Agriculture production's sensitivity to changes in climate in South Africa

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Agriculture production's sensitivity to changes in climate in South Africa

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South Africa in general has been approximately 2% hotter and at least 6% drier over the ten years between 1997 and 2006 compared to the 1970s. The use of water has also increased greatly over this same period. By 2000, 98.6% of that year's surface water yield and 41% of the annual utilisable potential of groundwater was allocated to use. Irrigation agriculture, comprising 60% of total consumption, is by far the largest single consumer of water. Given these climatic and water use changes as a backdrop, we employed a panel data econometric model to estimate how sensitive the nation's agriculture may be to changes in rainfall. Net agricultural income in the provinces, contributing 10% or more to total production of both field crops and horticulture, is likely to be negatively affected by a decline in rainfall, especially rain-fed agriculture. For the country as a whole, each 1% decline in rainfall is likely to lead to a 1.1% decline in the production of maize (a summer grain) and a 0.5% decline in winter wheat. These results are discussed with respect to both established and emerging farmers, and the type of agriculture that should be favoured or phased out in different parts of the country, in view of current and projected trends in climate, increasing water use, and declining water availability.

Key words: agriculture production, rainfall, drought, climate change, water scarcity

Introduction

This study focused on the impact of changes in climatic conditions on agriculture: it is motivated by the fact that agriculture is the mainstay of rural economies in South Africa, and indeed throughout much of Africa. Agriculture's importance cannot be overemphasised from a food security perspective, or from its vital role in assisting the country to enhance and maintain political stability through successful land reform. Understanding changes in agriculture already taking place, or likely to take place in the near future, in response to climate change is therefore of utmost importance.

To map the historic changes in rainfall and temperature with changes in agriculture production in South Africa we were constrained to using existing provincial data, rather than biome-level data, which would have been preferable, but were unavailable. In addition, we had to limit ourselves to the period for which relevant data were available, i.e. from 1970 onwards. This of course affects the predictive powers of the models. Notwithstanding these limitations, some valuable insights were gained as to the relationships, and the challenges ahead, concerning the links between climate and agriculture.

We first consider recent changes in climatic conditions in South Africa's nine provinces, and then discuss the use of water based on a panel data econometric analysis of the relationship between rainfall and various components of agricultural production. We conclude with an assessment of the impact of rainfall specifically on field crops, as they are most likely to be adversely affected by sudden or gradual changes in climatic conditions.

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Changes in climatic conditions

It is widely assumed that ongoing changes in climatic conditions will have an adverse effect on agricultural production in Africa.[1–3] While the impact of climate change is felt by farmers predominantly through changes in the timing, frequency and intensity of rainfall events, and in the distribution of these events within a season of growth, most macroeconomic and agricultural production data are only available as annual averages. Yet annual numbers and averages for level of, or changes in, temperature and rainfall do not provide an adequate indication of the impact of such variations from the mean on a specific farm. Given this limitation, it should be noted that this study was not an investigation into climate change *per se,* even though we did analyse and discuss the data used in determining the impact of changes in climate on agriculture. A further limiting factor is that, when dealing with annual numbers, one is strictly speaking not dealing with drought as defined by McKee,[4] who indicated that a drought occurs when the Standardised Precipitation Index over 12 months is continuously negative and reaches a value of –1 or less. We therefore did not consider the impact of individual drought events on agriculture, but rather the gradual drying trend on agricultural production as a whole. Our aim was to analyse the available data to examine whether changes in the variance from the mean for rainfall and temperature had indeed occurred.

Materials and methods

To address the broad-scale impact of climate change on agriculture, we considered rainfall and temperature data from 1970 to the present for South Africa's nine provinces. For rainfall (in mm), the annual sum of the provincial monthly average was used (Appendix 1 online). The data received were, in all cases, provided in a ready-to-use format and were not manipulated in any way. The temperature data (Appendix 2 online) consist of the annual averages of the daily maximum temperatures, in either two or three towns or cities per province. In general, daily minimum temperatures are considered a better indicator of climate change *per se,* but here we use daily maximum temperatures since it is these changes that are likely to have an impact on agriculture production in South Africa. The data received consisted of monthly averages of the daily maxima and, from these, we computed the annual averages.

First, the nine provinces of South Africa were clustered together in four broad climatic areas in terms of their average rainfall and temperature data (Table 1). Thereafter, we calculated the changes in the average rainfall and temperature, and the changes in the variance from the mean and the covariance (Table 2). This summary contains the results for the nine provinces for the periods 1970–1979 and 1997–2006, as well as 1970–1989 and 1990–2006. The data set was split into these four separate time periods to ascertain whether there are distinct differences between

Table 1. Clustering of South Africa's nine provinces based on temperature and rainfall data, with percentage changes between 1970–1979 and 1997–2006 (source: own analysis of data from Appendices 1 and 2).

Mean annual rainfall by region		Mean annual temperature by region		Final clustering	% Change in rainfall	% Change in temperature
<550 mm	Northern Cape	>25°C	Limpopo	**Hot and arid**		
	North West		North West	Northern Cape	–21.4%	1.7%
			Northern Cape	North West	–11.3%	2.3%
550–700 mm	Western Cape	24.5–25°C	Western Cape	**Hot and semi-arid**		
	Free State		Free State	Limpopo	–1.4%	3.8%
	Limpopo		Mpumalanga			
	Eastern Cape			**Temperate & semi-arid**		
				Western Cape	0.3%	1.5%
>700 mm	Gauteng	<24.5°C	KwaZulu-Natal	Free State	–3.5%	1.7%
	Mpumalanga		Gauteng	Mpumalanga	–5.7%	–2.1%
	KwaZulu-Natal		Eastern Cape			
				Temperate & non-arid		
				Gauteng	–7.1%	4.0%
				Eastern Cape	–4.8%	2.8%
				KwaZulu-Natal	–5.8%	2.1%
				South Africa	**–6.0%**	**2%**

the levels of rainfall and temperature among the various periods, and how weather patterns may have changed.

Results

Temperature

Several observations can be made from the results displayed in Tables 1 and 2. With the exception of a temperature decline at Mpumalanga, all the other areas showed a considerable increase—in places as much as 4%. For South Africa as a whole, the last 10 years have been on average 0.5°C—or 2%—hotter than the 1970s. The variance increased during the same period, implying that changes in temperature became less predictable, but were consistently higher in absolute terms and increased steadily over the entire period studied.

