietal improvement in South African agriculture involved the following: (a) estimating the size of investments in the development of new wheat varieties; (b) estimating the extent to which different varieties have been adopted by farmers; (c) estimating the yield gains achieved through the adoption of new varieties experienced by farmers; and (d) attributing the benefits to different sources of wheat varietal investments and to different time periods. The data and empirical estimations for each of the above steps are discussed in detail below.

The structure of the paper is as follows: The next section describes the data used for empirical estimations and the sources. Section 3 discusses investments in wheat varietal improvement research and use of new varieties. The estimations of economic benefits and potential yield gains derived from wheat varietal research is presented in Sections 4 to 6. The attribution and measurement of benefits by different sources and time periods are discussed in Sections 7 and 8. Section 9 presents the conclusion and recommendations of the paper.

2. Description of data and sources

The empirical analyses used secondary data from different sources and consultations with key informants at the ARC-SGI and Department of Agriculture, Fisheries and Forestry (DAFF). Data series on area planted to wheat, production, and yield were obtained from the DAFF's Crop Estimation Committee (CEC) and wheat prices were obtained from the South African Grain Information Service (SAGIS). The price data represents annual average producer prices of wheat per ton. Data of wheat varieties and other characteristics were collected from annual wheat reports of the former Wheat Control Board, agricultural statistics reports (gathered from Statistics South Africa and the National Library of South Africa) and the South African Grain Laboratory (SAGL). The information regarding the structure of the wheat varietal improvement sector was derived from a review of published articles and reports from the ARC-SGI, and from engagements with experts from the DAFF, ARC-SGI, CEC and SAGL.

The estimation of varietal adoption was based on estimating the areas planted to each ARC-SGI variety. Data on the proportion of each variety planted in each year in the national wheat crop was derived from wheat quality reports from the SAGL and wheat annual reports from the former Wheat Control Board. These sets of data were used to estimate areas planted to each variety, together with data from trends in area, production, and yield from the CEC. The three different time periods used in the analysis are: Pre-1991 (representing the period before establishment of the ARC-SGI – during this period it was still the Small Grains Centre); 1991-1996 (representing the period from establishment of the ARC) and deregulation of the wheat sector in Post-1996.

Information of pedigrees of varieties released during the study period were obtained from different sources including the CIMMYT wheat map website, the Farming in South Africa Journal and other published literature. Historical information on wheat varieties and the wheat-breeding programme in South Africa was gathered from the Farming in South Africa Journal. Data from these sources were obtained in hard copy format, as shown in Figure 1 below. We applied a rigorous process to capture the data from the old historical documents into spreadsheets that could be analysed. We visited the various organisation which had the hard copies of books, Farming in South Africa Journal and other articles on wheat. Photocopies, scanned copies and picture were taken. We went through the documents and captured all the relevant information on wheat into Microsoft excel. We developed a wheat master variety database that captured the breeding information of about 500 wheat varieties in South Africa.

The master variety database provided information on pedigrees of the selected wheat varieties that were used to determine the attribution of benefits from wheat varietal research from different sources.

varieties.

Wheat Varieties for the Winter-Rainfall Area.

For the Swartland, Koeberg, Stellenbosch and Caledon-Bredasdorp areas, *Sterling*, *Koalisie* and *Renown* are the obvious principal varieties. The last-mentioned two varieties may sometimes not produce the yields obtained from *Sterling*, but during years when rust is severe, the farmer need never fear a complete crop failure.

In the Swartland and Koeberg areas farmers may, if they prefer, also sow one or more of the following varieties, namely, *Farrartrou*, *Klipkous* and *Beltista*. In the Caledon-Bredasdorp area one or two of the following may be used as supplementary varieties, namely, *Regent*, *Spring Early*, *Caledon Knoppies* and *Izak Rust Knoppies*. The supplementary varieties should, however, always be subordinate to the first three varieties recommended.

For the south-western districts *Koalisie*, *Renown* and *Kenya Governor* are the most suitable varieties.

For the Breë River area, where wheat is sometimes sown in small quantities under irrigation and where rust is often severe, one of the following varieties may be chosen: *Koalisie*, *Renown* and *Klipkous*. If a late variety is preferred, either *Regent* or *Hope* may be sown.

Description of Varieties.

Sterling is a medium early variety, which stools well, grows vigorously, and has a reasonably strong straw. It has a dirty-white bearded ear, the glumes of which are covered with fine hairs. In some areas the ear sometimes has a blackish-brown appearance. The grain is large, red, with a wrinkled skin and does not readily shatter. It is fairly resistant to flag smut but susceptible to stem rust. If sown early, it is sometimes subject to *Septoria*. This variety has fairly good baking qualities and falls under Class A.

At present *Sterling* is by far the most popular wheat variety in the winter-rainfall area, accounting for 75 per cent. to 80 per cent. of the wheat grown in this locality. It owes its popularity to the fact that it is very well adapted to this locality, and produces good yields. Although *Sterling* has not been seriously damaged by stem rust during the past few seasons, its greatest defect is its susceptibility to this disease. According to reports received this year, this variety has been seriously damaged by rust in certain localities. Many farmers are therefore making a mistake in sowing *Sterling* exclu-

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Figure 1: Extracted page with wheat varietal information from the "Farming in South Africa Journal 1943"

The financial data on investments on wheat varietal improvement research by the ARC-SGI could not be obtained for the purposes of this research, and therefore no benefit cost analysis was possible.

3. Investments in wheat varietal improvement research and use of new varieties

The South African wheat seed industry consists of breeders and a developed private sector that multiplies and sells improved seeds to farmers. The main breeders of improved wheat varieties are Sensako, ARC-SGI and Pannar. Sensako has the largest proportion of seeds commercially grown in South Africa. The private companies develop wheat varieties for different growing regions of South Africa, and some of their seeds are also sold to neighbouring countries such as Lesotho and Swaziland. This also applies to ARC-SGI varieties, which are commercially sold in the market. In this case, both ARC-SGI-bred varieties "spill over" to other countries. Similarly, wheat varietal improvement research by the ARC-SGI benefits from collaboration with various institutions (public and private).

This paper gathered data on all wheat varieties released since the establishment of the ARC-SGI from all sources (ARC and other research centres). Table 1 summarises wheat varietal releases from 1976 to 2013. The data indicates that the private sector in South Africa is commanded by Sensako which dominates release of new wheat varieties in South Africa. However, the ARC-SGI has been central to wheat varietal releases in the country since the establishment of the Small Grains Centre in 1976 and has provided varietal releases, most of which were licensed to the private sector for multiplication. However, the contribution of the ARC-SGI has declined in line with declines in public funding since the deregulation of the wheat market in 1997.

Table 1: Summary of wheat varieties released by main breeding institutions

Institution	**Varieties**		**Percentage share of total from 1976 to 2013**	**Percentage share of total, 1996 to 2013**
	Total	**Average per year**		
Sensako	102	2.6	59	61.8
ARC-SGI	51	1.1	24.1	16.5
Pannar	41	0.74	16.9	21.8

Source: Author calculations based on wheat varietal improvement data gathered from various sources

Table 2 summarises the wheat varieties that were included in the multiple regression analyses. The selection was based on the commercial success of the varieties, as derived from the proportion of the variety in the national crop output for each year. The 82 varieties selected in Table 2 had a proportion of share in the national crop of at least 1%. The proportion represented by the varieties selected ranged from 92% to 99% of the national crop each year. About 48% of the selected varieties were grown under irrigation, while about 40% of the selected varieties were grown under dryland summer areas, and the remainder were produced under dryland winter conditions.

