The effect of drought and rising temperatures on total factor productivity in pasture-based dairy farming in the Eastern Cape

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Abstract

A region's climate is determined by its long-term rainfall, temperature, wind and evaporation profile, and weather is the short-term variations around these long-term expected values. This study uses weather to investigate the potential future effects of climate change without making any predictions about when and how much climate change will occur. The study is of the total factor productivity of pasture-based dairy production systems in the Eastern Cape.

An unbalanced panel dataset of 206 observations collected from 62 farms over nine years was used to fit a stochastic frontier production function with technical inefficiency effects. Rainfall is part of the frontier because it is an essential input into dryland pasture production and temperatures are the main inefficiency effects. Since presented by Battese and Coelli (1995) this approach has become a mainstay in modern production economics and its application to climate change is just beginning to appear in the international literature (Qi et al., 2015). As far as could be established, this is the first study of its kind in South Africa.

The stochastic frontier production function takes into account the number of cows in milk, the cost of concentrates fed to cows in milk, the cost of purchased roughage, the cost of fertiliser to grow pastures, and millimetres of rainfall per year. Capital, land and labour inputs were not available, but this was not insurmountable since all three of these factors are used in fixed proportions to herd size. A generalised likelihood ratio test confirmed the existence of significant inefficiency effects associated with daily minimum and maximum summer temperatures and an uneven rate of dissemination. The translog functional form was chosen over Cobb Douglas based on another generalised likelihood ratio test. Output elasticities indicate increasing returns to scale in production and identify cows as the main factor of production followed by the amount spent on concentrates and rainfall. Roughage and fertiliser expenditure are of minor importance in the production process.

The mean level of efficiency was 94% and it varied between 82% and 99%. There is a small but statistically significant difference in efficiency between farms in the coastal belt and those in the interior which reflects the benefits of having access to a reliable source of irrigation water. Productivity is only marginally positively correlated with rainfall ($r = 0.100$, $p \leq 0.153$). It is positively correlated with maximum summer temperatures, indicating better conditions for pasture growth, and strongly negatively correlated with minimum temperatures. This latter is difficult to explain and could be due to irrigation conditions rather than temperature.

The importance of this study is that it demonstrates the viability of a method that could be used to assess the likely effects of the predicted climate change on a specific agricultural enterprise that could help that sector to mitigate those changes more effectively than it would have been able to do in the absence of such study.

Table of Contents

List of Figures

List of Tables

1. Introduction

There is growing concern amongst policymakers and members of the public about the impact of climate change on food security and agricultural sustainability, as droughts and rising temperatures could have adverse consequences for agricultural production, despite technological advances. The climate change predictions for southern Africa include rising temperatures of 1.5°C to 2°C and more erratic rainfall towards 2050 (Engelbrecht, Engelbrecht and Dyson, 2013; Malherbe, Engelbrecht and Landman, 2013). The Intergovernmental Panel on Climate Change (IPCC) predicts that unless society cuts greenhouse gas emissions, the global warming prediction for southern Africa could be as high as $3-6$°C (Niang et al., 2014). Mukherjee, Bravo-Ureta, and De Vries (2013) state that it is not only natural disasters, such as droughts, floods and wildfires that pose a risk towards agricultural output, but also minor climatic variations in temperature and rainfall could have a strong effect if farmers are not adequately prepared. Jury (2020) found a clear warming trend for Cape Town over the period since 1956, which combined with constant to slightly declining rainfall results in more evaporation and less run-off. Hot weather is a limiting factor for livestock production, especially in combination with high humidity, which can lead to decreased livestock productivity. Besides the direct effects on animals, pasture-based production systems are particularly vulnerable to climatic change due to its influence on pasture growth. Adoption of available and emerging innovations to counteract these effects is essential, but farmers require information to shape their perceptions and to formulate appropriate strategies.