Rainfall

All but one of the nine provinces received progressively less rainfall since 1970. The exception was the Western Cape, which, on average, received consistent annual rainfall over the entire study period (Table 1). The Northern Cape and the North West provinces have in general been the most affected, both in terms of percentage change (Table 1) and absolute change (Table 2). South Africa as a whole received on average 40 mm less rain per annum over the last 10 years than during the 1970s, which means 6% less average rainfall. However, the deviation from the mean for all the hot and arid areas was less during the last ten years than during the 1970s. The variance from the mean has increased for other less arid areas, indicating increasing unpredictability and occurrence of extreme events.

In sum, South Africa has been hotter during the last 10 years compared to the first 10 years of the study period, and with more variation from the mean. Additionally, average annual rainfall was less during the last decade than during the 1970s. The variance around these lower rainfall numbers is declining for the two westernmost provinces, implying more predictability at low and declining levels of rainfall for the hottest, most arid regions. Variance, however, is increasing for the other areas, implying increasing unpredictability.

Covariance of rainfall and temperature

The relationship between rainfall and temperature was analysed using ANOVA for the individual provinces of South Africa, yielding the results shown in Table 2 and Fig. 1. For both periods studied and for all areas, the covariance of rainfall and temperature was very significantly negative ($P < 0.001$) for most provinces. Indeed, with the exception of the arid areas, the covariance observed between temperature and rainfall has actually become stronger over the last decade: the hotter it gets, the less rainfall there is in all regions. Should the evidence produced here signal a lasting trend, then the prevailing adverse climatic conditions are likely to persist and possibly deteriorate further. In the next section we will consider how changing climate, especially reduction in rainfall, may affect agriculture.

Water use in agriculture in South Africa

Given that South Africa, overall, is getting hotter and drier, the question is, how big is the buffer? How much surplus water does South Africa have, who is using it, and can the trend be changed in view of the declining supply? The South African Department of Water Affairs and Forestry[5] estimates that in 2000 South Africa had a total reliable surface water supply of 13 226 million m^3. In the same year, the nation used 13 041 million m^3, leaving a surplus of only 186 million m^3, or 1.4% of the supply (at 98% assurance of supply) for that year. Additionally, 12 of the country's 19 water catchments reported water deficits, which were only partially offset by an intricate system of inter-basin water transfer schemes. These statistics are supported by the water resource accounts, produced by Statistics South Africa.[6] In theory, as the remaining annual supply of a vital natural resource approaches zero—crossing clearly identifiable thresholds of scarcity—the marginal value of that resource approaches infinity.[7] This implies that the economic value of the last 1.4% of unutilised water resource is very high, far exceeding that of the prevailing bulk water tariff. Matters are complicated by the fact that, as water supply is annually recharged through precipitation, it does not imply that only 1.4% is available into perpetuity, but rather that for the year 2000, specifically, only 1.4% of the water supply was unallocated or not used. This implies that should the water demand grow by more than 1.4%, the only way to accommodate such growth is by reducing water use in some of the currently water-intensive sectors, which in turn implies that some tough decisions have to be made.

Moreover, the meagre water reserve mentioned above includes the water imported from neighbouring Lesotho. Unutilised domestic sources of water are limited to two river catchments in

Table 2. Changes in climatic conditions, as indicated by changes in temperature and rainfall, for South Africa's nine provinces: 1970–2006 (source: own analysis of data from Appendices 1 and 2).

	Temperature				Rainfall: changes in mm				CoVAR 1st period	CoVAR 2nd period	CoVAR Dif
	Difference between 1970–1979 & 1997–2006		Difference between 1970–1989 & 1990–2006		Difference between 1970–1979 & 1997–2006		Difference between 1970–1989 & 1990–2006				
	Average change in °C	VAR	Average change in °C	VAR	Average change in mm	VAR	Average change in mm	VAR			
Hot and arid											
Northern Cape	0.43	−0.14	0.11	0.05	−67.4	−12357	−35.8	−7159	−34.35	−11.33	23.02
North West	0.59	0.17	0.30	0.00	−70.7	−2767	−34.9	−3308	−79.68	−67.45	12.23
Hot and semi-arid											
Limpopo	1.01	0.30	0.83	0.18	−9.3	52021	−4.9	37254	−43.33	−113.67	−70.34
Temperate & semi-arid											
Western Cape	0.37	−0.05	0.07	0.11	1.7	−9118	0.9	−4583	−6.10	−18.69	−12.59
Free State	0.42	0.49	0.26	0.29	−21.3	3477	−22.7	3092	−58.21	−86.34	−28.13
Mpumalanga	−0.52	−0.02	−0.37	0.24	−49.3	28267	−39.3	23343	−23.56	−68.69	−45.13
Temperate & non-arid											
Gauteng	0.93	0.10	0.58	0.02	−53.2	17011	−3.9	13916	−34.20	−76.18	−41.98
Eastern Cape	0.65	0.17	0.38	0.09	−32.4	2856	−24.2	−1165	−12.53	−26.98	−14.44
KwaZulu-Natal	0.51	0.14	0.28	0.17	−56.3	9799	−73.3	2893	−9.80	−56.88	−47.08
Total South Africa	**0.49**	**0.08**	**0.27**	**0.07**	**−39.8**	**5758**	**−26.5**	**6951**	**−22.82**	**−47.33**	**−24.51**

the ecologically-sensitive and relatively undeveloped Eastern Cape province. Water-supply constraints are therefore an issue with unparalleled economic development implications. Further supply options are limited, but include further water importation from Lesotho, and, additionally from the distant Congo River, and/or desalination of seawater. All three of these options are costly and capital intensive and their implementation would have a significant effect on water tariffs with the result of making drinking water less accessible to those who are most in need. In other words, only 1.4% of South Africa's water yield is currently available to address the demands of the poor, most of whom who do not have any access to potable piped water currently. But has the market reacted to these changes? Have water use extraction and allocation trends already changed?

Surface water use

Irrigation agriculture is by far the largest single surface water user, consuming 60%, with agriculture in general consuming 65% of total available water.[6] Use of surface water for irrigation has also increased steadily from 7630 million m^3 in 1995 to 7921 million m^3 in 2000, an increase of 291 million m^3, or 4%. This use represents 160% of the total water surplus remaining at the end of 2000. The official water use for 2005 has not yet been released, but if the volume of water used for irrigation increased by the same margin, without any compensatory reduction in water use by other sectors having taken place, there must have been a deficit for the country as a whole. Furthermore, the total increase in water consumption for all sectors from 1995 to 2000 was 348 million m^3, which implies that irrigated farming's share of the increase was 84%.