Table 2: Wheat varieties included in multiple regression analysis

Production type	Variety**	Breeder	Type of Breeder	Year of Release
Irrigation	Adam Tas	Sensako	Private	1989
	CRN826	Sensako	Private	2002
	Dias	Other	Other	1988
	Duzi	ARC-SGI	Public	2004
	Elize	CIMMYT	International Research	1975
	Elrina	ARC-SGI	Public	1976
	Gamtoos	ARC-SGI	Public	1985
	Helene	CIMMYT	International Research	1975
	Inia	CIMMYT	International Research	1970
	Kariega	ARC-SGI	Public	1993
	Krokodil	ARC-SGI	Public	2004
	Marico	ARC-SGI	Public	1992
	Nantes	Sensako	Private	1989
	Olifants	ARC-SGI	Public	2001
	Palmiet	ARC-SGI	Public	1984
	PAN3471	Pannar	Private	2008
	SST 2	Sensako	Private	1979
	SST 23	Sensako	Private	1981
	SST 25	Sensako	Private	1984
	SST 3	Sensako	Private	1973
	SST 44	Sensako	Private	1979
	SST 55	Sensako	Private	1992
	SST 57	Sensako	Private	1994
	SST 65	Sensako	Private	1995
	SST 66	Sensako	Private	1979
	SST 806	Sensako	Private	2000
	SST 822	Sensako	Private	1992
	SST 825	Sensako	Private	1992
	SST 835	Sensako	Private	2003
	SST 843	Sensako	Private	2008
	SST 86	Sensako	Private	1987
	SST 875	Sensako	Private	1997
	SST 876	Sensako	Private	1997
	SST 877	Sensako	Private	2009
	SST 884	Sensako	Private	2011
	SST 895	Sensako	Private	2010
	Steenbras	ARC-SGI	Public	1999
	T 4	ARC-SGI	Public	1965
	Zaragosa	CIMMYT	International Research	1978
Dryland (summer)	**Belinda**	ARC-SGI	Public	1970
	Betta	ARC-SGI	Public	1970
	Betta DN	ARC-SGI	Public	1992
	Caledon	ARC-SGI	Public	1996
	Carina (205)	Carnia	Private	1988
	Caritha (301)	Carnia	Private	1986

Production type	Variety**	Breeder	Type of Breeder	Year of Release
	Carol (310)	Carnia	Private	1987
	Elands	ARC-SGI	Public	1998
	Flamink	ARC-SGI	Public	1979
	Gariep	ARC-SGI	Public	1994
	Hugenoot	Sensako	Private	1987
	Karee	ARC-SGI	Public	1981
	Komati	Monsanto/ ARC-SGI	Public and Private	2002
	Limpopo	ARC-SGI	Public	1994
	Matlabas	ARC-SGI	Public	2003
	Molen	ARC-SGI	Public	1986
	Oom Charl	ARC-SGI	Private	1988
	PAN3211	Pannar	Private	1992
	PAN3235	Pannar	Private	1993
	PAN3349	Pannar	Private	1994
	PAN3377	Pannar	Private	1997
	PAN3408	Pannar	Private	2001
	Scheepers 69	ARC-SGI	Public	1969
	SST 101	Sensako	Private	1978
	SST 102	Sensako	Private	1978
	SST 107	Sensako	Private	1979
	SST 124	Sensako	Private	1981
	SST 356	Sensako	Private	2005
	SST 399	Sensako	Private	1992
	SST 94	Sensako	Private	1999
	SST 966	Sensako	Private	1996
	Tugela	ARC-SGI	Public	1985
	Tugela DN	ARC-SGI	Public	1992
Dryland (winter)	Gouritz	Other	Other	1978
	SST 015	Sensako	Private	2001
	SST 027	Sensako	Private	2002
	SST 047	Sensako	Private	2005
	SST 056	Sensako	Private	2005
	SST 087	Sensako	Private	2009
	SST 127	Sensako	Private	2013
	SST 16	Sensako	Private	1977
	SST 33	Sensako	Private	1979
	SST 88	Sensako	Private	1998

[a]ARC-SGI varieties are identified in bold letters

Every production year, wheat varieties are grown across the country, based on farmers' preferences and other factors that include access to the seeds, suitability to specific agro-climatological regions, and quality of grain yield. Varieties that have the most preferred characteristics have higher chances of being adopted by farmers. The amount of land area planted to each wheat variety determines the commercial success of the variety. However, no variety can be successful in all environments and at all times as some have specific areas where they are partially successful (Maredia et al., 2010).

The wheat varieties that were adopted by farmers and have been successful commercially, or partially successful, were selected for empirical analysis in this study. The selection criteria involved analysis of the shares of wheat varieties in the national crop. The shares of each wheat variety for each year were gathered from estimates from SAGL and the former Wheat Control Board (from the wheat quality reports). In addition to having a proportion of at least 1% in the national crop, a variety was only selected if it was represented in at least two years between 1978 and 2015. Based on technical expert advice from the ARC-SGI, the average wheat varietal research lag was assumed to be 8 years. This meant that wheat varieties released post-1986 were considered to be the benefits from investments in varietal improvement from 1978 onwards, which is the period of analysis for this study. Therefore, for the empirical analysis, varieties grown commercially for at least 2 years from 1985 to 2015 were included in the analysis. The year 1985 was selected as the base year – this is the last year before the release of new wheat varieties based on varietal improvement efforts invested in the post-1978 period. Based on these assumptions, the following varieties were dropped from the analysis, as they were grown prior to 1985 (Elrina, Gouritz, Helene, SST 101, SST 2 and SST 3).

Figure 2 presents a summary of shares for irrigation, summer dryland and winter dryland wheat production in South Africa. The results indicate that irrigation wheat production dominates shares of the national wheat crop in South Africa, while the share of dryland wheat has been declining over the years. On the other hand, shares of winter wheat show an increasing trend in recent years. Figure 3 presents the shares of main wheat breeders, based on area estimates from cultivar composition of production for the period 1978 to 2015. The results indicate that prior to the deregulation of the wheat industry in 1997, public contributions to wheat varietal improvement research played a major role in the wheat sector. The shares of breeders based on area estimates planted to wheat varieties indicate that publicly produced varieties dominated in terms of area estimates prior to 1997. Since the disbandment of the Wheat Control Board, the private sector (mainly Sensako) has dominated the shares of area planted by variety. The share of ARC-SGI varieties took a dramatic decline since deregulation of the wheat sub-sector in 1997, while the trend peaked slightly in the last 2000s and declined again in recent years to 2015. The market shares of each variety in the national crop were assumed to constitute a good proxy of the adoption rate of each variety. The age of a variety reflects wider adoption over long periods, and a short average age indicates that either the variety became popular recently or it is for a niche market. Wheat varieties developed by the ARC-SGI and other breeders are sold both in South Africa and other parts of the region.

