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District-level agricultural total factor productivity for the Karoo, South Africa: 1952–2002

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ABSTRACT

An earlier study of district-level agricultural total factor productivity in the Western Cape province of South Africa Conradie et al. (2009a, b) is extended to include eleven Northern Cape districts that in combination make up the Karoo. Tornqvist Theil total factor productivity (TFP) indices are calculated using accounting data from 10 years of the farm census between 1949/50 and 2001/2. The Northern Cape districts experienced the same general productivity decline as those of the Western Cape's Central Karoo. Both parts of the broader Karoo region show a similar mean rate of decline. However, the reasons for this are different, with developments in irrigation systems a major factor.

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Total factor productivity; arid areas; Karoo; Tornqvist Theil

1. Introduction

Innovation does not spread from leaders to followers as quickly in agriculture as in other industries, largely due to immutable geographical and climatic differences that cannot be overcome by research or extension. This means that national or even provincial averages can hide extremes of low and high growth rates and hence without disaggregated data policy can be misinformed. For example, during the second half of the twentieth-century annual productivity growth in the Western Cape was 50 basis points higher than the national average although some districts experienced a productivity fall while others grew at more than 2% per annum (Thirtle, von Bach, and van Zyl 1993; Conradie, Piesse, and Thirtle 2009a). This has implications for land reform, climate mitigation strategies and infrastructure development plans and many of these policies are developed, or at least executed, at the Provincial level. Research at this level of disaggregation means that agricultural policy for the Western Cape can benefit from detailed longitudinal productivity data that have up to now been denied elsewhere in South Africa. It is in the interest of South African farmers that the 2009 productivity map is extended to the other eight provinces so that land reform can be fast-tracked in high potential areas and food security and employment can be protected in climate hotspots. There has long been a realisation that whereas national TFP indices provide a concise summary of major historical changes in the process of agricultural development, such studies are of limited use to the provincial agriculture departments, who have the responsibility of advising farmers. Indeed, interest in this level of disaggregation to inform policy is apparent in the number of citations resulting from the productivity map by researchers mostly in SACD but also further afield.

The Karoo region has received considerable attention from rangeland scientists who are still struggling to resolve the apparent contradiction between improved vegetation coverage (e.g., Shearing 1994) and the sharp decrease in the region's carrying capacity for sheep and goats (Hoffman et al. 2018; Wessels et al. 2007; Archer 2000; Dean et al. 1995). One explanation is that

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the herds of the 1950s consisted of smaller, less productivity animals kept for subsistence purposes, as is still the case in communal areas today (e.g., Nenzhelele, Todd, and Hoffman 2018) while current herds contain fewer, larger animals that are more productive. This potential shift will be revealed by the total productivity estimates presented below and can be compared to Australian estimates of technical change in sheep farming in their arid rangelands, where public investments in research and development delivered productivity growth of more than 2% per year between 1950 and 1980 (Lawrence and McKay 1980; Beck et al. 1985; Bell et al. 2013; Chisholm 1992). In addition, by disaggregating productivity growth by magisterial district, the often-hypothesised relationship between rainfall, land productivity and overall productivity can be investigated. The Karoo is an arid rangeland bounded by the Atlantic coast in the west and the Cape Fold Mountains in the south moving into the Kalahari Desert somewhere around the Orange River. The eastern boundary is open and was predicted to drift eastwards over time (Acocks in Hoffman and Cowling 2003). The region is characterised by a strong rainfall gradient from east to west, so that it is expected that productivity will be higher in districts in the east and less so in districts in the west. All of this is overlaid by the importance of water for crop production, either as winter rainfall in the Succulent Karoo or by irrigation along the Lower Orange River where estimates for the Breede and Olifants Rivers in the Western Cape predict aggregate productivity growth rates of more than 2% per year (Conradie, Piesse, and Thirtle 2009b).

This paper takes Conradie, Piesse, and Thirtle (2009b) as a starting point by using the districts in the Western Cape that form the Central Karoo and adding other districts with similar climatic and other characteristics in the Northern Cape to create a wider sample of the extended Karoo including Namaqualand. The districts in this new sample face unique conditions and problems for agriculture, few of which have changed from 2002, which was the final year of the earlier study and in fact are more pertinent now as climate change issues are even more a global issue. This paper is the first to construct total factor productivity indices (TFP) for the Karoo in its entirety and is an important initial step to developing a targeted policy to promote growth. A major contribution is the detailed discussion of the TFP results that draws on an in-depth knowledge that enables the authors to address the unique features of the region.

The paper proceeds as follows. The next section puts the analysis into context by briefly reviewing previous work in the area. Section 2 explains the method used to construct the TFP indices and provides details of the data, including some of the issues that were problematic. The results follow with a district-level discussion and a comparison between those in the Western and Northern Cape areas of the Karoo.

2. Review of the literature and objectives of the study

Whilst some work has been done on agricultural productivity in the Karoo region of South Africa and none that uses cross province district-level data. Previous research has established that the Central Karoo is the most marginal region in Western Cape agriculture, with three of the four districts recording a fall in productivity during the second half of the twentieth century and the fourth growth of just above zero (Conradie, Piesse, and Thirtle 2009b). The most likely reasons for this decline include overgrazing, drought, decaying infrastructure that raises transport and other business costs and land use changes (Conradie et al. 2013). Interestingly, this is contrary to the view of farmers who consider problems with predation to be the most likely cause (Wustro and Conradie 2020).