Groundwater use

Surface water use is increasing rapidly, with no signs of a decline in use in any sector. Use of groundwater is increasing rapidly as well.[8,9] Vegter[8] estimates that by 1999 there were approximately 1.1 million water boreholes in the country, compared to only 225 000 recorded on the National Groundwater Database. From drilling data and agricultural records, Vegter[8] calculates that the groundwater use in 1999 was about 3360 million m^3 per year and is increasing at, on average, approximately 3.4% per year. The estimated use at the end of 2001 was approximately 3850 million m^3, or 49% of the surface water usage. The exploitable groundwater usage for 2000 is estimated[6] at 9500 million m^3, which implies that groundwater usage at that stage was about 41% of the potential. This allows room for some further development, but clearly the surplus is dwindling fast. In fact, water abstraction of both surface and groundwater has increased so quickly in recent years, being used primarily to drive the development of agriculture, mainly in the horticulture and animal production sectors.

Water: The limiting factor

Water is therefore one of the main, if not the, limiting resource upon which intelligent, sustainable economic investments should be concentrated.[10–13] Water use, given the supply constraints, cannot continue to grow at current rates. This situation is exacerbated by the likely decline in the water availability due to changes in climatic conditions, and socio-economic and demographic pressure to increase the use of potable water for domestic use and to allocate water to higher value added industries. Another complicating factor is the plausible introduction of a wide-scale biofuel programme and its plausible impact on future water demand.

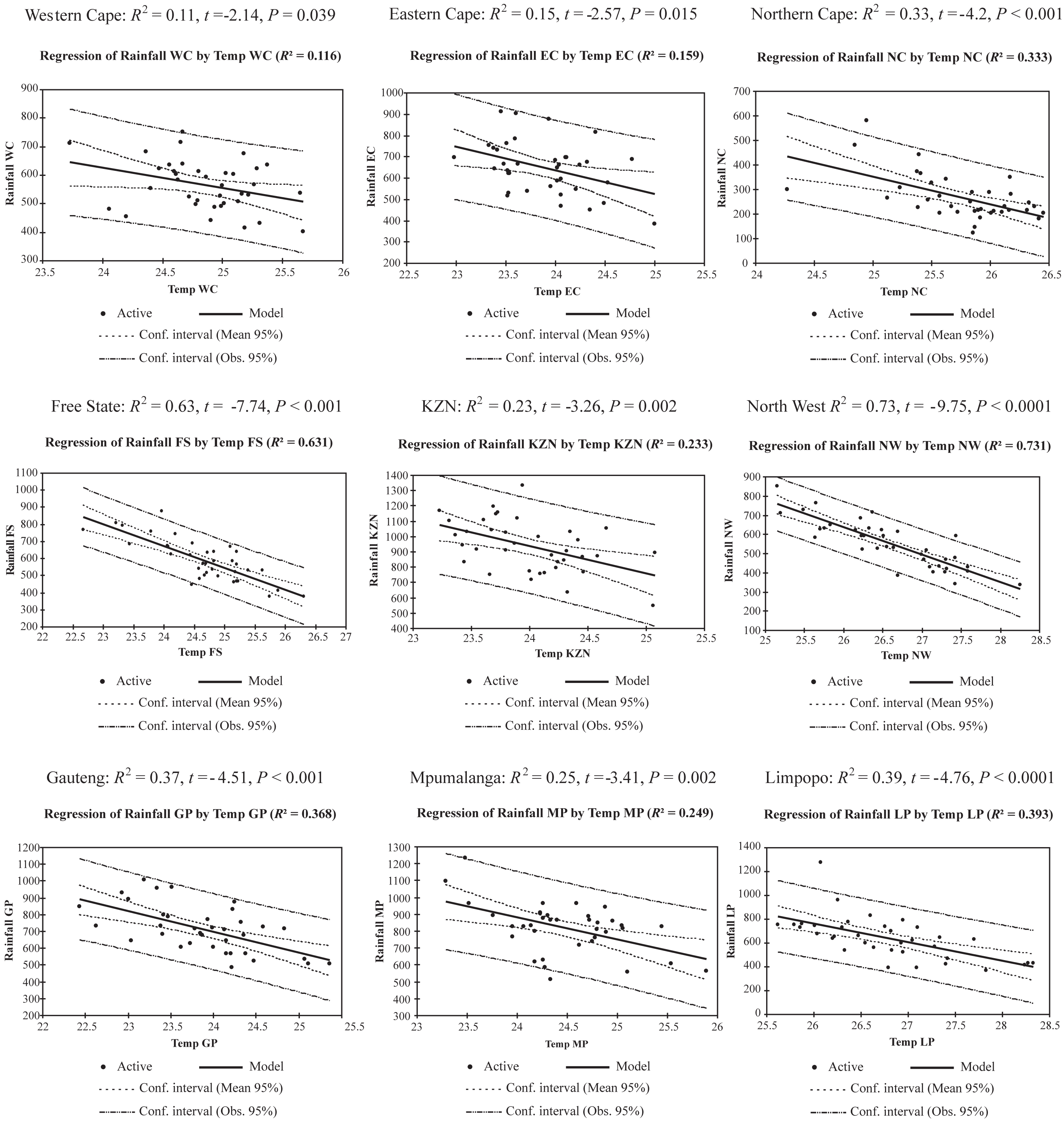

Fig. 1. The statistically-significant relationship between rainfall (mm) and temperature (°C) in South Africa from 1970 to 2006 (source: own analysis of data from Appendices 1 and 2 in online supplement).

Quantifying rainfall's contribution to agriculture

Model

We developed a Seemingly Unrelated Regression (SUR) model (Appendix 3 online), using a three-dimensional panel data set, to quantify the contribution of rainfall to agriculture. Hsiao[14] defines a panel data set as one that follows a given sample of individuals—provinces in this case—over time, and thus provides multiple observations on each individual in the sample. Here the dimensions are time, geographic area (nine provinces), and a series of variables. From a modelling perspective, panel data is therefore very powerful, as it combines regular time-series and cross-sectional regressions, and has numerous other advantages.[14–16]

Data

We gathered data for each province over the period 1970–2006, for gross income from agriculture (subdivided into three sectors: field crops, horticulture, and animal production), expenditure on intermediate goods and services, labour and other expenditures, net income, and contribution to GDP. It was not possible to allocate the cost items to specific agricultural sectors since no method to do so exists. To estimate provincial shares, we used data from unpublished sources, mostly from the archives

Table 3. Results of the SUR model for field crops, horticulture, and animal production