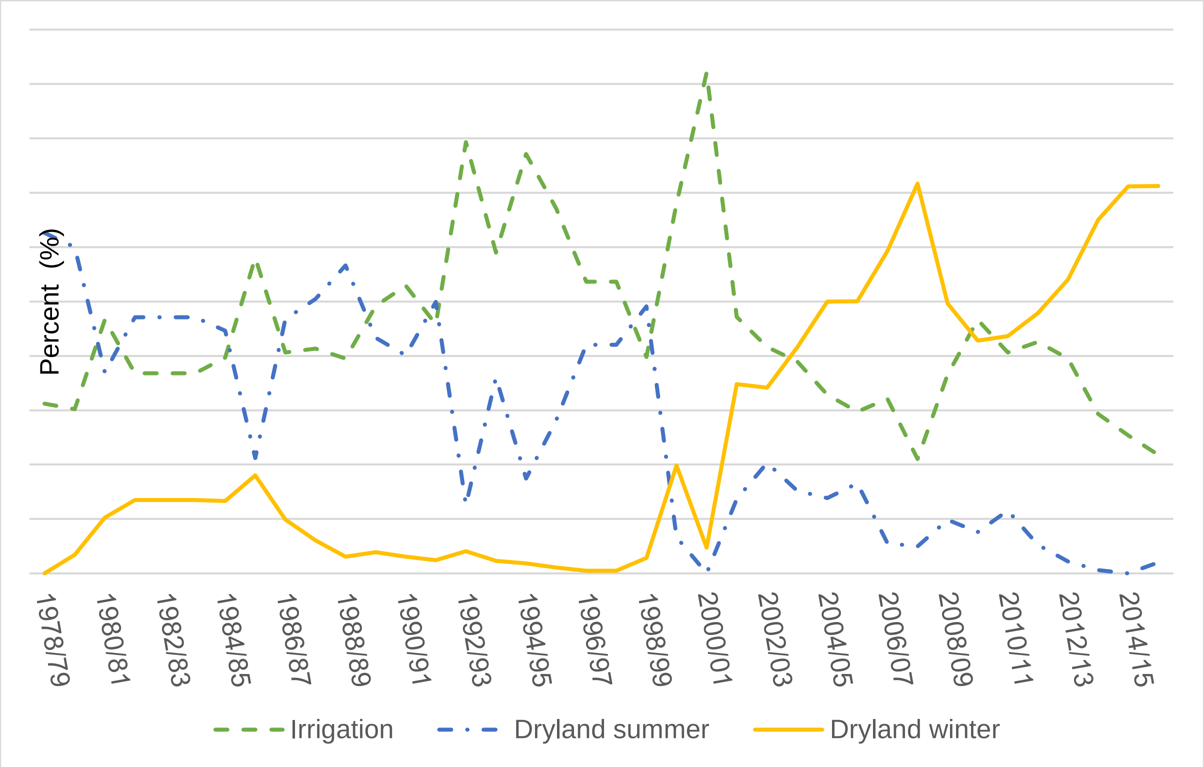

Figure 2: Share production area of wheat based on estimates from cultivation composition in national output

Source: Author calculations based on area by variety estimates from wheat reports by the former Wheat Control Board and South African Grain Laboratory

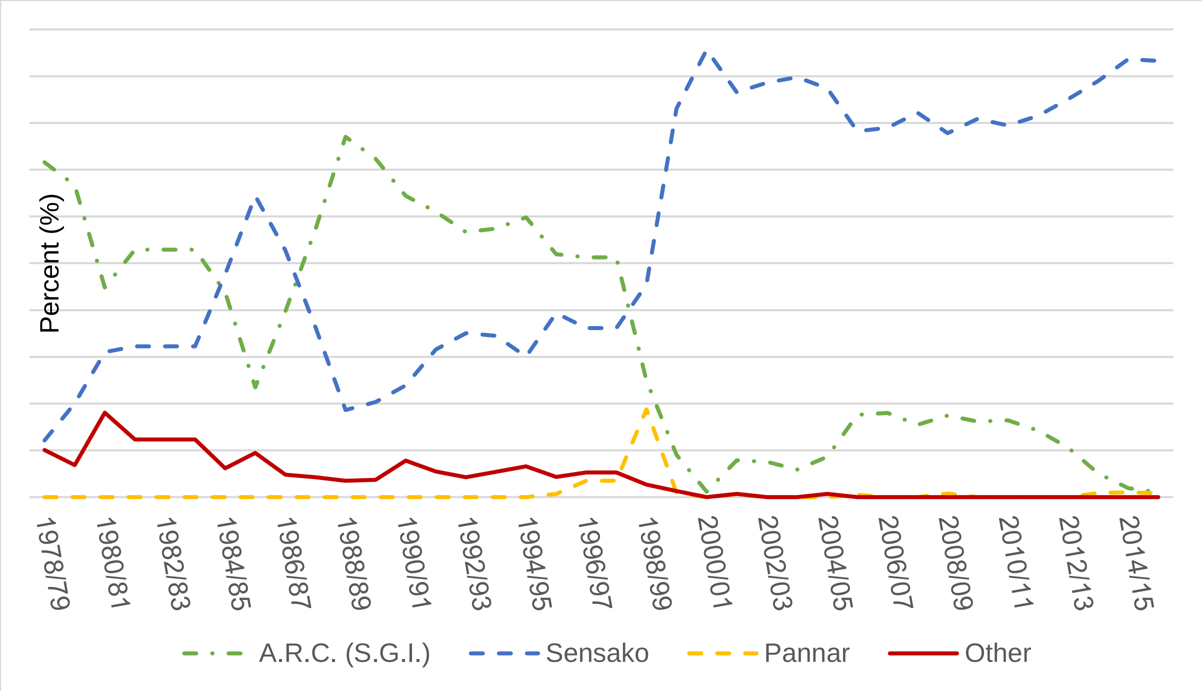

Figure 3: Summary of breeders' shares of wheat varieties based on area estimates from cultivar composition in national output

Source: Author calculations based on area by variety estimates from wheat reports by the former Wheat Control Board and South African Grain Laboratory

4. Estimating economic benefits of wheat varietal improvement research

The data on varieties released and estimated adoption rates referred to in the previous section provides the foundation for estimating the benefits of wheat breeding research in South Africa. Benefits from varietal improvement to farmers and society are derived from increases in crop yields, improved quality, cost reduction, etc. (Maredia et al., 2010). The Gross Annual Research Benefits (GARB) to ARC-SGI from wheat varietal improvement research are estimated using the following formula: $GARB = KPQ$; where K is the proportion of the crop output that is attributed to use/adoption of new varieties released from variety research efforts (or supply shift factor); P is the producer average price of wheat; Q represents the amount of wheat produced. The same approach developed by Griliches (1958) has been applied in many studies estimating benefits from crop varietal improvement research (such as Maredia et al., 2010, Pardey et al., 2006, Heisey et al., 2002, Lantican et al., 2016, Lantican et al., 2005, Reyes et al., 2016).

The estimation of total research benefits using this approach is based on the following assumptions: there is a linear and parallel shift in supply as a result of gains/losses from research; increase in supply does not affect the world market price; changes in wheat varieties in South Africa do not affect wheat production in other countries – no spillover effects. The limitations of the GARB measure include the point that it assumes a parallel reduced–induced supply shift; however, in reality, it is pivotal and the GARB estimate will overstate the benefits from research – this is, however, inevitable in the absence of information on national supply shift.

The supply shift factor, K, measures proportional gains in grain yield attained by farmers adopting new wheat varieties. The estimation of economic benefits of variety research requires the yield gain of the improved varieties to be calculated on all farms on which they are grown. Due to challenges in obtaining farm-specific estimates of yield gains, the practical approach is to estimate an index of crop varietal improvement research attributable to the development of new varieties and their adoption over time by using a scenario with research, and the counterfactual without research (Maredia et al., 2010; Reyes et al., 2016).