Research on agricultural productivity for the Central Karoo and intensive and extensive versions of the production system have been described (see for example, Conradie and Piesse 2015). Success factors have been identified (Conradie 2019) and performance linked to farmer knowledge (Conradie 2016). However, the role of climate change, with respect to rising temperatures and drought is still unclear (Conradie, Piesse, and Stephens 2019). On a small-scale, D'Haese et al. (2001) described institutional and marketing constraints in the Transkei while Nyam, Matthews, and Bahta (2020)

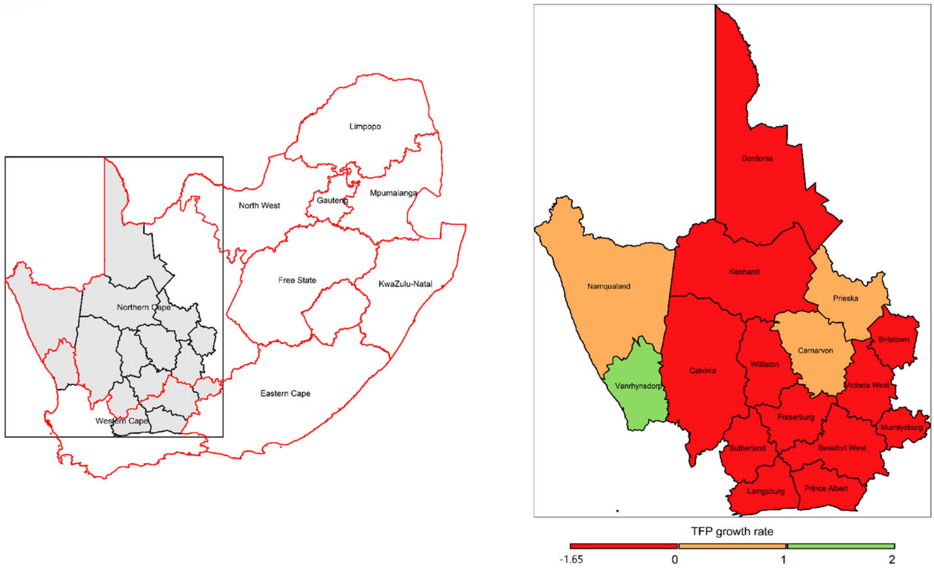

Figure 1. Spatial distribution of TFP changes in the Karoo, 1950–2002.

documented the performance of communal wool farmers in the Free State. But importantly, both studies conclude that district differences call for targeted specific regional policy interventions.

To develop a broader understanding of how TFP in the Karoo has evolved since the middle of the twentieth century, this study uses a Tornqvist Theil index number method. The sample is eleven Karoo districts in the Northern Cape in addition to the five in the Western Cape. Data are from censuses for the period 1949/50 to 2002. A map of the sample districts is in Figure 1. Estimates for the five Western Cape districts which were in the 2009 study are refined here. Four of the five are from the Central Karoo and the fifth is the Western Cape's Van Rhynsdorp district, which was previously analysed with a daughter district. The expanded map now covers South Africa from Cape Town to the Namibian border and from the west coast to about 24°*E* (Beaufort West, Prieska). The methods replicate those in Thirtle, Van Zyl, and Vink (2000) and are briefly stated in the next section.

3. Methods and data

3.1 Construction of Tornqvist Theil indices

The Tornqvist Theil approximation of the Divisia index of productivity growth computes changes in total factor productivity (TFP) changes from aggregate input and output quantities. This derivation is from Thirtle, Van Zyl, and Vink (2000, 85–8) and it relies on earlier work by Evenson, Landau, and Ballou (1987) and Chambers (1988).

For a single output Y and several inputs X_j the production function may be written as

$$Y = f(X_1 \cdots X_n{:}T)$$

where T represents a set of variables that determine the firm's performance. This function imposes linear homogeneity and assumes that the determining variables are held constant. Total differentiation with respect to time t gives

$$\left(\frac{\partial Y}{\partial t}\right)\mathrm{d}t = \sum_j f_j \frac{\partial X_j}{\partial t} + F_t \mathrm{d}t \qquad (1)$$

where f_j is the marginal physical product of input j. The change in productivity over time, $F_t\mathrm{d}t$, is equal to the change in output over time minus the sum of the input changes over time.

$$F_t\mathrm{d}t = \left(\frac{\partial Y}{\partial t}\right)\mathrm{d}t - \sum_j f_j \frac{\partial X_j}{\partial t} \tag{2}$$

Assuming perfect competition, substitute the marginal products in the input term with $f_j = P_j/P_y$ and divide through by output Y. Then multiply each input term on the righthand side by X_j/X_j.

$$\frac{F_t}{Y}\mathrm{d}t = \frac{\partial Y}{\partial t}\frac{1}{Y}\mathrm{d}t - \sum_j \frac{P_j X_j}{P_y Y} \cdot \frac{\partial X_j}{\partial t}\frac{1}{X_j}\mathrm{d}t \tag{3}$$

The result defines TFP growth as output growth minus the sum of the appropriately weighted growth in the j inputs. The costs shares, P_jX_j/P_yY, act as weights. This can be written more compactly as

$$\widehat{TFP} = \frac{F_t}{Y}\mathrm{d}t = \hat{Y} - \sum_j C_j\widehat{X_j} = \hat{Y} - \hat{X} \tag{4}$$

where $\hat{Y}$ and $\hat{X}$ are the appropriately weighted output and input growth rates. This result only applies to data that are generated continuously. The expression following the summation sign in Equation (3) defines the Divisia input index and the commonly used Tornqvist Theil discrete approximation of the Divisia input index derived by Chambers (1988) is written as

$$\hat{X} = \frac{1}{2}\sum_j (C_{jt} + C_{jt-1})\ln\left(\frac{X_{jt}}{X_{jt-1}}\right) \tag{5}$$

The Divisia input index is the logarithm of the ratio of two successive input quantitates weighted by the moving average of its share of input costs. According to Evenson, Landau, and Ballou (1987) where there are multiple outputs, the same aggregation can be applied to derive the Tornqvist Theil output index

$$\hat{Y} = \frac{1}{2}\sum_i (S_{it} + S_{it-1})\ln\left(\frac{Y_{it}}{Y_{it-1}}\right) \tag{6}$$

The TFP index computed in this study is calculated by taking the exponent of Equation (6) minus Equation (5) and then chained. National and provincial indices typically use starting points of 100, but to differentiate between districts we used the ratio of output to input values in 1950 as starting points for each district.