	Field crops			Horticulture			Animal production		
	Coeff.	s.d.	% Contrib. to SA prod. 2006	Coeff.	s.d.	%Contrib. to SA prod. 2006	Coeff.	s.d.	% Contrib. to SA prod. 2006
Input	–0.263***	(0.055)		–0.451***	(0.053)		–0.212***	(0.039)	
Wages	–0.304***	(0.053)		–0.322***	(0.060)		–0.542***	(0.036)	
Contribution to GDP	0.391***	(0.021)		0.175***	(0.034)		0.252***	(0.018)	
Productivity	0.215***	(0.015)		0.120***	(0.013)		0.267***	(0.007)	
Temperature	–0.054*	(0.030)		–0.012	(0.045)		–0.064**	(0.023)	
Rain – Western Cape	–0.024***	(0.022)	8%	0.043***	(0.041)	42% (x)	–0.006***	(0.015)	17% (x)
Rain – Eastern Cape	–0.045***	(0.037)	1%	0.021***	(0.052)	6%	0.019***	(0.025)	10% (x)
Rain – Northern Cape	–0.007***	(0.023)	6%	–0.002	(0.047)	7%	0.006***	(0.023)	7%
Rain – Free State	0.031***	(0.031)	31% (x)	–0.039***	(0.055)	4%	–0.007***	(0.021)	15% (x)
Rain – KwaZulu-Natal	0.017***	(0.034)	17% (x)	–0.032***	(0.059)	4%	–0.008**	(0.025)	13% (x)
Rain – North West	0.028***	(0.027)	15% (x)	–0.048***	(0.047)	3%	0.003	(0.0254)	10% (x)
Rain – Gauteng	–0.026***	(0.045)	2%	–0.007	(0.058)	6%	0.033***	(0.029)	12% (x)
Rain – Mpumalanga	0.021***	(0.036)	16% (x)	0.007	(0.064)	11% (x)	–0.020***	(0.026)	9%
Rain – Limpopo	–0.010**	(0.044)	5%	0.070***	(0.107)	16% (x)	–0.032***	(0.044)	7%
R-squared		0.99			0.99			0.99	
Adjusted *R*-squared		0.92			0.97			0.98	
Durbin-Watson stat		1.90			1.54			1.61	
F-statistic		42280.91			6819.52			61431.05	
Prob (*F*-statistic)		0.00			0.00			0.00	

***Statistical significance at 1%; **statistical significance at 5%; *statistical significance at 10%; without *, no statistical significance.
(x) denotes a province where the provincial contribution to national production is 10% or more.

of the National Department of Agriculture (NDA) in Pretoria, including agriculture surveys from 1971, 1973, 1975, 1978, 1981, 1983, 1988, 1993, 1995, and 2002. Interpolation was used to construct a complete time series for all the provincial shares for which no data exist. Most importantly, all nominal values were deflated using relevant price indices obtained from the NDA. Gross income in constant prices was plotted against the volume of production index revealing the same trend and slope—a clear indication that an appropriate deflator was used.

Results

The results from the SUR model for field crops, horticulture, and animal production are summarised in Table 3. The model does not allow for variation in the slope of the net income function among regions, but the variation in the intercept of the regions through the SUR model specification has been permitted. The Adjusted *R*-squared values of 0.92 and higher indicate that the SUR models represent a good fit of the data, supported by significant *F*-statistics of 42 281 (field crops), 6 820 (horticulture), and 61 431 (animal production), respectively. The coefficients of the interaction variables are almost all significant at the one per cent level ($P < 0.01$).

Based on the estimations obtained in Table 3, the net income function (Equation 1) can be specified for field crops, horticulture, and animal production for each province.

Field crops:

$$YFC_{it}^* = C_i - 0.26input_{it} - 0.30wages_{it} + 0.39con_{it} + 0.21\mathrm{Pr}od - 0.05temp_{it_i},$$

where $C_i = \alpha_i \mathrm{rain}_{it}$ (*province*)

Horticulture:

$$YH_{it}^* = C_i - 0.45input_{it} - 0.32wages_{it} + 0.18con_{it} + 0.12\mathrm{Pr}od - 0.01temp_{it_i},$$

where $C_i = \alpha_i rain_{it}(province)$

Animal production:

$$YA_{it}^* = C_i - 0.21input_{it} - 0.54wages_{it} + 0.25con_{it} + 0.27\mathrm{Pr}od - 0.06temp_{it_i},$$

where $C_i = \alpha_i rain_{it}$ (*province*)

Since these net income functions were estimated in log terms, the coefficients can be interpreted as percentage changes, implying, for example, that a 1% increase in expenditure on intermediate goods and services will lead to a decline in net income of 0.26% for field crops.

Discussion

Gross farm income (gross revenue or turnover) in real terms (constant 2000 prices) over the entire period has grown only marginally, with the exception of the Western Cape. Here the growth in viticulture contributed significantly to the growth in the sector over the initial few years of the study period. This steady growth has been offset by a rapid rise in production costs in all provinces leading to a declining net income (revenue minus cost), which is currently at worrisomely low levels. Within the context of this paper, this suggests that first, increases in gross income occurred despite increasingly adverse climatic conditions; and, second, that the decline in net income is predominantly the result of an increase in input cost. The evidence from Table 3 supports this conclusion. The size of the coefficients of the costs, productivity, and sector size for each of the three agriculture sectors is far bigger than that of either rainfall or temperature. Third, this suggests that the increase in gross production could only be attained through the relative increase in the use of financial capital to attain this growth in gross income, but at a significant financial cost. The use of capital, as indicated by the formation of fixed capital (or investment), has remained constant in real terms since 1970 at approximately R6 000 million,[17] but employment has declined from more than 1.6 million in 1970 to just over 600 000 in 2005—or about 36% of the 1970 level.[4,18] This trend runs counter to the steady growth in both population and unemployment, and therefore signals a clear shift towards more capital-intensive agriculture. Fourth, the increase in capital intensification, also illustrated by the size of the coefficient for input costs, coincides with an increase in irrigation as discussed above. This suggests that, if it were not for irrigation, the growth in gross income might have been much