The focus of this paper is on dairy farming, a significant agricultural industry in South Africa and an important source of growth and employment. Although global warming is expected to increase both the frequency and severity of heat stress in dairy cattle, there are few studies assessing the impact of global warming on the total factor productivity of the entire production system. This study takes advantage of a recent drought in the Eastern Cape to investigate the effects of greater aridity on the performance of pasture-based dairy farms and thus contributes to the understanding of the effects of climatic variables on dairy farm output (Table 2). By combining stochastic frontier modelling, a popular means of analysing agricultural production efficiency, and climatic variables, this study intends to a contribute to the current literature. Following Qi, Bravo-Ureta and Cabrera (2015) temperature and rainfall variables are used, instead of an index such as the temperature-humidity index (THI), in order to estimate a direct effect of climate change on the dependent variable. The aim is to explain variations in total factor productivity with measures of rainfall and temperature. Battese and Coelli's (1995) technical efficiency effects model is used as theoretical framework to assess the technical efficiency with which all inputs are converted into all outputs.

The remainder of this paper is structured as follows: section 2 provides an overview of the current literature on the link between climatic conditions and dairy milk production; section 3 presents the data and empirical model; section 4 provides a discussion of the results; and section 5 considers the limitations of the study and further work; and section 6 concludes.

2. Total factor productivity models that capture climate effects

As incomes and populations continue to grow, agriculture will have to become more productive without compromising the environment to meet rising global demand for food. According to Mukherjee *et al.* (2013) there are two important factors that must be considered when it comes to dairy farm sustainability. Firstly, an understanding of location-specific heat stress risk and possible adaptation strategies is required. Heat or cold stress in dairy cattle occurs when the effective temperature conditions venture outside of the thermo-neutral zone of 5°C to 25°C. As a result, the cow will need to expend more energy to maintain body temperature and thus less energy can be used for milk production (Qi *et al.*, 2015). Secondly, in order to promote sustainability in the dairy industry, managerial capabilities, often measured by technical efficiency (TE), need to be enhanced so as to contribute to productivity conditions (Mukherjee *et al.*, 2013).

Stochastic production frontiers (SPF) have been widely used to analyse crop and livestock production in a variety of settings (Reinhard, 2000; Hadley, 2006; Bravo-Ureta *et al.*, 2007; Gaspar *et al.*, 2009; Mukherjee *et al.*, 2013; Conradie & Piesse, 2015). The negative effect of weather extremes (e.g. heat stress) on dairy productivity is well documented (St-Pierre *et al.,2013;* Kompas and Che, 2006; Mukherjee *et al.*, 2013; Seo and Mendelsohn, 2008; Rust & Rust, 2013; Key and Sneeringer, 2014; Qi *et al.*, 2015). St-Pierre *et al.* (2003) estimated the total annual economic losses to the United States' livestock industry due to heat stress by comparing animal performance, reproduction, and mortality under current conditions to a hypothetical "ideal" climate scenario. Using a model that relies on experimental data linking dairy productivity to heat stress, the authors estimated a loss of $897 to $1.5 billion (depending on implementation of abatement systems) in the US dairy subsector.

A review of the related economics literature has shown that only in recent years has the SPF approach been used to examine the relationship between weather or climatic conditions, milk production and efficiency. Kompas and Che (2006) assessed the efficiency of the Australian dairy industry and incorporated a dummy variable to account for the 1998 drought in Victoria in a dairy production function analysis. Estimated results for the effect of the drought indicate a substantial reduction in dairy output of 10 per cent, however, the approach used cannot capture the gradual increases in heat likely to result from climate change. Mukherjee *et al.* (2013) incorporated climatic indexes in a stochastic frontier specification and found that these variables explained some of the output shortfall for dairies in Florida and Georgia, which otherwise would have been attributed to management inefficiency. The results indicate that there is little room for productivity growth by enhancing managerial skills and a moderate rate of technological progress. This suggests that future productivity growth in dairy farming can be hampered by a warmer climate in the region. Evaporative cooling produced by fans combined with sprinklers was found to be an effective method of mitigating the impacts of heat stress on dairy cows. Thus, adaptation practices can make a significant contribution to gross farm income. Seo and Mendelsohn (2008) also found that changing livestock species and numbers is a mechanism farmers can be used to adapt to climate change and the negative effect on livestock productivity. These results corroborate Rust & Rust’s (2013) study, which predicted the impact of climate change to be worse in developing countries, as the animals are kept in less protected environments, and are frequently reliant on natural forage.