Following the approach applied by Pardey et al. (2006), Maredia et al. (2010) and Reyes et al. (2016), the K-factor is calculated using estimates of gains in grain yield based on observed/actual rates of adoption for the new varieties in each production year – the case "with-varietal research". The K-factor for the counterfactual scenario is calculated based on estimates of grain yield gains assuming that base-year conditions (varieties and weights for adoption rates) are kept constant over the analysis period. The other scenario is the counterfactual, which is based on yield gains. The "with" and "without" scenarios are used to estimate the proportional gain in grain yields that is attributable to wheat varietal research, K. The index of wheat varietal improvement is estimated as follows:

$$K_t = \frac{Y_t^a - Y_t^c}{Y_t^a} \tag{1}$$

where Y_t^a is the "observed area-weighted index of experimental yield" in South Africa in year t – indicating gains in yield from the adoption of improved varieties over time; Y_t^c is the "counterfactual" index for experimental yields in year t (based on base-year area weights) – indicating that the adoption of new varieties does not change during the period of analysis. The base year was calculated based on the assumption of 8 years research leg for wheat, implying that the benefits from release and growing of new wheat varieties generated from investments post-1978 were realised in 1986. Therefore, 1985 which is the preceding year was used as the base year for the analyses in this paper. The estimation of these yield indices is presented in the next section. The data were prepared in Microsoft Excel and empirical estimations were calculated using SAS University Edition (2016 version).

5. Estimating potential yield gain from wheat varietal improvement research

Experimental yields from the ARC-SGI wheat improvement research programme for the period 1985–2015 (based on the assumption of an 8-year research lag) were used to measure gains (rate of) in wheat yields for the varieties that succeeded commercially. The experimental trials for wheat varietal improvement were based on research efforts in different parts of the country where wheat is produced, particularly in the Free State and Western Cape. The experimental trials of the ARC-SGI reflect the wheat varieties that succeeded commercially and benefited from research efforts from other research programmes in South Africa and from other countries.

As with other research efforts that have applied the same methods to estimate benefits from variety research (Maredia et al., 2010; Pardey et al., 2006), the data from experimental trials had gaps since the varieties in the sample were not all included in variety trials each year for the entire period of analysis. Therefore, the process to estimate yield gains involved initially estimating the adjusted yield for individual varieties in the sample (Maredia et al., 2010; Pardey et al., 2006; Reyes et al., 2016). The least squares estimation of the adjusted yield gains for each variety i in a given time period (year) t from an experimental site located in area j is given by the following equation:

$$Y_{ijt} = a + \sum b_t D_t + \sum c_i D_i + \sum d_j D_j + \mu_t \qquad (2a)$$

where D_t represents time dummies; D_i represents variety dummies (for selected varieties in Table 2); D_j represents experimental site location dummies; μ_t represents the error terms; and the estimated parameters are represented by a, b, c, and d.

Equation (2a) presents an ideal scenario where the trials are consistently conducted in all locations across the entire time period and the same varieties are tested in all experimental sites. However, this is not possible in reality and a modification of Equation 2a (Maredia et al., 2010) is presented below:

$$Y_{it} = a + \sum b_t D_t + \sum c_i D_i + \mu_t \qquad (2b)$$

where Y_{it} represents the average yield of variety i for all experimental sites for each given year t.

The predicted yield $\hat{Y}_{it}$, based on results from Equation (2b), represents the adjusted average yield for each variety i, accounting for the estimate of the year effect. Since any particular variety included in the sample was not tested across the entire time period (including periods of high and low yields), the method compensates for this fact by adjusting the yield effect either upward or downward. To avoid the dummy trap, the regression analysis excluded the oldest variety in each model. The estimated coefficients in each model represent losses or gains in yield in comparison with the excluded variety. The varieties that were excluded are T4 (irrigation model), Scheepers 69 (dryland summer model) and SST 33 (dryland winter model). Table 3 summarises the descriptive statistics of estimated wheat yields based on the estimation of Equation (2b) using wheat experimental data for the period 1985–2015.

Table 3: Summary descriptive statistics of estimated wheat yields based on wheat experimental data, 1985–2015

Year of Release	Variety	N	Mean	Std Dev	Std Error	Lower 95% CL for Mean	Upper 95% CL for Mean	Minimum	Maximum
Irrigation wheat									
1989	**AdamTas**	4	6.45	0.97	0.48	4.91	7.99	5.58	7.77
2002	**CRN826**	10	6.69	0.84	0.26	6.09	7.28	5.25	8.02
1988	**Dias**	4	6.59	0.97	0.48	5.05	8.13	5.72	7.91
2004	**Duzi**	12	6.71	0.85	0.25	6.17	7.26	4.97	7.74
1975	**Elize**	7	4.94	1.07	0.40	3.95	5.92	3.81	6.94
1985	**Gamtoos**	10	6.09	0.45	0.14	5.76	6.41	5.23	6.64
1970	**Inia**	19	5.14	0.85	0.20	4.73	5.55	3.99	7.12
1993	**Kariega**	21	6.36	0.77	0.17	6.00	6.71	4.79	7.64
2004	**Krokodil**	11	7.13	0.69	0.21	6.67	7.59	5.96	8.00
1992	**Marico**	16	6.32	0.91	0.23	5.83	6.80	4.80	8.28
1989	**Nantes**	4	6.42	0.97	0.48	4.88	7.96	5.55	7.74
2001	**Olifants**	12	6.28	0.81	0.23	5.76	6.80	4.94	7.71
2008	**PAN3471**	8	7.45	0.96	0.34	6.65	8.26	5.50	8.27
1984	**Palmiet**	15	6.24	0.86	0.22	5.76	6.72	4.93	8.06
1984	**SST25**	7	5.17	0.63	0.24	4.59	5.74	4.32	6.23
1979	**SST44**	7	5.69	0.95	0.36	4.81	6.57	4.74	7.53
1992	**SST55**	6	6.47	0.86	0.35	5.57	7.36	5.82	8.14
1994	**SST57**	4	6.23	0.75	0.37	5.04	7.42	5.60	7.29
1995	**SST65**	2	5.97	0.16	0.12	4.50	7.43	5.85	6.08