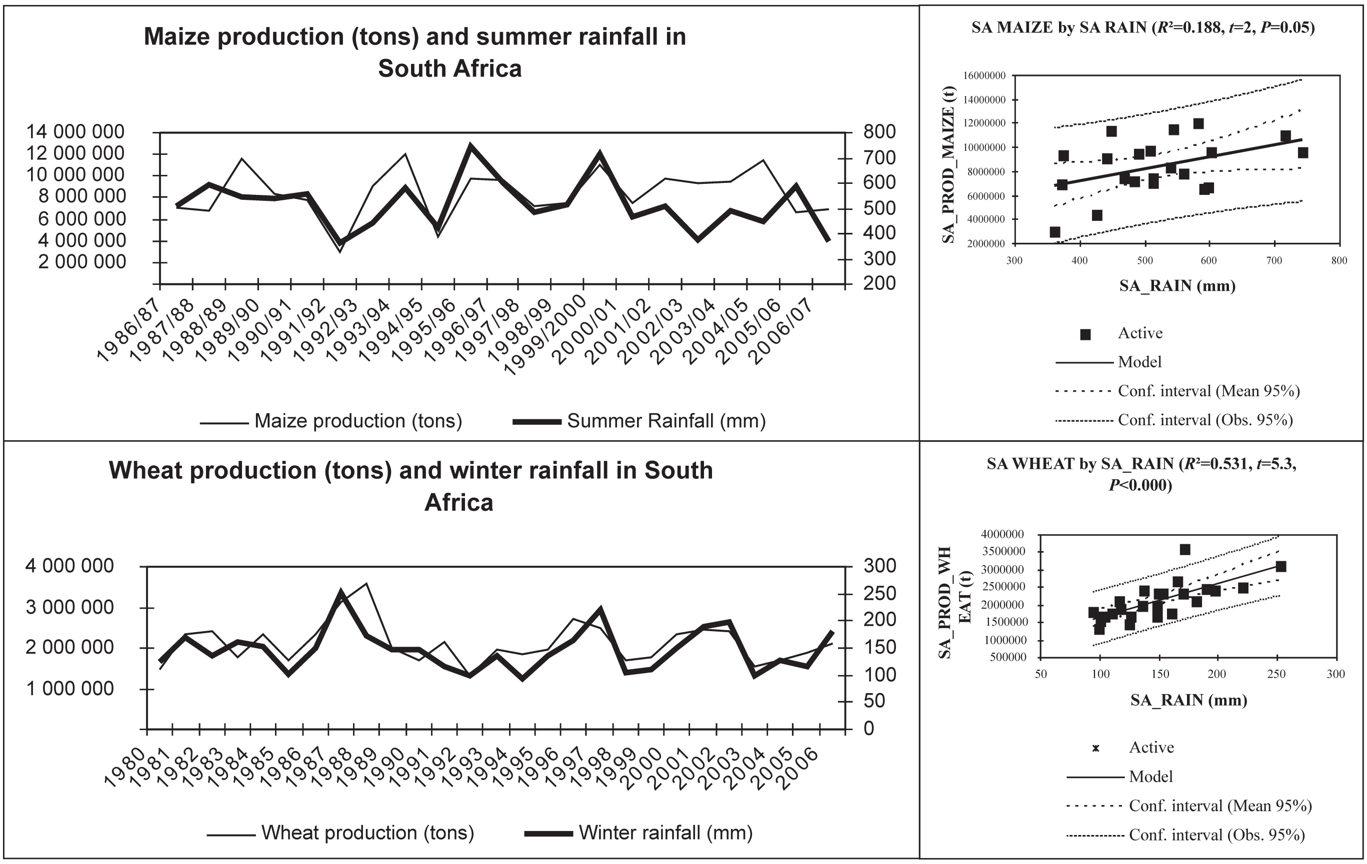

Fig. 2. Maize and wheat production (tons) with the annual total summer (Oct–March) and winter (April–Sept) rainfall (mm), respectively, in South Africa in the two left panels with their respective covariance indicated in the right panels (source: maize and wheat production: National Department of Agriculture; rainfall: South African Weather Bureau).

less, but that such expansion and intensification have important financial costs, which are rising much faster than the value of the product. Fifth, temperature is indeed negatively correlated with net farm income for the three sectors, but has a very small coefficient, and is not statistically significant for horticulture production. However, the results from Table 3, with regard to rainfall, reveal a positive correlation between rainfall and net income for field crops and horticulture, for each of the provinces that produce more than 10% of the national output—indicated with an 'x' in Table 3. These data are important from a food security perspective.

For animal production, the relationship is less clear. Animal production includes poultry farming—which is currently the single largest agricultural sector in the country—and cattle farming for beef. Beef production in South Africa today is largely feedlot-based, though most of the animals originate from cattle farmers. In other words, calves are free-ranging until they are about nine months old, when they are auctioned to feedlot owners. Cattle, however, are counted as part of animal production only after being slaughtered. Therefore, there is no direct link between rainfall and animal production, as both poultry and beef production use abstracted water. For beef production, this can lead to erroneous conclusions, as the productivity of free-range cattle husbandry is adversely affected by any reduction in rainfall. This degree of dependence is not reflected in the data used here, as livestock sales are not counted as animal production. In 2004, so-called subsistence farmers owned 5.6 million head of cattle, i.e. 41% of the national total of 13.8 million.[19] These individuals are extremely vulnerable to changes in climate and, given the small scale of their operations and the limited access they have to open markets, the value of their animal production is not captured adequately in a macro-economic data set, such as the one used here. This is also a group of farmers which has not yet been integrated into the formal agriculture sector, despite governmental pressure to do so. Adverse climatic conditions are likely to make this process more difficult to accomplish.

We have seen that rainfall is significant to the dominant horticulture production areas such as the Western Cape, where viticulture plays a major role. Horticulture, like animal production, makes extensive use of irrigation that temporarily offsets any sudden decline in rainfall. In contrast, dry-land agriculture, especially involving field crops, cannot make use of irrigation and is therefore much more vulnerable to changes in climatic conditions than horticulture and animal husbandry. Given both the importance of rainfall for field crop production, and that field crop production is likely to be most affected by any adverse changes—sudden or gradual—in climatic conditions, we conclude our analysis by considering the relationship between rainfall and field crop production in more detail.

Production of field crops and rainfall

There is a remarkable correlation between rainfall and crop production, whether summer (e.g. maize) or winter crop (e.g. wheat), as seen in Fig. 2, where we distinguish winter rainfall (April–September) from summer rainfall (October–March). We use maize and wheat as proxies for all seasonal field crops to demonstrate the link between rainfall and crop output.

To determine the specific relationships between rainfall and crop production for these respective crops, for each area, an elementary equation was used:

$$\%\text{ change in production}_{i,j} = \%\text{ change in rainfall}_i\,,$$

Table 4. The relationship between rainfall and gross income in field crops in the nine provinces of South Africa: 1970–2006.