3.2 Data: census periods and components

This TFP index summarises ten approximately equally spaced census events, with the spacing determined in the period after 1981. The starting point is the first comprehensive farm census in South Africa in 1949/50 and the series ends with the 2002 farm census. Two further censuses were taken in 2007 and 2017, but no input data were published for 2007 and in 2017 data are no longer available by magisterial district. The other data points are 1956, 1960, 1965, 1971, 1976, 1981, 1988 and 1993. In the early part of the study period, partial censuses were taken more regularly so that some variables, like machinery and land values, had to be taken from adjacent years to the main census.

The 16 districts included in this study remain the same over the study period with the exception of Van Rhynsdorp that lost 28% of its surface area to Vredendal between 1960 and 1965 when new irrigation developments on the lower Olifants River turned Vredendal into a strong growth region. While the combined district produced mainly raisins and lucerne in the early years, Van Rhynsdorp reverted to a typical Karoo production system after the split. With both inputs and outputs severely reduced after 1965, it is an open question if productivity increased or decreased as a result.

The output index uses a reduced commodity set specific to the Karoo. Mutton, wool and karakul pelts account for almost 80% of the value of output over time across the region. Beef, dairy produce and pork account for the livestock output. Field crops include summer and winter cereals, dry beans and peas and fodder for sale, while horticulture consists of wine grapes, table grapes and raisins and stone fruit. Maize makes up more than 90% of the very small summer cereals category and wheat more than 80% of winter cereals in the region, and therefore these commodities substituted where cereal prices were needed. Initially, most of the crop production on Karoo farms was to ensure farm self-sufficiency and as the need for self-sufficiency declined crop production fell. By the end of the twentieth century, the Karoo's crop production was limited to pockets and edges. Along the Lower Orange River Prieska and Gordonia produce grains and grapes, winter cereals are still important in Calvinia, Van Rhynsdorp and Namaqualand, and Laingsburg and Prince Albert produce fruit and seed along the Swartberg.

The census reports crop volumes and outputs from 1981 onwards. Between 1960 and 1981 national prices from the Abstract of Agricultural Statistics (Department of Agriculture Fisheries and Forestry 1985/2005, various years) were applied to the district-level output of annual data to calculate the value of production, and where those stopped national price indices were used to project annual prices back to 1950. Price and output series in the Abstract are updated annually and most of what was required were in the 1985 and 2005 editions. For orchards and vineyards, the census only sporadically reported tree counts before 1981 and no district-level output. This was proxied by allocating national output figures from the Abstract proportional to each district's share of the national tree or vine stock. Due to the importance of livestock in the economy of the Cape Colony, sheep and wool are recorded in more detail in the early editions of the census. Herd data are complete for the entire period, except for the karakul sheep series, which stops in 1993, by which time this industry was a spent force. In 2002, the 1993 shares of the national karakul flock were applied to the 2002 flock to estimate district-level karakul sheep numbers. Wool, pelts and livestock slaughtered are reported periodically and missing values were interpolated by allocating national totals for livestock slaughter and products according to district herd numbers. Nominal values were generated by applying national prices to district-level production and prices projected backwards before 1960 using the same assumptions as for crops.

The input index includes land, two types of labour, tractors as proxy for the machinery stock, three types of herds and eight items of intermediate consumption, all using the same assumptions as in Thirtle, von Bach, and van Zyl (1993) and United States Department of Agriculture (USDA 1980). The rental value of land was taken as 5% of the value of land and infrastructure, with the infrastructure component serving as a quality adjustment factor. In the Karoo, land price variation captures rainfall differences with the amount and condition of fencing playing a minor role. Recently, prices have been bolstered by lifestyle purchases in which house and building values and scenic considerations override productive values (Reed and Kleynhans 2009).

The census reports employment and remuneration in most years. Our calculation only considers hired labour but covers both casual and regular staff. These were treated as separate inputs to avoid having to make assumptions about the average work spell of casual workers. It is assumed that work spells are determined by the nature of production and have remained stable over the period covered in the study. The missing observations of the remuneration of casual workers for the early periods were imputed from district-level data collected in 1960.

The quantity aspect of the machinery input was proxied by tractor numbers, which are available at the district level from 1950 to 1981. In this period small tractors dominated. National census figures show that South African farms have become saturated in tractor numbers around this time, although since then tractors have continued to grow bigger and more expensive. However, the new quality-adjusted tractor series in Gandidzanwa et al. (2019) reveals that accounting for size has only made a significant difference since 2000. To generate district-level tractor numbers for 1988, 1993 and 2002, district shares in 1981 were applied to the national tractor stock for the later years. The value component of machinery includes all farm vehicles and machinery, not just tractors. Thirtle, Van Zyl, and Vink (2000, 89) explain the principles and difficulties of calculating machinery flows from capital stocks. The rental price of machinery is determined by running costs, interest and depreciation. Running costs are dealt with under intermediate consumption. In Thirtle, von Bach, and van Zyl (1993) and Conradie, Piesse, and Thirtle (2009a, 2009b) 10-year straight-line depreciation was used. In the Karoo, where machinery is much less important than in arable or irrigated agriculture, this period was increased to 15 years. The point of including interest is to account for the opportunity cost of holding machinery. As suggested in USDA (1980) this was valued at an arbitrary fixed after-tax yield of 3%. The value of machinery is available at the district level only since 1981. To estimate figures for the earlier period, national totals were assigned to districts according to total tractor numbers. This simplifying assumption assumes that the Karoo held a similar tractor stock than other farms during the second half of the twentieth century, which is not onerous in the early period, but could distort figures substantially during the latter decades of the twentieth century. Fortunately for the latter period, the census contains actual machinery resale values at the district level.

Farm-produced intermediate goods like seed, compost and manure and feed can be counted either as both input and output or as neither, with only the primary inputs required to produce these items reflected. To only reflect primary inputs and not count farm-produced intermediate inputs as part of the input index, this study follows the principle applied in USDA (1980) and Thirtle, von Bach, and van Zyl (1993). Intermediate inputs produced off the farm, such as sprays and dips, inorganic fertiliser, purchased seed, fuel and electricity, repairs and maintenance and so on, are normally only reported as values. The relevant price indices reported in the Abstract of Agricultural Statistics to calculate real values in constant 1975 prices are used to serve as quantity proxies.