Key and Sneeringer (2014) incorporated annual average the temperature-humidity index (THI), a measure of thermal stress frequently used by animal scientists, in a stochastic production frontier model. The estimates indicate a robust, statistically significant negative relationship between heat stress (THI load) and milk output. The authors found that, with no market response, the additional heat stress caused by global warming could reduce milk yields for the average US dairy by approximately 0.60% to 1.35% per year in 2030, depending on the climate model scenario. Another point worth mentioning is that these estimated losses do not account for other potential costs of climate change for dairies, including higher prices for feed crops, reductions in pasture growth, or increases in the prevalence of livestock parasites and pathogens. Further, although producers can adapt to mitigate some of the output losses associated with higher THI loads, increasing inputs lowers factor productivity relative to what it would be in the thermoneutral zone. Although the predicted production effects in 2030 are modest, there may be more extreme efficiency losses over a longer time horizon.

Qi *et al.* (2015) specified a novel SPF model to analyse the relationship between dairy farm productivity and climatic effects using a Cobb-Douglas functional form. The model specification made it possible to estimate a total annual climatic effect, as well as partial effects for temperature and precipitation and jointly for all seasons. By analysing the effects of climatic conditions on output in the state of Wisconsin the authors found higher temperature in summer or in autumn to have a negative impact on milk production, whereas warmer winters and springs had a positive impact. Clearly summer temperatures are beginning to exceed the thermoneutral zone for cows while higher winter temperatures are making Wisconsin more suitable for dairy production than it was before. Their analysis also showed that more precipitation was a limiting factor for dairy output.

Cows have a bad reputation for methane production when it comes to climate change and feedlot-based dairy farms are often criticised for point-source water pollution. *Galloway et al.* (2018a,b) found that farm systems which optimized milk production on the available land, while applying the least amount of fertiliser and feeding the least amount of purchased feeds per unit of milk produced, had the lowest environmental impact. This study looked at fertiliser efficiency and carbon footprints. These new insights help to inform efforts to mitigate the sector's environmental impact (Thomassen and De Boer, 2005; Capper et al., 2009), which is significant because dairy is an important source of growth and employment in parts of South Africa. Galloway *et al.* (2018a) analysed a subset of the data used in this study with data envelopment analysis (DEA) and bivariate statistics (ANOVA tests). With five extra years of data in the panel dataset (n = 206), a full stochastic frontier analysis with climatic inefficiency effects can now be attempted. As such, this study contributes to the production economics literature by assessing the effect of heat stress on dairy farms in the Eastern Cape province.

3. Data and modelling

Eastern Cape dairies produce around a quarter of the country's milk, making the province South Africa's second largest milk-producing region, after the Western Cape (MPO, 2020). It is therefore ideal to locate a study of the effect of weather and climate on total factor productivity of dairy farms in this region. The province's humid coastal belt is ideally suited for rain-fed pasture-based dairy farming and in the arid interior, dependable supplies of irrigation water supports a variation of the coastal production system. Both are potentially vulnerable to rising temperatures and more erratic rainfall.

3.1 Origins of the dataset

The data used in this analysis is obtained from Trace & Save, a consulting company which aims to advise farmers on the implementation of sustainable farm management practices. Trace & Save provides measures of various indicators of sustainability on farms to enable participating farmers to monitor and promote more sustainable agricultural practices. The company operates the Woodlands Dairy's Sustainability Project (WDSP) in the Eastern Cape Province, South Africa (Galloway *et al.*, 2018a). Woodlands Diary is a private milk processor and one of the largest manufacturers of UHT milk in South Africa. Located in the heart of the Eastern Cape dairy region in Humansdorp, Woodlands Diary, in partnership with Trace & Save, offers the WDSP as a voluntary service to all farmers that provide milk to them. This project aims to increase cost effectiveness, assist participating dairy producers to become more economically sustainable, and limit the environmental impact of their farming practices. Recently Trace & Save has also taken on clients who are not suppliers to Woodlands Dairy both in the Western Cape and KwaZulu-Natal. In the Eastern Cape Woodlands Dairy sources milk from pasture-fed cows from the Sarah Baartman District Municipality in the western part of the Eastern Cape Province (Figure 1).