	Coefficient	*t*-statistic	Adj. R^2	DW	Contribution to SA production in 2006
Western Cape: maize	n.a.*	n.a.	n.a.	n.a.	n.a.
Western Cape: wheat	0.37	2.86	0.22	2.02	35%
Eastern Cape: maize	–0.003	–0.012	–0.026	2.1	1%
Eastern Cape: wheat	0.30	2.1	0.13	1.47	0.5%
Northern Cape: maize	0.07	1.01	–0.17	1.93	8%
Northern Cape: wheat	–0.07	–0.89	–0.02	2.56	12%
Free State: maize	1.18	2.5	0.2	2.36	40%
Free State: wheat	0.53	4.26	0.37	2.79	37%
KwaZulu-Natal: maize	0.27	1.79	0.13	2.5	5%
KwaZulu-Natal: wheat	–0.03	–0.22	–0.12	1.98	1%
North West: maize	2.55	3.89	0.41	2.31	18%
North West: wheat	0.06	1.04	0.00005	1.95	7%
Gauteng: maize	1.12	3.55	0.38	2.22	4%
Gauteng: wheat	–0.53	–0.57	–0.03	1.95	0.5%
Mpumalanga: maize	0.68	3.2	0.33	2.75	21%
Mpumalanga: wheat	0.06	0.28	–0.5	2.76	4%
Limpopo: maize	0.17	0.7	–0.02	2.6	2%
Limpopo: wheat	0.5	1.67	0.05	2.35	4%
South Africa: maize	1.16	2.8	0.25	2.5	100%
South Africa: wheat	0.53	3.94	0.36	2.8	100%

*Not applicable, since the Western Cape is not a maize-producing area of any significance.

where i represents each province and j a given crop (Table 4). As the function was estimated as a percentage change, coefficients indicate that for every 1% change in rainfall, the expected change in gross production is 'x'. For all the provinces contributing approximately 20% or more to national production for either maize or wheat—the Free State (40%), Mpumalanga (21%), and the North West (18%) for maize, and the Western Cape (35%) and the Free State (37%) for wheat—highly statistically-significant relationships ($P < 0.0001$) were found between crop production and rainfall. Maize production is generally more sensitive to changes in rainfall than wheat production, as indicated by the respective sizes of the coefficients. Alarmingly, a 1% change in rainfall should lead to more than a 1% change in maize production. This does not augur well for provinces such as the Free State, the North West, and the Western Cape, as these provinces were considerably warmer from 1997 to 2006 than in the three preceding decades (Table 2). Additionally, there is a strong negative relationship between temperature and rainfall, especially in the two former provinces. Should it become still warmer in the future and rainfall continue to decrease, then the three major maize and wheat production areas of the country will be susceptible to marked reductions in crop production.

Conclusion

South Africa, on average, has been hotter and drier during the last 10 years than during the 1970s. If this represents future climatic trends this has major implications for South African agriculture. Notably, there is very little scope for expansion of irrigation, given the limited supply of non-saline water and pressing socio-economic needs. This scenario implies that farmers are likely to rely increasingly on water-saving techniques that may drive up costs even further, in a sector that has a small net income margin and which is already facing rapid cost rises. This is likely to make it increasingly difficult for emerging farmers to enter the sector, despite the official national policy to help them. In addition, there likely will be significant impacts on food security, which is already under pressure.

Furthermore, there is a statistically-significant positive correlation between the production of field crops and horticulture in all the provinces that contribute more than 10% of the national supply. Given trends of declining rainfall and increasing average temperature, and the statistically-significant negative relationship between these two variables, this implies that both field crop production and horticulture are extremely vulnerable, especially rain-fed field crops. A 1% decline in rainfall is likely to lead to a decline in maize production of 1.16% and a decline in wheat production of 0.5%. Such a decline in rainfall is also likely to lead to a decline in net income in the most productive provinces.

As we have seen, only 1.4% of South Africa's water yield is currently available to address the demands of the poor, most of whom currently have no access to potable piped water. These 15 million people, who comprise 35% of the population,[20] are obliged to find and physically carry water to their homes and their livestock on a daily basis—clearly not a tenable situation.

Even under pre-industrial conditions, ecological systems, including agrosystems, were subject to influences from extreme events and global forcing factors, such as new markets or the collapse of old ones. In the context of recent massively accelerating anthropogenic climate changes, we need to adapt our ways of thinking, acting, farming, and managing vital resources, particularly water.

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Appendix 1. Annual rainfall (mm) for South Africa's nine provinces: 1970–2006.

	Western Cape	Eastern Cape	Northern Cape	Free State	KwaZulu-Natal	North West	Gauteng	Mpumalanga	Limpopo	South Africa
1970	455	621	203	466	774	405	569	609	421	502
1971	481	697	257	539	1010	631	893	912	639	673
1972	433	538	230	534	911	528	607	893	730	600
1973	416	561	290	502	946	591	686	966	655	624
1974	638	914	583	792	955	713	732	879	733	771
1975	528	635	364	675	1033	764	930	965	748	738
1976	683	904	481	806	1198	852	850	907	755	826
1977	751	684	329	573	977	623	716	862	829	705
1978	443	644	206	619	1108	591	800	890	777	675
1979	500	623	213	572	750	531	679	716	538	569
1980	530	470	217	484	759	520	731	866	762	593
1981	715	739	307	683	919	585	644	828	754	686
1982	524	517	213	498	721	470	568	556	395	496
1983	612	546	218	531	843	428	726	830	469	578
1984	565	519	179	466	1149	340	487	866	560	570
1985	676	816	283	521	1053	404	678	832	661	658
1986	603	647	184	585	836	519	713	742	540	597
1987	592	589	217	670	1334	477	830	945	622	697
1988	488	785	443	879	1121	714	627	809	678	727
1989	639	752	265	624	1024	630	786	866	602	687
1990	553	528	227	463	832	433	604	762	522	547
1991	583	662	373	687	1001	590	723	814	598	670
1992	613	451	123	380	550	337	507	566	429	440
1993	637	675	231	587	872	495	757	797	571	625
1994	533	597	208	446	763	387	691	585	396	512
1995	623	665	274	639	1042	612	876	832	647	690
1996	711	733	301	761	1103	647	959	1097	958	808
1997	510	665	232	636	1167	685	962	895	700	717
1998	563	697	215	638	878	594	719	848	631	643
1999	403	386	245	378	892	420	526	798	650	522
2000	498	763	289	671	1160	629	1006	1233	1274	836
2001	603	696	342	744	905	624	646	770	738	674
2002	608	663	251	566	794	431	569	620	367	541
2003	491	481	146	413	637	407	506	517	419	446
2004	537	689	205	516	865	534	690	828	731	622
2005	507	578	205	532	766	468	535	631	428	517
2006	624	879	351	771	1032	730	771	964	796	769
Average	**564**	**649**	**267**	**590**	**937**	**550**	**711**	**819**	**641**	**637**

Source: South African Weather Bureau.