As an example of farm-produced capital, herds are an input as well as an output. In principle, herds are treated in the same way as farm-produced feed, that is, by leaving them off the balance sheet. However, herds are also capital stock whose flow is captured as a rental value. The practice of renting land with livestock is common across the Karoo, but these data on livestock rentals are not counted anywhere and therefore must be estimated. The tenant farmer usually captures the whole income in exchange for a rental fee and must return the capital stock in the same condition as it was received. Clearly, depreciation does not apply and running costs take the form of primary inputs in the same way as they do for farm-produced feed, but there is still an opportunity cost to holding the capital. As in the case of machinery, an arbitrary 3% after-tax return on investment is assumed, as recommended by the USDA (1980).

3.3 Other data issues

In the early censuses units of measurement varied by commodity, with grains and vegetables measured in bags of different weights. Land was registered in morgen and financial data in Sterling. On 14 February 1961 the South African Rand replaced the British currency at a rate of R2.00 to the Pound. The same exchange rate was applied to all Sterling figures in the previous census data. Metrication of other units took place over a 10-year period from 1967 to 1977 under the direction of the South African Bureau of Standards, although by 1971 the census was reporting almost exclusively in metric units. Imperial units and measures were converted into metric units and Rand values at the point of capturing.

The 2002 census did not report area farmed. In most districts it is not problematic to assume that land use would have stayed the same as it was in 1993, but in some districts a strong expansion in the network of national parks requires some adjustments. Based on park sizes at various dates, the 2002 land figures were adjusted as follows: Namaqualand was reduced by 953,304 hectares, Beaufort West by 90,883 hectares and Van Rhynsdorp by 90,082 hectares (Table 1).

Table 1. Farmland converted into protected areas.

District	Park name	Size	%	Dates
Beaufort West	Karoo National Park	90,883	6	1979–2019
Calvinia	Tankwa National Park	142,269	4	2014
Laingsburg	Anysberg Nature Reserve	56,639	18	various
Namaqualand	Namaqua National Park, Richtersveld	953,304	20	1991–2019
Van Rhynsdorp	Knersvlakte National Park	90,082	7	2014

The 1981 census presented outputs mainly by farm type and not by magisterial district. To generate value estimates for 1981 the district-level percentages recorded in 1988 were applied to the district-level totals for animals and animal products listed in the 1981 census. Additional assumptions were needed to generate quantity estimates for 1981. Wool and mohair production were easiest to estimate, because kilograms of wool are available and mohair production is small enough to ignore. Only two districts had substantial milk and cream production in 1981, and for them the estimated district-level value was divided by the national milk price for fresh consumption listed in the Abstract (R245/kilolitre). To estimate the number of animal sales per district, value estimates were partitioned into mutton and beef sales according to the 1988 proportions, then divided by national prices and then reassembled in LSU terms. For example, in 1981 the split in Namaqualand was 98% mutton and 2% beef, which means that the likely value of sales of mutton and beef in 1981 were R6122,000 and R126,000 respectively. According to Abstract, 6.85 million sheep and goats were slaughtered in South Africa in 1980/81, which yielded 172,300 tons of mutton. This gives an average carcass weight of 25.15 kg, which multiplies by the average price of R1.95 per kilogram achieved at auctions imply a carcass value of R49.05 per animal slaughtered. For beef, the figures are 2238,000 cattle slaughtered and 545,100 tons of beef produced which gives an average carcass weight of 243.57 kg. At the auction price of R2.02 per kilogram, it implies a carcass price of R492/animal slaughtered. Therefore, the estimated livestock sales numbers for Namaqualand for 1981 are 124,811 sheep and goats and 256 cattle. While the cattle estimate is substantially off, the sheep and goat estimate was within half a per cent of the 1988 figure, which validates the approach.

One systematic error found is that the headings on boer goats and angoras were switched in the 1965 census and this was corrected in our dataset. We also suspect problems with the irrigation estimate which do affect the TFP calculation directly. See footnote 1 in Section 4.3. In addition, the 2002 census contains a flawed entry for Gordonia. Cattle sales for the year consisted of 201 dairy cattle and 46,663 beef cattle. There has been a gradual increase in cattle numbers as a response to stock theft and predation, but in 1993 Gordonia produced only 9584 cattle for sale. In 1988 the figure was 8,099. The five-fold increase between 1993 and 2002 is so unlikely that the triple sixes in the 2002 entry was probably a double-type, which was corrected. To bring the values in line, the value of those sales was changed to R13,831 million, which puts the average price per carcass in line with the national price reported in the Abstract. To minimise capturing errors input and output shares and growth rates were reviewed at length until some consistency was achieved.

4. Results and discussion

4.1 Aggregate growth

Productivity changes in the Northern Cape Karoo districts follow broadly the same pattern as in the Western Cape while the revised figures reassuringly confirm the earlier estimates, now over an area ten times larger than the previous sample and covering 75% of the Karoo region. Figure 1 shows the spatial distribution of growth rates with district-level input, output and productivity indices recorded in Appendix. Positive growth was the exception, and was highest at 1.1% per year in Van Rhynsdorp along the lower Olifants River.

In the 12 districts where productivity fell, TFP losses varied between as little as −0.26% per year in Calvinia and as much −0.80% per year in Murraysburg. The regional productivity loss was −0.59% per year since 1950. This is due to inputs growing twice as fast as outputs (1.26% vs. 0.66% per year). Sustained above-average rainfall since the early 1970s (Conradie and Theron 2019) improved shrub coverage (Hoffman et al. 2018; Shearing 1994) which must have contributed to output growth. Nenzhelele, Todd, and Hoffman (2018) noted that in Namaqualand, where dwarf shrubs are interspersed with flowering annuals, shrub coverage continue to support grazing capacity when annuals fail due to droughts. In the Eastern Grassy Karoo annual grasses have the same grazing function as the flowers of Namaqualand so that there too better shrub coverage ought to translate into better grazing potential. This in turn should result in output growth, although Hoffman et al. (2018) noted that the Karoo's primary plant productivity has remained unchanged since satellite tracking began in 1982.