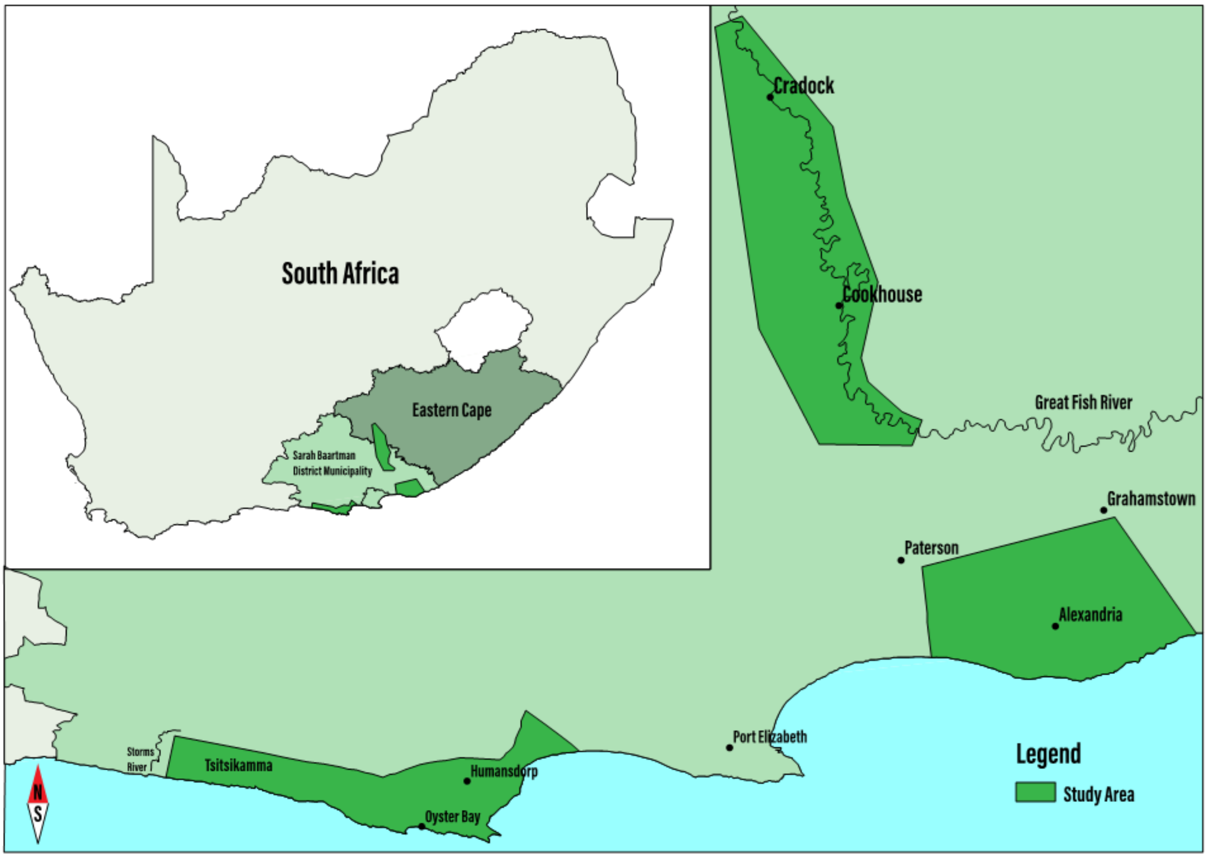

Figure 1: Study area

New clients are continuously recruited by Trace & Save, and data collection is an ongoing process. By October 2020 Trace & Save had six observations for 2020 and 47 observations for 2019. In the 2019 sub-sample there was just one farm which had been in the group from the very beginning (2012). Five farms joined in year two (2013) while nineteen (40%) joined over the last two years (since 2018). For the 2019 subsample of 47 observations, the average time in the group is 3.64 years. The datafile made available by the company in October 2020 contained an unbalanced panel dataset of 218 observations from twelve production areas of which four are in KwaZulu-Natal (n = 11) and one in the Western Cape (n = 6). The Western Cape data was retained but observations from KwaZulu-Natal deleted because it was not possible to source suitable climate data for those observations in the time available. This left a dataset consisting of n = 206 observations from 62 farms collected between 2012 and 2020. The time coverage is sufficient to capture the effect of temperature and rainfall on farm productivity and the spatial coverage provides useful insight into how climate mitigation can be approach differently depending on the production context.

Most of the variables of interest were available, and although the Trace & Save dataset does not have all the variables needed to fit a comprehensive stochastic frontier model, its time coverage is much better than would have been possible the researcher independently had to collect primary data (Galloway *et al.*, 2018b). Although not without its challenges, using this source is time-saving and cost-efficient, however the disadvantage is that certain important variables such as labour input were not available.