Year of Release	Variety	N	Mean	Std Dev	Std Error	Lower 95% CL for Mean	Upper 95% CL for Mean	Minimum	Maximum
1979	**SST66**	11	5.84	0.84	0.25	5.28	6.41	4.68	7.81
2000	**SST806**	15	6.96	0.86	0.22	6.49	7.44	5.40	8.17
1992	**SST822**	20	6.35	0.79	0.18	5.98	6.72	4.77	7.62
1992	**SST825**	12	6.61	0.75	0.22	6.13	7.08	5.52	7.97
2003	**SST835**	12	7.16	0.85	0.25	6.62	7.71	5.42	8.19
2008	**SST843**	8	6.63	0.96	0.34	5.83	7.44	4.68	7.45
1987	**SST86**	9	6.16	0.76	0.25	5.58	6.75	5.38	7.91
1997	**SST875**	7	7.53	0.60	0.23	6.98	8.08	6.69	8.07
1997	**SST876**	17	6.89	0.85	0.21	6.46	7.33	5.31	8.16
2009	**SST877**	6	7.45	0.52	0.21	6.91	7.99	6.48	7.85
2011	**SST884**	5	7.99	0.22	0.10	7.72	8.27	7.68	8.20
2010	**SST895**	5	8.03	0.22	0.10	7.76	8.31	7.72	8.24
1999	**Steenbras**	11	6.00	0.73	0.22	5.51	6.49	4.93	7.30
1965	**T4**	14	6.21	0.89	0.24	5.70	6.72	4.87	8.00
1978	**Zaragosa**	9	6.94	0.93	0.31	6.22	7.66	5.83	8.96
Dryland summer wheat									
1970	**Belinda**	5	2.32	0.98	0.44	1.11	3.53	1.01	3.18
1970	**Betta**	12	2.08	0.74	0.21	1.60	2.55	0.96	3.13
1992	**BettaDN**	18	2.40	0.67	0.16	2.06	2.73	1.44	3.72
1996	**Caledon**	16	2.62	0.65	0.16	2.28	2.97	1.59	3.87
1988	**Carina205**	8	2.30	0.57	0.20	1.83	2.78	1.55	3.12
1986	**Caritha301**	11	2.33	0.66	0.20	1.88	2.77	1.44	3.31
1987	**Carol310**	11	2.51	0.66	0.20	2.06	2.95	1.62	3.49
1998	**Elands**	18	2.64	0.62	0.15	2.33	2.94	1.61	3.89
1979	**Flamink**	9	2.31	0.81	0.27	1.68	2.94	1.21	3.38
1994	**Gariep**	21	2.61	0.61	0.13	2.34	2.89	1.61	3.89
1987	**Hugenoot**	10	2.25	0.52	0.16	1.88	2.62	1.66	3.00
1981	**Karee**	12	2.05	0.74	0.21	1.58	2.53	0.94	3.11
2002	**Komati**	9	2.52	0.77	0.26	1.93	3.12	1.61	3.89
1994	**Limpopo**	16	2.46	0.66	0.17	2.11	2.82	1.47	3.75
2003	**Matlabas**	13	2.90	0.68	0.19	2.49	3.31	1.94	4.22
1986	**Molen**	13	2.46	0.65	0.18	2.07	2.85	1.54	3.41
1988	**OomCharl**	7	1.99	0.59	0.22	1.44	2.54	1.37	2.94
1992	**PAN3211**	8	2.33	0.62	0.22	1.81	2.85	1.39	3.07
1993	**PAN3235**	11	2.39	0.59	0.18	1.99	2.78	1.53	3.23
1994	**PAN3349**	13	2.58	0.70	0.19	2.16	3.00	1.55	3.83
1997	**PAN3377**	13	2.70	0.70	0.19	2.28	3.12	1.68	3.96
2001	**PAN3408**	6	3.46	0.43	0.18	3.01	3.92	3.03	4.09
1978	**SST102**	11	2.24	0.78	0.23	1.72	2.77	1.11	3.28
1979	**SST107**	5	2.37	0.97	0.44	1.16	3.58	1.06	3.23
1981	**SST124**	16	2.26	0.65	0.16	1.92	2.61	1.35	3.24
2005	**SST356**	9	2.79	0.50	0.17	2.41	3.17	2.21	3.58
1992	**SST399**	12	2.72	0.71	0.21	2.27	3.18	1.75	4.03

Year of Release	Variety	N	Mean	Std Dev	Std Error	Lower 95% CL for Mean	Upper 95% CL for Mean	Minimum	Maximum
1996	**SST966**	12	3.10	0.73	0.21	2.63	3.56	2.03	4.31
1969	**Scheepers69**	12	2.06	0.83	0.24	1.53	2.59	0.82	3.25
1985	**Tugela**	11	2.51	0.76	0.23	2.00	3.02	1.54	3.67
1992	**TugelaDN**	9	2.64	0.71	0.24	2.09	3.19	1.70	3.96
Dryland winter wheat									
2001	**SST015**	7	3.45	0.46	0.18	3.02	3.88	2.82	4.09
2002	**SST027**	7	3.47	0.46	0.18	3.04	3.90	2.84	4.11
2005	**SST047**	5	3.41	0.43	0.19	2.87	3.95	2.84	3.99
2005	**SST056**	6	3.53	0.48	0.20	3.02	4.03	2.95	4.22
2009	**SST087**	6	3.55	0.48	0.20	3.04	4.05	2.97	4.24
2013	**SST127**	2	3.44	0.59	0.42	-1.90	8.78	3.02	3.86
1979	**SST33**	5	2.31	1.49	0.66	0.46	4.15	1.06	4.67
1998	**SST88**	7	3.41	0.46	0.18	2.98	3.84	2.78	4.05

Source: Author calculations based on regression results from equation (2b)

Using Equation (2b), a simple vintage regression model was estimated, as presented below:

$$\ln(\hat{Y}_{it}) = a + \sum b_t D_t + gV_i + \mu_t \qquad (3)$$

where $\ln(\hat{Y}_{it})$ represents the natural logarithm of the predicted yield (from Equation 2b), and V_i represents the year of release for each variety i (this is the "vintage variable"). The log function specification of the predicted yield provides the estimate of "relative increase in yield" $[100d\ln(Y_{it})/dV_i) = 100g]$ which measures the yield gain per year, expressed as a percentage (Maredia et al., 2010).

Table 4 presents the results from the vintage multiple regression models estimated using fitted values from Equation (2b). The vintage model regresses the natural log of the predicted yield values (from Equation 2b) as a function of time dummy variables D_t and the year of release of each variable V_i (the vintage variable). The hypothesis that the dummy variables are all equal to zero $(D_1 = D_2 = \cdots = D_n = 0)$ was tested by including the time dummies from the long time period in the vintage regression models. The results of the F-ratio are statistically significant at a 1% significance level, indicating that there are significant variations in average wheat yields from year to year.

The result of the vintage variable V_i in each model gives the rate of yield gain per year released from varietal improvement research. The coefficients from the models are 0.008 for dryland summer, 0.005 for both irrigation and dryland winter models. The estimations from the vintage models indicate that the wheat yield gain per year from new wheat varieties was 0.8% for the dryland summer model and 0.5% for the irrigation and dryland winter models. The results are consistent with findings from other studies, such as that of Maredia et al. (2010) who estimated yield gains from bean research in Michigan, and Reyes et al. (2016) who estimated yield gain from bean research in five countries in Latin America.

Combining the results and estimations of yield presented in Table 3 above, the average estimated yield for dryland summer wheat was 2.48 tons/ha/year – this implies that the wheat yield gain per year from new varieties is equivalent to 19.84 kg per ha, per year. The estimated wheat yields per ha for the irrigation and dryland winter models were 6.44 tons/ha/year (irrigation) and 3.33 tons/ha/year (dryland winter). This means that the estimated yield gains are equivalent to 32.20 kg/ha/year and 16.65 kg/ha/year for irrigation and dryland winter wheat, respectively.

The results of the residual normality plots show that the data approximate a normal distribution for the estimation of linear regression equations. Overall, the test indicates a statistically significant model fit for all estimations based on the Analysis of Variance (ANOVA) F statistic, and the residual normality plots. The Variance Inflation Factors (VIF) were all less than 10, indicating that multicollinearity was not a problem in the vintage model estimations.