Other possible sources of growth could be the development of infrastructure that allows rotational grazing (Archer 2000) or extension efforts to ensure that farmers adopt these scientific grazing practices. In Australia, the combined effect of extension, rangeland research and infrastructure development delivered productivity growth of more than 2.5% per year during the 1950s, 1960s and 1970s (Beck et al. 1985; Lawrence and McKay 1980). According to Bell et al. (2013), stocking densities have stabilised in Australia's pastoral zone during the period since 1990 while off-take rates continued to increase, indicating the growing importance of non-land inputs into pastoral production as the climate deteriorates. Input data for the Karoo reveals that here non-land inputs continued to grow in importance too. For example, the feed and seed index grew by 5.36% per year and capital inputs by 0.72% per year but the most important inputs into pastoral production, were stable in the case of grazing land and declined at 1.44% per year for sheep and goat herds. The puzzle is why stocking density dropped so dramatically while according to Hoffman et al. (2018) land productivity has been stable or improving. This could be due to measurement problems on either side and will require more detailed analysis to resolve.

This section now considers two aspects of the productivity results that are of interest: firstly, a comparison of the two provinces' Karoo districts and secondly the impact of irrigation in the Olifants and Lower Orange Rivers as this is a major factor in explaining relative performance. Special characteristics of the Succulent Karoo Biome are also commented on.

4.2 Cross province comparisons

To explain the trend in TFP in the Northern Cape, it is necessary to provide some historical context. The Wool Boom of 1952 was the main economic event of the twentieth century in the Karoo. A drought in Australia and the Korean war's demand for wool for uniforms caused the wool price to rise three times above its long-term average for a year or two (Nattrass and Conradie 2015). Instead of substituting from mutton to woolled sheep, woolled sheep were added to existing mutton flocks. In the Northern Cape, small stock numbers went up by 18% between 1950 and 1956 and the number of animals offered for slaughter rose proportionally by 94,000 per year. Wool production almost doubled from 9953 to 18,529 tons and the number of karakul pelts sold increased by 115,500 (30%). The output index rose by 55 basis points, mostly due to an increase in herds since all inputs (herds included) rose by 20%.

With respect to the Western Cape Central Karoo region, the wool boom only increased herd size by 8% although the wool crop also almost doubled between 1950 and 1956. This indicates better grazing conditions in the Western Cape than in the Northern Cape. Karakul pelt production rose by 13,700 units (160%) while mutton production kept pace with the expansion in the herd size, as in the Northern Cape. The combined output index for the Western Cape rose by 39 basis points and the input index by 22 points. The increase in the size of the herd accounts for a third of the input growth in the period, while the remaining two-thirds were due to the intensification of the system. Surprisingly, feed expenditure did not respond

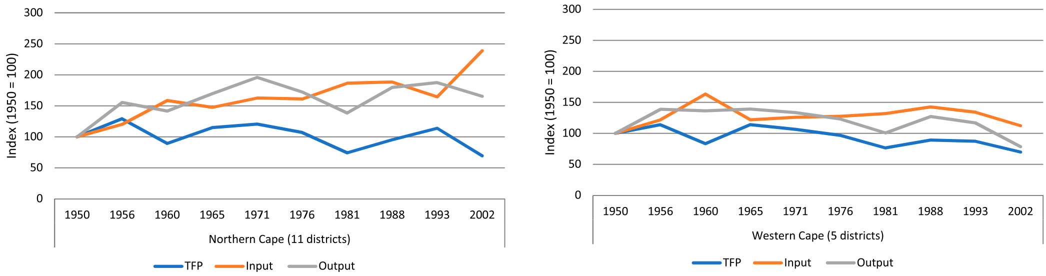

Figure 2. Comparison of TFP performance in Karoo districts of the Northern and Western Cape Provinces of South Africa.

much to the higher wool price. Instead seed and fertiliser use rose by 165% and fuel use by 85%, while the number of tractors increased by 181% and the area under lucerne increased by 48%. These changes indicate a large-scale increase in farm-produced fodder to support expanded wool production.

After 1956, output data in both the Northern and Western Cape track rainfall, as is expected in extensive grazing areas where total factor productivity is closely related to land productivity. Prominent turning points include the droughts of 1960 and 1981 and the bumper years of 1971 and 1993 (see Figure 2). Both regions show a downturn in output at the end of the study period that is not attributable to low rainfall at the time, although possibly to the cumulative effects of earlier droughts.

In the Northern Cape, the 1981 drought lowered output by 20% and raised the input index by 16%, which combined to reduce productivity by almost a third. Sheep and goat numbers peaked at 5.7 million in 1976 and dropped by only 9% during the 1981 drought. The additional expense on fodder required to support the larger herd through this serious drought explains why inputs rose sharply in that year. After the 1981 drought, output recovered by 30% and livestock numbers came down by 28%. Surprisingly, inputs did not adjust. By 1993 small stock numbers were down a further 14% and the input index by a similar amount while outputs remained constant, causing productivity to rise by 19%. By 2002 small stock numbers fell by a further 17% and outputs by 12%, while aggregate inputs continued to rise due to additional expenditures on packing materials (620%), seed and fertiliser (208%) and agro-chemicals (113%), which indicate the arrival of table grapes on the Lower Orange River. By then the table industry, which has done well for the Western Cape in the 1980s, expanded as much as it could in the Hex River valley (Worcester) and along the Lower Berg River (Malmesbury, Piketberg) and producers look north for more land and suitable climate to bring product to market by Christmas. The combined input index rose by 45% and the lack of corresponding output growth drove productivity down by 39% between 1993 and 2002.