Each observation in the Trace & Save dataset was identified with a unique farm number and the production year to which the data refers. It also indicated the production area, usually a sub-district, and lists several inputs and outputs at the farm level. Output was measured in energy-corrected litres of milk which takes milk solids into account (Table 1)[1]. Cows is a simple count of the animals in production, in other words it excludes dry cows and heifers, which are raised on all farms in the sample. Fodder and fertiliser expense are measured in nominal South African Rand (ZAR) and rainfall is in millimetres per year. See Table 1. In order to model temperature, mean maximum and minimum summer temperatures were appended from data obtained from nine weather stations in the study area.

3.2 The typical pasture-based dairy farm

Dairy cows are fed on a combination of roughage (or "hay") and high-energy and protein-rich concentrates into which the right balance of micronutrients is usually mixed in. These two types of feeds are complements in the production process, although Galloway *et al.* (2018) established that some less efficient farmers do treat them as substitutes. Almost all dairy farms buy concentrates, but roughage can be purchased or grown on the farm. If roughage is bought, milk can be produced under feedlot conditions, in a system that is referred to as total mixed rations (TMR) production. The alternative is to grow roughage on the farm and utilise these pastures through grazing and by cutting surplus fodder for hay and silage. There are no pure TMR observations in this dataset although some farms have to supplement farm-produced roughage with purchased hay, equivalent to R2.15 million per year. The proxy for farm-produced roughage is the farm's expenditure on fertiliser, which amounts to R1.46 million per year. Both these amounts are tiny compared to concentrates which cost more than R9 million

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[1] Energy corrected milk production corrects raw litres for butterfat and protein percentages to reflect the impact of these variables on the farm-level milk price. For example, if a farm produces a million litres of milk with an average butterfat of 4% and an average protein content of 3%, then its energy corrected milk output is calculated as: litres of milk production x {[(0.383 x butterfat%) + (0.242 x protein% + 0.7832]/3.14}, which equals 968,535 kg of energy corrected milk (Galloway, 2018a).

per year. It is fortunate that there are no TMR farms in the sample since TMR farms will experience climate change quite differently from pasture-based production systems and have a different environmental impact (Galloway *et al.*, 2018b).

Table 1: Descriptive statistics for the pooled sample of 62 farms over 9 years (n=206)

Variable name	**Description and units**	**Mean**	**Std deviation**
Frontier variables			
Output	Energy corrected milk in litres	6,011,94	3,478,832
Hay bought	Expense in ZAR millions	2.15	2.37
Cows	Number of cows in milk	847.42	451.74
Concentrates	Expense in ZAR millions	9.05	5.24
Fertiliser	Expense in ZAR millions	1.46	1.19
Inefficiency effects			
Rainfall	In millimetres per year	630.89	260.18
S max	Average monthly maximum summer temperature (January– March)	27.08	2.08
S min	Average monthly minimum summer temperature (January– March)	15.31	1.93

On dairy farms male offspring are usually sold off within days of birth. Some farms raise their own heifers while others operate progeny share schemes in which heifers are raised by third parties off-site. Details vary and the choice of strategy obviously has implications for feed requirements and feed use efficiency. To avoid these complications the sample was limited to farms that raise their own heifers. Another important partial productivity indicator is inter-calf period which measures the ratio of productive to unproductive cows in the herd. This sample did not come with information on the proportion or number of dry cows in the herd but since the inputs required for the upkeep of dry cows are reflected, longer inter-calf periods will show up as lower efficiency levels.

The typical farm is family owned and operated and has an average of 847 cows in milk and an produces an average annual output of 6,011,694 litres of energy corrected milk. Table 1 presents the descriptive statistics for output, inputs and climatic variables.

This spatial variation in the dataset introduces rainfall variation and a difference in the degree of access to irrigation water. Due to higher more regular rainfall on the coast, irrigation is less important on coastal farms than in the interior, where rainfall is typically limited to the summer season only. But dairy farmers congregate along the Great Fish River because this area is served by the Fish Sundays irrigation scheme, a reliable source of cheap irrigation water. Fodder production is predominantly rain-fed along the coast, while further inland it is fully irrigated (Galloway *et al.*, 2018a).