Table 4: Multiple regression analysis results of the vintage models using wheat experimental data, 1985–2015

Variable	Irrigation wheat model		Summer wheat model		Winter wheat model	
	Parameter Estimate	t Value	Parameter Estimate	t Value	Parameter Estimate	t Value
Intercept	-7,249***	-7,54	-15,281***	-12,46	-8,247***	-4,98
Released	**0,005*** **	**9,66**	**0,008*** **	**13,24**	**0,005*** **	**5,62**
d85	-0,363***	-11,12	-0,740***	-17,87		
d86	-0,302***	-9,24	0,316***	7,90		
d87	-0,185***	-5,85	0,399***	10,70		
d88	-0,186***	-5,49	0,331***	8,90		
d89	-0,252***	-7,94	-0,247***	-6,79	0,597***	19,52
d90	-0,133***	-4,41	-0,313***	-8,62		
d91	-0,044	-1,46	0,455***	8,06	0,112***	4,04
d92	0,133***	4,50	-0,177***	-4,95	-0,607***	-19,86
d93	-0,181***	-6,37	0,205***	5,78		
d94	-0,094***	-3,11	-0,467***	-13,21	-0,886***	-28,95
d95	-0,097***	-3,32	-0,221***	-6,45	-0,506***	-16,53
d96	-0,195***	-6,57	0,272***	8,02		
d97	-0,150***	-5,19	-0,113***	-3,33		
d98	0,067**	2,15	0,166***	4,90		
d99	0,072**	2,24	-0,129***	-3,77		
d00	-0,137***	-4,17	0,204***	5,85		
d01	-0,331***	-10,90	0,291***	8,25		
d02	-0,171***	-5,61	0,028	0,79		
d03	-0,251***	-8,50	-0,427***	-12,30		
d04	-0,261***	-9,44	-0,386***	-10,99		
d05	-0,113***	-3,86	-0,055	-1,56		
d06	-0,121***	-4,23	0,325***	9,29		
d07	-0,137***	-4,82	0,454***	12,94		
d08	-0,151***	-5,41	-0,173***	-4,95		
d09	-0,387***	-13,61	0,170***	4,80	0,234***	19,75
d10	-0,142***	-5,18	-0,126***	-3,56	0,030**	2,54
d11	0,032	1,23	0,115***	2,99	0,288***	19,34
d12	0,045*	1,71	0,288***	6,93	0,358***	30,23
d13	-0,018	-0,66	0,156***	3,53	0,133***	11,20
d14	0,040	1,37	-0,073*	-1,74	0,248***	21,81
n	**340**		**357**		**45**	
F - statistic (Pr > F)	**58.41 (0.0001)**		**240.70 (0.0001)**		**683.97 (0.0001)**	
Adjusted R^2	**0,84**		**0.95**		**0.99**	

*NB: ***, **, * Significance at 1%, 5% and 10% respectively*

Source: Author's estimation using vintage model Equation (4.3) and experimental data from 1985 to 2015

6. Estimating yield gains "with" and "without" research scenarios

Economic benefits from varietal improvement research are generated when farmers adopt new varieties. Factors that determine the type of new varieties that farmers adopt include their agricultural land characteristics, risk perspectives and differences in adoption lags. This means that the economic benefits generated by farmers growing newly released varieties vary from year to year, and might be less than the estimated gains in yield reflected in Table 4 above are. The average weighted mean for yield $\hat{Y}_t^a$ for $t = 1985 - 2015$ was estimated using the following formula to account for the effects of the above factors:

$$\hat{y}_{wt}^a = \sum_i (\ddot{Y}_{it} \alpha_{it}) \qquad (4)$$

where $\ddot{Y}_{it}$ represents the actual yields for each variety i for each experimental year t (Y_{it}), alternatively, $\ddot{Y}_{it}$ can be the estimated yields using Equation (2b) $(\hat{Y}_{it})$ (Maredia et al., 2010). Area shares for each variety i for each experimental year t are measured by α_{it}.

As there is no information available on actual areas grown to new wheat varieties (or on the rates of adoption of the new wheat varieties), the study used reported shares in the national crop as proxies of adoption rate α_{it} of each variety in farmers' fields in each corresponding year. The yield index $\hat{Y}_t^a$ is a measure of yields of actual farmer growing patterns (rate of adoption) of new wheat varieties.

The yield gains for the case "without" varietal improvement research, or the "counterfactual scenario", were estimated by using the same weights of adoption of new wheat varieties in the base year across the entire period of analysis. That is, the "counterfactual scenario" was represented by holding constant for the entire period of analysis the area shares of wheat varieties grown in the base year. In Equation (4), α_{it} was replaced by α_{ib} for $b = 1985$, which was the preceding year before the release and growing of new wheat varieties generated from investments post-1978. The estimated area weighted wheat yield gains $\hat{y}_t^b$, keeping the base year conditions constant in year t, is derived using the formula:

$$\hat{y}_{wt}^c = \sum_i (\ddot{Y}_{it} \alpha_{ib}) \qquad (5)$$

The estimated yield gains $\hat{y}_{wt}^a$ and $\hat{y}_{wt}^c$, using Equations (4) and (5) across all wheat production regions, give the gains in yield for the scenario "with varietal improvement research" ($\hat{y}_{wt}^a$ in

Equation 1) and the counterfactual scenario yield gains ($\hat{y}^{a}_{wt}$ in Equation 1) "without varietal improvement research". The proportional gain in experimental yields generated from wheat improvement research is given by:

$$k_{wt} = \frac{\hat{y}^{a}_{wt} - \hat{y}^{c}_{wt}}{\hat{y}^{a}_{wt}} \quad (6)$$

The actual yield index reflects farmers' decisions in changing the composition of varieties they grow from year to year to take advantage of improved varieties derived from improvement research programmes. Assuming area weights remain constant – that is, the variety mix does not change from year to year – the estimate of the "counterfactual yield index" $\hat{y}^{c}_{wt}$ is different from the actual yields index $\hat{y}^{a}_{wt}$ as a result of changes in "variety-specific yield response" to the environment and varietal mix planted over time (Maredia et al., 2010). Figure 4 presents changes in the "estimated proportional yield gains or losses" attributable to wheat varietal research.

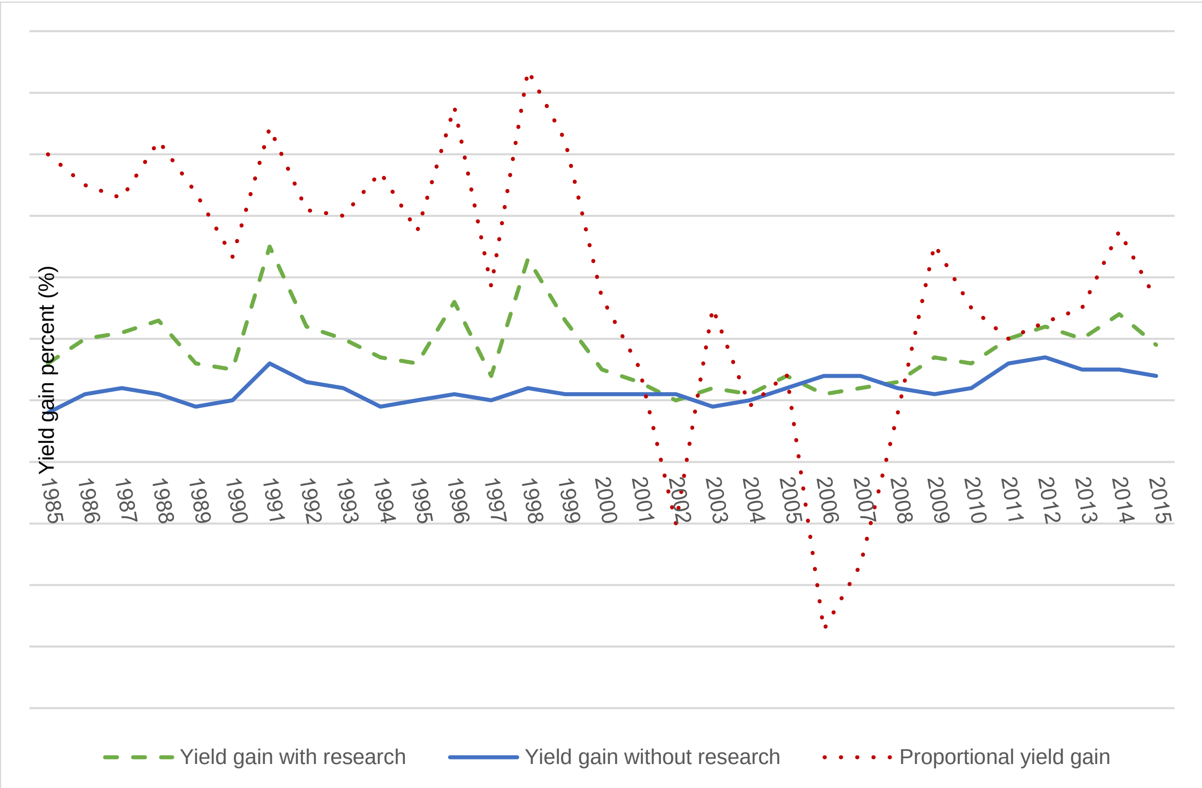

Figure 4: Wheat yield gain with and without research and proportional yield gain from wheat research, 1985–2015