In the Western Cape Central Karoo, small stock numbers peaked in 1956, directly after the wool boom. The drought of 1960 had a minimal impact on livestock holdings, but the stock removal scheme of the late 1960s reduced the herd by 32% between 1965 and 1971. By 1976 livestock numbers went up by 20% again, after which there is a steady decline of 11% by 1981, 5% by 1988, 26% by 1993 and finally 43% by 2002. In 2002 the region had only 40% of the 1981 herd left and less than a third of the peak sheep and goat numbers. The 1981 drought reduced outputs by 18% while inputs remained high, which drove productivity down by a −21%. As in the Northern Cape, there was some recovery from the 1981 drought by 1988. Inputs rose by 8% and outputs by 26%, causing a productivity gain of 16% over the period. All three indices remained steady over the next five years to 1993, but after 1993 outputs fell by 33% and inputs by 16%, which resulted in 20% lower productivity. These data paint a picture of declining fortunes and general distress across the Karoo to which Figure 1 offers few exceptions. However, these deserve a closer look.

4.3 Development in irrigation

Conradie, Piesse, and Thirtle (2009b) argued that the spatial distribution of productivity growth in the Western Cape is a function of access to irrigation water. This argument goes a long way towards explaining the history of the Northern Cape. In the 2009 productivity map, Van Rhynsdorp appeared dark green to signal productivity growth rate of more than 2% per year. This district lies on the Lower Olifants River and extends northwards across the Knersvlakte into Namaqualand. Its dramatic productivity growth was credited to irrigation developments in Van Rhynsdorp's daughter district, Vredendal, which benefitted from development in electrification and irrigation during the early 1980s (Conradie, Piesse, and Thirtle 2009b). In the present study, Van Rhynsdorp was analysed separately with the expectation that it would follow a more typical Karoo path than the combined area used in the 2009 study. However, even without Vredendal's strong growth, Van Rhynsdorp still performed much better than any other district. Here, the TFP index grew at 1.1% per year between 1950 and 2002, the same as George (1.15%) and Tulbagh (1.16%) (Conradie, Piesse, and Thirtle 2009b). More importantly, it survived the big drought of 1960 without losing productivity. Van Rhynsdorp lost about 90% of its irrigated area when Vredendal split off. Output fell by 118 basis points (49%) and inputs came down even more leaving the TFP index 32 points higher than it was in 1960 (+25%). This is the first panel of Figure 2. There is not much change over the next two decades. Growth only resumes between 1981 and 1988, with a 94% increase in output, probably due to the commodification of rooibos tea. After 1988 inputs continued to rise slowly, while output stagnated causing a slowdown in productivity growth. An in-depth investigation of the sources of productivity growth during the 1980s and the subsequent slowdown is notable and will be addressed in a further study.

The Lower Orange River forms the northern boundary to the Karoo. Between Upington and Kakamas, irrigation has existed on a limited scale since the late nineteenth century. The settlement at Kakamas, near Upington, was born out of the Rinderpest of 1895–1897 and was originally a labour colony for the poor created by BPJ Marchand, a minister in the Dutch Reformed Church in Knysna. The construction of the Gariep Dam between 1965 and 1971 and Van der Kloof Dam between 1973 and 1977 created substantial additional capacity that ought to be reflected in the productivity figures of riparian districts. Available estimates of the size of the area under irrigation in the four Orange River districts included in this study are shown in Table 2. Of the four, Gordonia benefitted most, with irrigation doubling between 1959 and 1988, and almost again by 1993. Kenhardt and Prieska experienced similar strong growth but off a lower base and in Namaqualand there was almost no growth.

Prieska is the most interesting of these four from a productivity point of view. In 1960 irrigation was still practiced on a limited scale and two-thirds of farm revenue in the district was derived from mutton, wool and karakul pelts, with crops, mainly lucerne, contributing 7% of output. Between 1976 and 1981 crop production quadrupled. The big gains were in wheat, which went from 2% to 6% of the value of output and in lucerne for sale whose share increased from 2% to 17%, the latter due to the 1981 drought. The share of output attributed to crops continued to increase after 1981 and

Table 2. Extent of irrigation developments along the Lower Orange River at selected census dates.

	Prieska	Gordonia	Kenhardt	Namaqualand[a]
1959	2093	15,468	673	660
1976	2740	25,477	1773	8844
1988	4699	30,263	2498	14,954
1993	5076	56,051	5893	6134

[a]Three errors were found with the Namaqualand irrigation figures that were corrected. In 1976 the entries for dryland and irrigated lucerne were reversed. In 1988 die areas under the main irrigated crops add up to a total of 744 hectares which we substituted for the implausibly high irrigated area of 14,954 hectares under land use. In 1993, the figure for lucerne is plausible, but the production records indicate only 220 hectares of irrigated vegetables and 75 hectares of irrigated fruit areas, which are more likely than the figures of 2638 hectares of vegetables and 2945 hectares of irrigated fruit presented under land use.