3.3 Climate and recent weather in the study area

Climate is the expected rainfall, temperature, wind and evaporation conditions of an area, and weather is the random noise around the long-term mean. In other words, climate *change* predictions expect a change in average weather conditions, which will only become apparent over time. Many studies have attempted to predict climate change for South Africa (e.g. Engelbrecht *et al.*, 2013; Malherbe *et al.*, 2013; Williams *et al.*, 2016) and there is growing international consensus on how to approach such modelling exercises. In this study the recent variation in weather is used to test the effect of greater aridity or more heat on farm productivity. In the process no claims are being made about whether weather patterns are evidence of climate change or simply expressions of the climate's normal variability, and for the purposes of this study it does not matter which of the two is true. The aim is simply to investigate how observed variations in rainfall and temperature affect farm outcomes.

Pasture-based production systems are more vulnerable to climate change than TMR systems because pastures are rainfed. As noted above, climate change predictions for southern Africa include rising temperatures of 1.5℃ to 2℃ towards 2050. It is anticipated that it will become drier in the southern African region, with slightly higher total annual rainfall in the central parts of the country and the Eastern Cape (Williams *et al*., 2016; Jury, 2020). Even if rainfall does not decrease, aridity will increase due to higher rates of evaporation at higher temperatures. The effect on rainfed production could be substantial (Kurululasuriya *et a*l., 2006). In some parts of Africa crops will be replaced by extensive livestock production (Jones and Thornton, 2009) and livestock will become sicklier and less productive (Rojas-Downing et al., 2017). There is still some degree of uncertainty, as Gbetibouo and Hassan (2005) predicted climate change to have only mild effects on crop production, while Conradie *et al.* (2019) have shown low rainfall and low rainfall interacted with high temperatures already to have a significant impact on total factor productivity in Karoo agriculture.

Table 2: Percentage deviation in rainfall from long-term average for some Eastern Cape sites

	Avg. rainfall (mm)	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Tsitsikamma	836.7	+3%	+12%	+14	-5%	-10%	-	+4%
Alexandria	617.1	-27%	+15%	+49%	-30%	+4%	-31%	-23%
Cradock	307.2		+35%	+13%	-16%	+47%	+7%	-13%

Table 2 compares rainfall figures recorded in the Trace & Save dataset to long term data for three locations in the study area as recorded in Midgley *et al.*'s (1990) Surface Water Resources Atlas for South Africa. It reveals that 2014 and 2015 were comparatively good years across the Eastern Cape, while 2016 and 2017 were drier than normal at most locations in the study. In 2018 and 2019 conditions varied from region to region. Delving down to the farm level there is even more variation. For example, in Tsitsikamma where mean rainfall was equal to the expected value in 2018, individual figures varied from -14% to +22% of the long-term average in that year. There is therefore a good chance that rainfall will affect productivity.

Dairy cattle may be affected by heat stress due to higher temperatures, beyond what can be modified by shade and evaporative cooling. The comfort zone for a cow is 5-25°C, much lower than for humans. When ambient temperature exceeds 25°C, with concurrent humidity, solar radiation and low air movement, the risk of heat stress increases. When the heat load is greater than a cow's capacity to lose heat, it will increase respiration rates, decrease voluntary feed intake and increase water intake. As the cow spends more energy on cooling down, milk production will decrease. Temperatures exceeding a lactating dairy cows' thermal neutral zone are known to decrease the protein, lactose, and fat percentage of milk (Key & Sneeringer, 2014). As heat stress caused by future climate change is predicted to increase, the negative impact on milk production will become more severe (Williams et al., 2016). Figure 2 shows the projected mean temperature range for January for 2046-2065 for southern Africa relative to the historical long-term. Rising temperatures may impact certain milk-producing areas in South Africa more than others (Meissner et al., 2013; Williams et al., 2016). Tsitsikamma, Oyster Bay and Humansdorp are predicted to warm more than most coastal areas in South Africa and the Fish River Valley will warm to the same degree as the coastal belt.