The benefits in wheat production derived from varietal improvement for the period 1985–2015, assuming everything remains constant, were estimated using the formula:

$$B_t = k_t P_t Q_t \qquad (7)$$

The benefits from adopting improved varieties can be negative in years when the actual/observed yields were less than yields from the counterfactual scenario (Figure 4). Negative benefits that arise from adopting improved varieties might indicate that farmers preferred old varieties to new, improved ones. This could be driven by factors such as consistent performance of the variety and other yield qualities. In addition, climate-related events such as droughts contributed to the significant declines observed above, especially for the years 2002 and 2006. For example, South Africa experienced an El Niño event in 2002, with most parts of the country recording below-average normal rainfall (Reason and Phaladi, 2005). The Department of Agriculture, Forestry and Fisheries and the South African Weather Services further confirm that the period 2006 to 2007 received below-normal rainfall, with devastating impacts of agricultural activities (South Africa Weather Services, 2017, Department of Agriculture Forestry and Fisheries, 2006). The drought conditions affected wheat production in the main producing areas of the Free State and Western Cape, contributing to the observed trends shown above.

7. Attribution of benefits to ARC-SGI's wheat research improvement programme

This section focuses on estimating the benefits attributable to the wheat varietal improvement research programmes of the ARC-SGI for the period 1978–2015. The critical question that should be addressed in estimating the benefits of wheat varietal improvement research relates to what proportions of the benefits should be attributed to the efforts of the ARC-SGI and to those of other research institutions. An analysis of the pedigrees of each variety helps to illustrate the need for attributing benefits among different sources, and presents a practical and transparent way of addressing the attribution problem. The analysis of the pedigrees of the ARC-SGI varieties and those from other sources clearly indicated that the wheat varietal releases by the ARC-SGI draw upon the prior research of many other research institutions, such as universities, private research companies, international organisations, etc. Other research programmes also draw from germplasm developed by the ARC-SGI. It is therefore important to estimate the share of wheat varietal improvement benefits that is attributed to the efforts of the ARC-SGI, as compared with that of other institutions. Plant breeding, by its nature, is cumulative and crediting all the benefits for wheat varietal releases to the ARC-SGI would be inappropriate.

Based on the analysis of pedigree information for the selected varieties, every variety i that was released by an institution post-1985 contains some proportion E_i of benefits that were generated from ARC-SGI research efforts from post-1978 investments (formerly as SGC). Using the same approach as that used by Maredia et al. (2010) and Pardey et al. (2006), the benefits/credits to ARC-SGI research efforts post-1978 are estimated by applying the area share of each planted variety α_{it} and the benefits to ARC-SGI investments B_{it}^S, and are expressed as:

$$B_t^S = B_t \sum_i \alpha_{it} \tag{8}$$

where B_t measures the aggregate benefits from wheat varietal research in South Africa after 1978, estimated using Equation (7).

Therefore, for the selected varieties, the estimated credit weight E_i for every variety measures the amount of benefits attributed to ARC-SGI varietal improvement efforts, given the contributions of other private, public and international wheat breeding programmes. Different attribution methods are used in the literature to measure the benefits that are attributable to the research efforts of different institutions. For the purposes of this paper, following Maredia et al. (2010) and Pardey et al. (2006), two attribution rule methods (the last cross rule and geometric rule) were used to determine the weights E_i to apportion credit for wheat varietal research.

The last cross rule (rule 1): Based on this rule, the benefits from every variety i developed after 1978 (that is, released after 1985) are credited to the institution that released the variety. No credit is given to any of the parents of the variety. Therefore, a value of 1 is assigned in the base scenario analysis of the ARC-SGI wheat research programme for varieties released after 1985, and 0 for all others. The same applies to credit the research investments of other programmes (private sector, public sector) and to pre-1978 research efforts (by all institutions involved in wheat varietal improvement).

The geometric rule (rule 2): The geometric rule applies geometrically declining weights to variety improvement efforts generated from prior research for each variety. In this case, the institution that developed each variety is credited with 50% of the benefits, 1/8 is given to the institution that developed each of the parents, and 1/32 to the institution that developed each of the grandparents, etc. Therefore, at generation g, $\frac{1}{2}^{(2g+1)}$ of benefits for variety i are attributed to the institution that developed each ancestor. Overall, for the benefits attributed to the last generation G, where the attribution stops, the weight of benefits attributed to that generation is $\frac{1}{2}^{2g}$. Credit to prior research efforts was applied up to the level of grandparents. In this case, the institution that developed the variety is allocated 50% of the credit for each variety; 25% is equally shared between the institutions that developed each of the parents, and the remaining 25% is equally shared among the institutions that developed the four grandparents. Based on the geometric rule, attribution weights for benefits for varieties released by the ARC-SGI range between 0.5 and 1, and are determined by the ARC-SGI's contribution to each of the varieties, the parents, and/or grandparents. In the case of varieties developed by other institutions, the attribution weights range between 0 and 0.49, determined by the amount of ARC-SGI genetic material as parents and/or grandparents.

8. Measuring and attributing benefits of wheat varietal improvement research

Equation 7 was used to estimate the aggregate economic benefits generated from wheat variety research efforts in South Africa. The estimation used estimates of gains in wheat yields (Figure 4), annual wheat farmer prices in South Africa, and annual quantity of wheat produced in the country. The estimated aggregate economic benefits over the analysis period (1985–2015) amounted to R22.81 billion from all sources (Table 5)[1] – indicating an average of R0.76 billion per year. About R7.52 billion (33%) of the aggregate economic benefits from wheat variety research programmes in South Africa were generated from varieties developed in the pre-1985 period. The results highlight the long periods often realised to reap the benefits from crop variety research and improvement. Furthermore, R4.4 billion (30%) and R5.2 billion (37%) of

[1] The benefits estimated only cover benefits from yield gains from varietal improvement and exclude benefits from other sources, such as improved management practices and increased inputs. The benefits also exclude benefits of improvements in other characteristics, such as improved variety qualities, reduced yield variability, and maturity.

the aggregate benefits were attributed to wheat varieties released before (1986–1997) and after (1998–2015) the deregulation of the wheat sector, respectively.

Using the last cross rule, the analysis shows that R4.73 billion (33%) was attributed to the wheat variety research programmes of the ARC. This estimation also includes the wheat variety research programmes of the SGC, and partitioning these benefits indicates that R2.28 billion (16% of aggregate benefits or 48% of the benefits attributed to ARC-SGI) was attributed to the research efforts of the SGC. The benefits attributed to the wheat research programmes of the ARC-SGI amounted to R2.45 billion (17% of aggregate benefits or 52% of the benefits attributed to ARC).