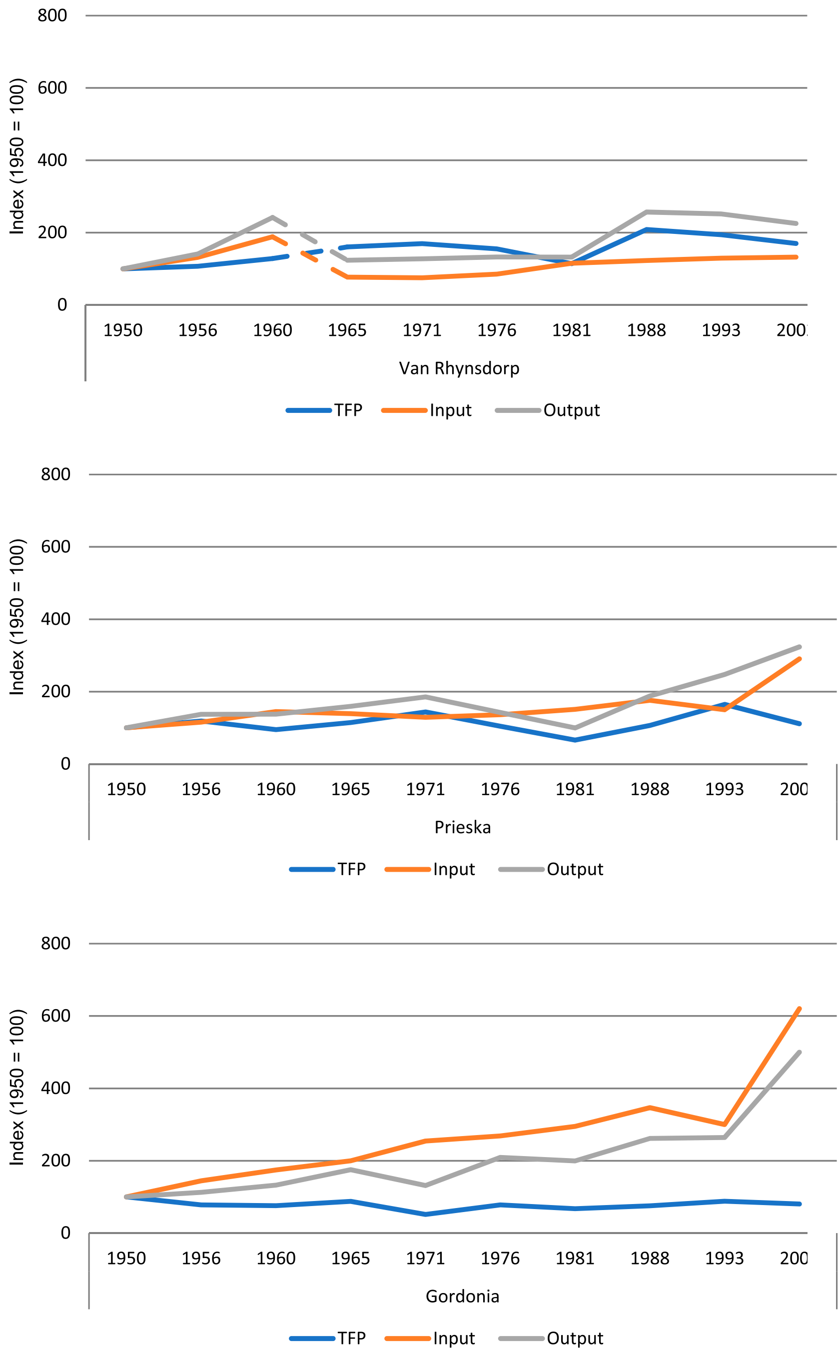

Figure 3. Input, Output and TFP in Van Rhynsdorp, Prieska and Gordonia.

reached 42% of the value of farm output by 1993. The 1993 census reported 1095 hectares were under irrigated lucerne and 3347 hectares under irrigated wheat and maize. By 2002 Prieska had become an almost exclusively crop producing district, with three quarters of farm revenue derived from crops and livestock contributing only 19% of output. There were nearly 11 thousand hectares under irrigation of which less than 300 hectares were under lucerne. The productivity effect of the move into crops is illustrated in the middle panel of Figure 3. The output index took off in 1981 with inputs lagging by two periods, which raised the TFP index by 100 basis points between 1981 and 1993 although a rapid increase in inputs between 1993 and 2002 reversed some of these gains.

Gordonia district, which lies to the north of the Orange River, combines the irrigated areas around Upington with the vast expanse of the Kalahari. In 1950, grapes mostly in the form of raisins contributed 6% of the revenue, with 25% from lucerne, 19% from other field crops and livestock, including beef cattle, contributed 48%. The righthand panel of Figure 3 reveals that the output index does not reflect the drought markers that are so evident in data for the rest of the Karoo. This confirms the importance of irrigation in the local economy. In the period between 1950 and 1993 the district experienced a gradual increase in output made possible by strong input growth, which left TFP unchanged over this period. In 1993 output consisted of 62% grapes (now mostly table grapes), 5% fodder crops, 6% cereals and 27% livestock and livestock products. Over the next decade fodder and cereals almost disappeared to be replaced by a growing share of wine grapes, raisins and table grapes, a shift which doubled the output index in the period. But inputs rose as strongly as outputs, leaving the TFP index on 81 basis points. Gordonia experienced a TFP decline of −0.14% per year over the full study period. It remains an open question why Gordonia failed to capitalise on technical progress as the Western Cape did during this period.

4.4 Succulent Karoo Biome

The Succulent Karoo Biome is the winter rainfall portion of the Karoo consisting of Namaqualand, Calvinia, Sutherland and Van Rhynsdorp, and Figure 1 clearly shows that winter rainfall confers some benefit to this region compared to the rest of the region. With a TFP growth rate of 0.48% per year and a shrinking area under irrigation Namaqualand is clearly a special case that deserves a study of its own. Until 1981 dryland wheat production accounted for 8% of the value of output. At that point livestock still represented more than 70% of the value of output. However, by 2002, cereal production had all but disappeared and livestock and livestock products had shrunk by 50% while table grapes have increased rapidly. It would be interesting to know how the developments in Namaqualand differ from those in Calvinia, which started out with the same mixture of sheep and wheat but did not have enough water to support a shift into grapes, and how Namaqualand managed a positive TFP growth as a result of table grapes while Gordonia did not.

5. Conclusions

This study has built on the district-level productivity map of the Western Cape districts of South African agriculture by Conradie, Piesse, and Thirtle (2009a, 2009b) to incorporate the Northern Cape districts that comprise the Karoo. There is now 75% of the Karoo included in the sample. Results largely confirmed those of the smaller Karoo sample in the Conradie, Piesse, and Thirtle (2009a, 2009b) analysis, which reported that the Karoo has been a region in decline during the second half of the twentieth century. Tailoring the calculation specifically to the Karoo did not affect the estimates and a comparison of local conditions with similar arid pastoral regions reveal that South Africa is paying a price of not investing enough in pasture science and extension. In Australia stocking density has plateaued since 1990 but off-take, and hence TFP, continues to increase. In South Africa the rangeland seems healthy enough (Hoffman et al. 2018), although it might be in decline in specific places (Nenzhelele, Todd, and Hoffman 2018) due to poorly understood management decisions from before the 1980s. The paper confirms that virtually the entire Karoo has been in decline since 1950 although the winter rainfall Succulent Karoo Biome performed marginally better than the summer rainfall Nama Karoo section. The only output growth found is that associated with expanded crop production, which is counter-intuitive for an arid rangeland such as this. There is no evidence that the rainfall gradient translates into a productivity gradient.