Appendix 2. Average daily maximum temperature (°C) for South Africa's nine provinces: 1970–2006.

	Western Cape	Eastern Cape	Northern Cape	Free State	KwaZulu-Natal	North West	Gauteng	Mpumalanga	Limpopo	South Africa
1970	24.2	23.5	25.6	25.2	24.00	27.1	24.2	25.5	27.4	25.2
1971	24.1	23.0	25.5	24.6	23.37	25.7	23.0	24.2	26.2	24.4
1972	25.3	23.7	26.4	24.8	23.80	26.4	23.6	24.3	26.3	25.0
1973	25.2	24.0	26.0	24.7	23.43	26.3	23.4	24.6	26.2	24.9
1974	24.6	23.5	25.0	23.3	23.87	25.2	22.6	24.3	25.9	24.2
1975	25.0	23.5	25.4	24.1	23.46	25.6	22.9	24.3	26.0	24.5
1976	24.4	23.6	24.8	23.2	23.69	25.1	22.4	24.2	25.8	24.1
1977	24.7	24.0	25.5	24.7	24.42	26.5	23.8	25.0	26.6	25.0
1978	24.9	23.4	25.7	24.4	23.60	26.2	23.4	24.7	26.4	24.8
1979	25.0	23.5	26.0	24.7	23.66	26.6	23.9	24.6	26.3	24.9
1980	25.2	24.1	26.2	24.6	24.09	26.2	23.4	24.4	25.9	24.9
1981	24.7	23.4	25.2	23.4	23.55	25.6	23.0	24.0	25.6	24.3
1982	24.7	23.5	25.9	24.9	24.02	27.0	24.2	25.1	26.8	25.1
1983	24.8	24.2	25.9	25.6	24.30	27.6	24.6	25.4	27.4	25.5
1984	25.3	24.1	26.4	25.2	23.71	27.4	24.2	24.3	26.6	25.3
1985	25.2	24.4	26.2	25.2	24.66	27.3	24.4	25.0	26.5	25.4
1986	25.1	24.0	25.9	25.1	24.25	27.1	24.1	24.7	26.8	25.2
1987	24.9	24.0	25.9	25.1	23.94	27.4	24.2	24.9	27.0	25.3
1988	24.9	23.6	25.4	24.0	23.89	26.4	23.7	24.8	26.0	24.7
1989	24.7	23.3	25.1	24.1	23.79	26.3	23.5	24.7	26.5	24.7
1990	24.4	23.5	25.4	25.2	23.44	27.2	24.0	24.8	26.9	25.0
1991	24.6	24.0	25.4	24.5	24.08	26.5	24.0	25.1	26.9	25.0
1992	24.6	24.3	25.9	26.3	25.06	28.2	25.4	25.9	28.3	26.0
1993	25.4	24.3	26.1	24.8	24.58	27.0	24.3	24.9	27.3	25.4
1994	25.2	24.1	26.1	24.5	24.13	26.7	23.8	24.3	27.1	25.1
1995	24.5	23.6	25.6	24.8	23.67	26.7	24.2	24.1	27.3	25.0
1996	23.7	23.4	24.3	23.8	23.31	25.8	23.3	23.3	26.3	24.1
1997	24.8	23.5	25.7	24.7	23.23	26.2	23.5	23.8	26.8	24.7
1998	25.0	24.1	26.3	25.2	24.19	27.4	24.8	24.8	27.7	25.5
1999	25.7	25.0	26.3	25.7	25.08	27.3	24.5	24.2	27.3	25.7
2000	24.8	23.5	25.8	24.1	23.73	25.7	23.2	23.5	26.1	24.5
2001	24.6	24.1	25.6	24.2	24.31	26.2	24.2	24.0	26.8	24.9
2002	25.0	24.2	25.8	25.2	24.23	27.1	24.4	24.2	27.8	25.3
2003	25.0	24.5	25.9	25.9	24.33	27.6	25.1	24.3	28.2	25.6
2004	25.7	24.8	26.5	24.7	24.46	26.6	23.8	24.1	27.1	25.3
2005	25.1	24.5	26.0	25.4	24.46	27.3	25.1	24.3	28.3	25.6
2006	25.3	23.9	26.2	22.7	24.35	25.5	23.9	23.5	26.9	24.7
	24.9	**23.9**	**25.8**	**24.7**	**24.0**	**26.6**	**23.9**	**24.5**	**26.8**	**25.0**

Source: South African Weather Bureau.

Appendix 3. Explaining the SUR mode.

We employed the SUR model with a one-way error component, which allows cross-section heterogeneity in the error term; i.e. $u_{it} = \mu_i + \nu_{it}$. On the other hand, a two-way error component model allows cross-section heterogeneity, as well as time effects; i.e. $u_{it} = \mu_i + \lambda_t + \nu_{it}$. We adopt Avery's[21] approach, as presented in Baltagi,[16] to explain a SUR model in a panel context. The SUR model has a set of M equations:

$$y_j = Z_j\delta_j + \mu_j \text{ with } \mu_j = Z_\mu \mu_j + \nu_j \qquad j = 1,\ldots M , \tag{1}$$

where y_j is $NT \times 1$; Z_j is $NT \times k_j^{`}$ and the residuals from each equation with random vectors of $Z_u = (I_n \otimes l_T)$; $\mu'_j = (\mu_{1j},\ldots\mu_{Nj})$ and $\nu'_j = (\nu_{11j},\ldots,\nu_{1Tj},\ldots,\nu_{N1j},\ldots,\nu_{NTj})$.