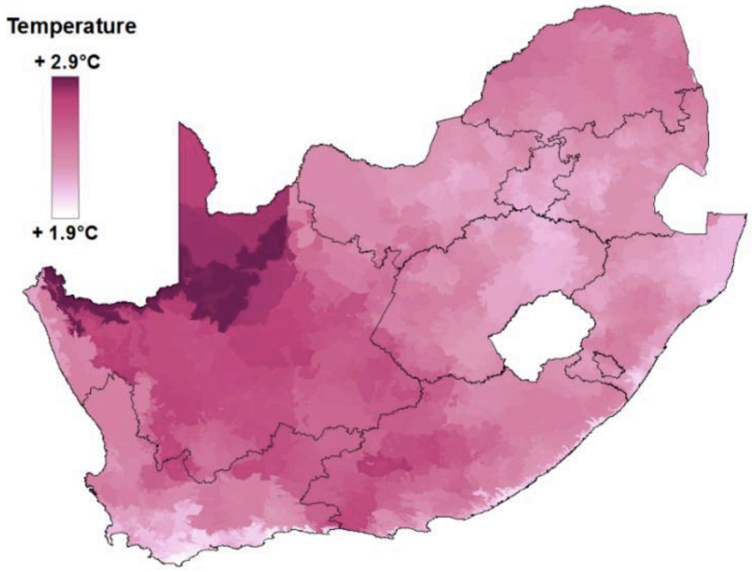

Figure 2: Projected January temperatures for 2046-2065 relative to the historical long-term mean (Source: Williams et al., 2016)

It was not possible to get raw temperature data for this study, and so it was not possible to specifically consider heat stress, for example, as days above 25°C. Raw data had already been summarised into average maximum and average minimum temperature per month at each weather station. Since summer temperatures are of most interest, an average of averages was calculated for the period January to March for minimum and maximum temperatures. These were also averaged to find a mean daily summer temperature, which is unlikely to provide much traction since most of the variation is already averaged out. At Cradock January 2014 was 25% hotter than the previous January during the day and 11% hotter than the previous January at night. Average maximum temperatures in January was higher than 30°C in Cradock in every year of the study, suggesting that heat stress might already apply on some farms in the sample. Since minimum summer temperatures fall within the range of cow tolerance, these are not expected to correlate with observed variations in productivity.

3.4 A model of farm productivity that accounts for weather differences

Total factor productivity (TFP) is a measure of technical efficiency calculated from all inputs and outputs involved in the production process. TFP analysis can be conducted using parametric or non-parametric methods. Data envelopment analysis (DEA) is the most basic non-parametric method. It uses linear programming to define a piece-wise linear best practice frontier which fits snugly around a set of observed input and output bundles. The best performers in the group trace out the frontier and each suboptimal firm's full deviation from this frontier is interpreted as its level of (technical) inefficiency. The main advantage of this approach is that it can be applied graphically for a very small number of observations and its main disadvantage is that it completely ignores potential measurement error.

For larger datasets where data quality might be a problem, it is useful to be able to detect measurement error. In 1977 Aigner, Lovell and Schmidt and Meeusen and van de Broeck independently presented the first stochastic production frontier (SPF) model (Battese and Coelli, 1995). Instead of assuming a normally distributed error term, as OLS models do, the SPF model extracts the non-normal portion of the error term leaving behind a normally distributed residual, v, which has all the same properties as the usual ε-term in an OLS model. The non-negative extracted component, u, is called the inefficiency term. Graphically u measures the deviation from the statistically determined best practice frontier for each observation in the sample. As in the OLS model, the normally distributed component of the SPF model's error structure captures mismeasurement and other random shocks to the system such as pest and disease infestations (Hadley, 2006).

The stochastic frontier production function model with climate-based inefficiency effects uses input and output data to fit a benchmark (equation 1) and explains deviations from the frontier (inefficiency effects) with temperature variables (equation 2). This specification is an application of Qi et al.'s (2015) technical efficiency effects model. This study specifies the stochastic production frontier using a translog (TL) functional from in which the natural logarithm of milk output is expressed as a second order log-linearised (all cross-terms included) function of key dairy inputs. All the variables are normalized by their geometric mean, and thus it is possible to interpret the first-order parameters directly as partial output elasticities (Coelli et al. 2003). The advantage of the TL functional form is that it avoids the Cobb Douglas restriction of a constant elasticity of substitution between inputs, but with more parameters to be fitted, TL demands more degrees of freedom.