For the most part, drought is not to blame for the decline during the second half of the twentieth century, as rainfall was much higher during this period than during the previous 50 years (Conradie and Theron 2019) and plant productivity has been stable since satellite surveillance began in 1982 Hoffman et al (2018). Villano, Fleming, and Fleming (2012) reported that there was no difference either between the productivity recorded in drier and wetter parts of Australia's arid pastoral zone. This suggests that farmers' low potential areas maintain high productivity by reducing complementary land-enhancing inputs (Conradie 2019).

Clearly much more needs to be done on land and total factor productivity in the Karoo, for example, to explain why Carnarvon and Namaqualand are islands of relative prosperity in a sea of hardship. Ideally, this work should be done as a collaborative effort between rangeland scientists and agricultural economists. However, it is crucial that this is done as soon as possible, before rising temperatures put all Karoo farmers out of business.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data appendix

District	Year	TFP index	Input index	Output index
Northern Cape districts in study	1950	100	100	100
	1956	129	120	155
	1960	89	158	142
	1965	115	147	169
	1971	120	163	196
	1976	107	161	172
	1981	74	186	138
	1988	95	188	179
	1993	114	164	187
	2002	69	239	165
Western Cape districts in study	1950	100	100	100
	1956	129	120	155
	1960	89	158	142
	1965	115	147	169
	1971	120	163	196
	1976	107	161	172
	1981	74	186	138
	1988	95	188	179

(*Continued*)

Continued.

District	Year	TFP index	Input index	Output index
	1993	114	164	187
	2002	69	239	165
Beaufort West	1950	100	100	100
	1956	116	126	145
	1960	73	160	117
	1965	112	147	166
	1971	106	143	151
	1976	107	142	151
	1981	71	138	98
	1988	89	148	133
	1993	89	132	117
	2002	81	99	80
Britstown	1950	100	100	100
	1956	121	108	131
	1960	81	148	120
	1965	114	132	150
	1971	154	143	220
	1976	118	132	155
	1981	93	130	121
	1988	76	144	109
	1993	92	126	116
	2002	84	100	84
Calvinia	1950	100	100	100
	1956	165	144	238
	1960	102	207	211
	1965	115	177	203
	1971	158	204	321
	1976	115	179	206
	1981	60	217	131
	1988	150	189	282
	1993	143	163	234
	2002	88	126	111
Carnarvon	1950	100	100	100
	1956	166	107	177
	1960	94	147	137
	1965	147	123	181
	1971	166	131	218
	1976	119	124	148
	1981	67	141	94
	1988	121	125	152
	1993	152	104	159
	2002	135	81	110
Fraserburg	1950	100	100	100
	1956	180	105	189
	1960	110	153	168
	1965	164	116	191
	1971	179	129	230
	1976	147	131	193
	1981	90	166	149
	1988	135	133	181
	1993	140	113	159
	2002	103	67	69
Gordonia	1950	100	100	100
	1956	78	144	113
	1960	76	175	133
	1965	88	200	175
	1971	52	254	132

(*Continued*)

Continued.

District	Year	TFP index	Input index	Output index
	1976	78	269	209
	1981	68	295	199
	1988	76	347	262
	1993	88	300	264
	2002	81	620	500
Kenhardt	1950	100	100	100
	1956	109	127	138
	1960	66	162	107
	1965	106	123	131
	1971	117	123	144
	1976	86	105	90
	1981	66	169	111
	1988	65	183	119
	1993	125	178	222
	2002	67	182	122
Laingsburg	1950	100	100	100
	1956	225	126	283
	1960	155	194	302
	1965	184	184	339
	1971	120	219	262
	1976	127	212	269
	1981	116	193	225
	1988	146	188	275
	1993	132	171	226
	2002	98	119	117
Murraysburg	1950	100	100	100
	1956	98	103	101
	1960	100	111	112
	1965	93	109	101
	1971	131	101	132
	1976	79	115	90
	1981	77	109	84
	1988	55	124	68
	1993	67	95	64
	2002	90	71	64
Namaqualand	1950	100	100	100
	1956	189	92	174
	1960	139	124	171
	1965	211	122	257
	1971	166	116	193
	1976	195	129	251
	1981	120	128	153
	1988	189	106	200
	1993	233	87	203
	2002	143	94	135
Prieska	1950	100	100	100
	1956	119	116	137
	1960	95	145	138
	1965	115	139	159
	1971	144	129	186
	1976	105	136	142
	1981	66	151	100
	1988	107	176	188
	1993	165	150	247
	2002	111	291	324
Prince Albert	1950	100	100	100
	1956	128	117	149

(*Continued*)

Continued.

District	Year	TFP index	Input index	Output index
	1960	101	158	158
	1965	169	138	233
	1971	142	161	229
	1976	107	147	158
	1981	124	145	180
	1988	121	172	209
	1993	106	174	184
	2002	81	145	117
Sutherland	1950	100	100	100
	1956	192	105	202
	1960	81	180	146
	1965	137	153	209
	1971	147	179	264
	1976	132	171	226
	1981	93	233	215
	1988	120	173	208
	1993	117	149	174
	2002	77	96	73
Van Rhynsdorp	1950	100	100	100
	1956	107	132	141
	1960	128	189	242
	1965	160	77	124
	1971	170	75	128
	1976	155	85	133
	1981	114	116	132
	1988	209	123	257
	1993	194	130	252
	2002	170	132	225
Victoria West	1950	100	100	100
	1956	121	102	123
	1960	81	133	108
	1965	110	118	130
	1971	110	124	137
	1976	100	114	114
	1981	79	124	98
	1988	72	131	95
	1993	109	108	118
	2002	61	108	66
Williston	1950	100	100	100
	1956	164	114	187
	1960	130	129	168
	1965	151	137	207
	1971	202	132	267
	1976	118	138	162
	1981	71	183	130
	1988	114	153	174
	1993	111	129	142
	2002	97	81	79