In addition, $\mu \sim (0, \Sigma_\mu \otimes I_N)$ and $\nu \sim (0, \Sigma_\nu \otimes I_{NT})$. From Equation 1, it follows that each different equation has the same standard variance-covariance matrix. However, within a panel SUR model, there are additional cross-equation variance components. Accordingly, Avery[21] defined a variance-covariance matrix that is not equation specific:

$$\Omega = E(\mu\mu^{`}) = \Sigma_\mu \otimes (I_N \otimes J_T) + \Sigma_\nu \otimes (I_N \otimes I_T) , \tag{2}$$

where $\mu' = (\mu_1',\ldots,\mu_M')$ is a $1 \times MTN$ vector of disturbances with μ_j and $\Sigma_u = [\sigma^2_{ujt}]$, as well as, $\Sigma_\nu = [\sigma^2_{\nu jt}]$ are both $M \times M$ matrices. Replacing J_T with $T\bar{J}_T$ and I_T by $E_T + \bar{J}_T$ provides the following:

$$\Omega = (T\Sigma_\mu + \Sigma_\nu) \otimes (I_N \otimes \bar{J}_T) + \Sigma_\nu \otimes [(I_{NT} - I_N \otimes \bar{J}_T)] . \tag{3}$$

It is then possible to estimate Equation 3 in a panel context, by replacing the matrix of disturbances for all M equations by OLS (Ordinary Least Squares) residuals[21] or within-type residuals.[16] To quantify the impact of rainfall's contribution to agriculture, we used an econometric model custom-made for this purpose. A net income function was estimated and fitted to the data with a cross-section SUR model for field crops, horticulture and animal production, respectively.

$$Y_i^* = f(input_i, wages_i, con_i, prod_i, temp_i, rain_i) , \tag{4}$$

where Y_i = net income for province i; Input$_i$ = expenditure on intermediary goods and services for province i; Wages$_i$ = wages, interest, and other sundry expenses for province i; Con$_i$ = proportional contribution to GDP for province i; Prod$_i$ = an index of gross income for province i; Temp$_i$ = temperature for province i; Rain$_i$ = rainfall for province i.

We compiled three separate models for each agricultural product, namely FC (field crops), H (horticulture), and AP (animal production), respectively, where each model contained the above independent variables per region/province and the dependent variable, i.e. the net income per province, for the respective agricultural product. After the initial round of estimating the net income function—for FC, H, or AP respectively—for each of the nine provinces, using the one-way error SUR model, two problems were encountered—heteroscedasticity and serial correlation—both of which had to be corrected, as we will now explain.

Heteroscedasticity

The standard SUR one-way error component model assumes that the regression disturbances are homoscedastic, when the same variance across time and individuals occurs. This may be a restrictive assumption for panels and agricultural type data, where the cross-sectional units may be varying in size and, as a result, may exhibit different variations.[22] Therefore, to correct for the potential problem of heteroscedasticity, White's cross-section heteroscedastic structure was specified in all the models, to ensure consistency and efficiency of the estimators.

Serial correlation

Another problem within the standard SUR one-way error component model is the assumption that the only correlation over time is due to the presence of the same individual effect across the panel.[22] This assumption ignores the effect of an unobserved shock that took place in the current period on the following periods, causing inefficient estimates of regression coefficients and biased standard errors. In an attempt to test for serial correlation, we employed the Durbin-Watson (DW) test and Lagrange Multiplier (LM) test. In particular, the LM-test is based on the test for random effects and serial correlation, where the null hypothesis is $H_0 = \sigma^2_\mu = 0; \lambda = 0$ or $H_0 = \sigma^2_\mu = 0; \rho = 0$. To construct the test, the following specification was used:

$$LM_1 = \frac{NT^2}{2(T-1)(T-2)}[A^2 - 4AB + 2TB^2] \overset{H_0}{\sim} \chi^2_2 , \tag{5}$$

where $A = [\hat{u}'(I_N \otimes J_T)\hat{u}/(\hat{u}'\hat{u}) - 1]$ $(\sigma^2_\mu = 0)$; $B = A = (\hat{u}'\hat{u}_{-1}/(\hat{u}'\hat{u})$ $(\rho=0)$ and $\hat{u}$ is OLS residuals.

The null hypothesis is rejected if the LM statistic exceeds the $\chi^2_2 (= 5.99)$ value. Moreover, Bhargava *et al.*[22] outlined the DW-test, with the null and alternative hypotheses as H_0: $\rho = 0$ and $H_A : |\rho| < 1$. These authors defined the test statistic as:

$$d_p = \sum_{i=1}^{N}\sum_{t=2}^{T}(\tilde{\nu}_{it} - \tilde{\nu}_{i,t-1})^2 / \sum_{i=1}^{N}\sum_{t=1}^{T}\tilde{\nu}^2_{it} , \tag{6}$$

with ν_{it} is the within residuals.

The critical values in Table II from Bhargava *et al.*[22] form the decision basis for this test. With the application of the DW and LM-tests, the results in Table A3.1 indicate that serial correlation was present.

Table A3.1. Results showing the presence of serial correlation.

Test	Field crops	Horticulture	Animal production
DW*	3.09	3.05	3.24
LM	69.35	50.27	50.73

*The DW-statistics show that negative serial correlation is present.

To correct for serial correlation, we estimate rho-values for each model and each province to account for the heterogeneity across the provinces. The rho-values reported in Table A3.2 confirm the presence of serial correlation in both models along with heterogeneity across the regions.

Table A3.2. Estimated rho-values as per region.

Province	Estimated rho-value		
	Field crops	Horticulture	Animal production
Western Cape	0.76	0.53	0.72
Eastern Cape	0.79	0.63	0.63
Northern Cape	0.78	0.89	0.79
Free State	0.67	0.81	0.78
Natal	0.79	0.93	0.69
North West	0.83	0.84	0.71
Mpumalanga	0.91	0.85	0.47
Gauteng	0.63	0.85	0.71
Limpopo	0.76	0.54	0.74

To correct for the serial correlation problem, the rho-values shown in Table A3.2 are used to transform the correlated errors into uncorrelated errors, based on a Prais-Winston transformation approach for each province. The DW- and LM-tests are performed again to determine whether serial correlation is still present in the models. Table A3.3 shows that the serial correlation problem has been addressed.

It is important to note that, with the correction for serial correlation, the sample size changed from the period 1971 to 2006, since observations have been lost through differentiation in the data transformation process. Given that the major data problems have been rectified, the final SUR models can now be presented. The results of each model are shown separately, first the field crops model, then the animal production model, and, last, the horticulture model.

Table A3.3. Results showing no serial correlation.

Test	Field crops	Horticulture	Animal production
DW*	2.21	2.16	2.26
LM**	5.69	5.54	5.59

*Constructing the critical value utilizing Table II from Bhargava *et al.*[22] with $T \approx 10$, $H \approx 250$ and $N \approx 9$. Following this approximation, the critical values yield 1.927 (D_{pL}) and 1.942 (D_{pU}).