Applying the geometric rule, the share of the benefits attributed to the wheat variety research programmes of the ARC-SGI, Sensako and Pannar (the main local wheat research breeding companies) decreased from R7.51 billion (33%); R11.4 billion (50%); and R1.67 billion (7%) to R4.90 billion (21%); R6.69 billion (29%); and R0.83 billion (4%) of the aggregate benefits, respectively. On the other hand, the benefits attributed to the efforts from CIMMYT and other sources increased from R0.83 billion (4%) and R1.39 billion (6%) to R2.99 billion (13%) and R7.39 billion (32%) of the aggregate benefits, respectively. This evidence indicates that local wheat research programmes have been relying on breeding efforts from CIMMYT and other sources. The results confirm that not accounting for attribution of benefits by source and time period will result in an overestimation of benefits to any specific research programme.

Comparing the attribution of benefits of the ARC-SGI and that of other local wheat breeding programmes indicates that the ARC-SGI remains an important source of successful wheat varieties in the country. The benefits attributed to the ARC-SGI were second to those of Sensako (the main private actor in wheat breeding research). Analysing the benefits among different time periods indicates that the benefits attributable to the ARC-SGI decreased after deregulation, while the benefits attributable to Sensako increased. The results highlight the impact of the drop in public funding for wheat variety improvement research after deregulation. Given the importance of wheat as a main cereal crop (second after maize) in South Africa, public funding for variety improvement remains critical for the country. The wide coverage of the ARC-SGI's wheat research programme across the country remains an important asset, which requires public funding to enable the institution to continue to support wheat variety improvement efforts for the country.

Table 5: Estimated wheat varietal research benefits and attribution to different institutional sources and time periods

Attribution of benefits based on periods varieties were released	ARC-SGI[1]	Sensako	Pannar	CIMMYT	Other[2]	Total
Last Cross Rule: R Billion						
Pre 1986	3.06	3.34		0,83	0,28	7.51
1986-1991	0.56	1.11			0,83	2.50
1992-1997[3]	1.95	2.50	1.11		0,28	5.84
1998-2015[4]	1.95	4.45	0.56			6.95
1985 – 2015	**R 7.51 billion**	**R 11.40 billion**	**R 1.67 billion**	**R 0,83 billion**	**1.39 billion**	**22.81 billion**
Geometric Rule: R Billion						
Pre 1986[2]	1.74	1.88		1.77	2.12	7.51
1986-1991[3]	0.57	0.73		0.17	1.03	2.50
1992-1997[4]	1.39	1.60	0.56	0.33	1.89	5.77
1998-2015[5]	1.20	2.49	0.28	0.71	2.35	7.02
1985 – 2015	**R 4.90 billion**	**R 6.69 billion**	**R 0.83 billion**	**R 2.99 billion**	**R 7.39 billion**	**R 22.81 billion**

[1]Benefits in the pre-1986 and 1986-1991 periods attributed to ARC were from varieties released by the Small Grains Centre

[2]This represents benefits to other sources such as international public research, and others not indicated in the share of national crop database collected by the author.

[3]Represents the period when the ARC was established and operated before deregulation of the wheat sector.

[4]Period after deregulation of the wheat sector.

9. Conclusion and policy recommendations

The main objective of this paper was to estimate the economic benefits that are attributable to the ARC-SGI's wheat varietal improvement research programme and research efforts over different timeframes. The empirical analyses used data on market shares of wheat varieties planted by farmers (used a measure of the adoption rate of the varieties) and estimates of their proportional yield gains; annual wheat-farmer prices in South Africa; and the annual quantity of wheat produced across different wheat production areas in South Africa (summer dryland, dryland winter, and irrigation). A vintage regression model was used to estimate the proportional yield gains from wheat varietal improvements in South Africa. The results indicated that the rate of gain in yield as a result of releases of new wheat varieties (variety research) was 0.8% per year (equivalent to 19.84 kg/ha/year) for dryland summer varieties and 0.5% for both irrigation (equivalent to 32.20 kg/ha/year) and dryland winter varieties (equivalent to 16.65 kg/ha/year). The estimated aggregate economic benefits that were achieved over the analysis period (1985–2015) amounted to R14.4 billion from all sources, at an average of R0.5 billion per year. About R4.73 billion (33%) of the aggregate economic benefits derived from wheat variety research programmes in South Africa were obtained from varieties developed in the pre-1985 period.

The results of the geometric attribution rule show that the total benefits attributed to ARC-SGI, Sensako and Pannar decreased, while that of CIMMYT and other sources increased when the geometric attribution rule is applied. This evidence indicates that local wheat research programmes have been relying on the breeding efforts emanating from CIMMYT and other sources. The results further show that not accounting for attribution of benefits by source and time period will result in an overestimation of benefits attributable to any specific research programme.

The results of the analysis of trends of sources of wheat varieties, by institution, in South Africa indicate that the share of ARC-SGI wheat varietal improvement dramatically decreased after deregulation, post-1997. The results highlight the impact of the drop in public funding for wheat variety improvement research after deregulation. Given the importance of wheat as a main cereal crop (second after maize) in South Africa, public funding for variety improvement remains critical for the country. The wide coverage of the ARC-SGI's wheat research programme across the country remains an important asset, which requires public funding to enable the institution to continue to support wheat variety improvement efforts for the country.

On the other hand, the share of the private sector significantly increased after the deregulation of the wheat sub-sector. The private sector has more resources for multiplying wheat varieties than the public sector (ARC-SGI) has, and this means that the private sector is in a more advantageous position to multiply and market their varieties, as compared with ARC-SGI varieties, although there might be some partnerships in this regard. There is a need for more beneficial arrangements to be made in any such private–public partnerships for the development and multiplication of wheat varieties by the ARC-SGI, so as to ensure that their varieties are not overshadowed by varieties from the private sector. In addition, and despite the progress in developing improved seed varieties, the public sector needs to aggressively market its research outputs to farmers, including even cutting, if it is to increase its opportunities of becoming commercially successful. However, to implement this recommendation, issues regarding "mandate, and comparative advantage to engage in aggressive marketing" of own varieties should be considered for public-sector research institutions (Maredia et al., 2010) such as the ARC-SGI.

In elaboration of the above recommendations, it should be noted that a public crop varietal improvement research programme such as that of the ARC-SGI does generate broader benefits that are not captured in the estimated economic benefits in the current study. For example, other benefits generated include the training of future plant breeders in collaboration with universities in the country, maintaining or conserving important genetic materials for wheat, and generating varieties that integrate specific public-good traits such as disease resistance, environmental suitability, and nutritional characteristics. Since there are no proximate economic values that are immediately derivable from these types of research, private-sector plant breeding institutions will not invest socially optimal resources to provide these services. This means that the contributions from public research described above could be completely lost if public investments in wheat varietal improvements are no longer provided, with consequent huge socio-economic costs to the economy.

Despite these important findings and the support recommended for public-funded crop breeding programmes, the stark reality is that the ARC is unlikely to regain its status as a prominent contributor to South Africa's new wheat varieties. This is largely due to the declining parliamentary grant to the ARC, poor maintenance of research infrastructure, and a large exodus of qualified and experienced breeders from the public research system. Add to this the dominance of international originations, as well as large global agribusiness such as Monsanto, it is probably unlikely that results similar to the present value of public crop breeding programmes will be seen in 10 years' time.

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