The general model is:

$$\ln Y_{it} = \alpha + \sum_{k=1}^{K} \alpha_k \ln x_{kit} + \sum_{k=1}^{K} \sum_{j=1}^{J} \alpha_{kj} \ln x_{kit} \ln x_{jit} + v_{it} - u_{it} \qquad [1]$$

$$i = 1, 2, \ldots, N = 62$$

and

$$-u_{it} = \beta_0 + \sum_{m=1}^{2} \beta_m \cdot z_{mit} + w_{it} \qquad [2]$$

in which ln denotes a natural logarithm; Y_{it} is the energy corrected milk output of farm i measured in litres in period t; the subscript k *(j)* refers to the *k*th input (*j*th input) and z_{mit} is the *m*th climatic variable determining inefficiency. The vectors of α's and β's are parameters to be estimated. A typical mean response (or OLS) model assumes that $u_{it} = 0$, in other words, that there is no inefficiency. The causes of $u_{it} \neq 0$ include exogenous factors, such as farm location, institutional arrangements or business cycle effects. Farm-specific variables such as employee and location variables could not be included in the regression as the entire dataset was received in anonymised form and if present they would also show up as part of the inefficiency effect.

Technical efficiency scores compare actual outcome to potential outcome given the same level of inputs, according to equation [3]. When $u_{it} = 0$, the normal mean response production lies on the stochastic frontier production function and the system is technically efficient, and when $u_{it} > 0$, production lies below the frontier and is technically inefficient.

$$TE_i = \frac{Y_i}{Y_i^*} = \frac{f(x_i; \beta)(v_i - u_i)}{f(x_i; \beta)(v_i)} \qquad [3]$$

The optimal functional form depends on whether the coefficients on the square terms and interaction variables in the TL functional form are statistically significantly different from zero.

This is tested with a generalised likelihood ratio test where:

$$LR = -2(\log likelihood_{restricted} - \log likelihood_{unrestricted})$$

This test is chi-squared distributed with degrees of freedom equal to the number of restrictions. If the test statistic is less than the critical value, we fail to reject the hypothesis that the Cobb Douglas restriction is true, in which case Cobb Douglas is an adequate representation of the data. On the other hand, rejecting the Cobb Douglas restriction means that translog is a better representation of the data than Cobb Douglas.

The same test is used to check if inefficiency effects are present. In this application the mean response model imposes restrictions on the stochastic frontier model equal to one plus the number of z-variables in equation [2]. The extra degree of freedom is taken up by gamma, the proportion of the overall error variance that explained by u_{it} (Battese and Corra, 1977). This result follows the mixed chi-squared distribution presented in Kodde and Palm (1986). The unknown parameters are estimated by maximum-likelihood using the programme FRONTIER 4.1 (Coelli, 1996) and analysis of efficiency patterns was conducted in Stata 15.1.

In this study, the basic production function has four inputs: the cost of purchased roughage in ZAR; the cost of concentrates fed to cows in milk in ZAR; the number of cows in milk; and the cost of fertiliser in ZAR, which together produce energy corrected milk, a quality-adjusted output measure. Descriptive statistics are in Table 1. The plan was to follow Qi *et al.* (2015) a study that populated the inefficiency sub-model with various temperature and rainfall variables. However, in this case, extensive experimentation with alternative specifications revealed that rainfall was an essential frontier variable which left temperature as the main explanatory variable in the inefficiency sub-model. Following Battese and Coelli (1992) a time trend in the frontier will provide for Hicks neutral technical progress and another in the inefficiency model will check for convergence. This specification ignores meat income and any incidental income from cow or heifer sales (<8%). It also ignores land, labour and capital use, which are not reported in the Trace & Save dataset made available for the study in October 2020.

Some of these omissions are more problematic than others. Animal sales income is small enough to be ignored. It is obviously problematic not to have capital or labour, but since the focus is on the role of climate in determining productivity, the only measure of capital that really matters is irrigation equipment. However, it would have been useful to have labour data, which Trace & Save considers too sensitive to collect (Galloway *et al.*, 2018a). It is safe to assume that the remainder of capital and most labour are used in fixed proportions to cows. Not having land is not a great problem either. In a homogenous production region, like the Eastern Cape, the degree of correlation between land and livestock is often so high that the statistical fit of the production function is compromised when both variables are included. To avoid this, either land or livestock must be omitted (Reinhard *et al.*, 2000). Conradie and Piesse

(2015) and Gaspar *et al*. (2009) avoided the multicollinearity problem by using a per-animal specification (which implicitly drops livestock). In this study, since output is determined by cows rather than by the land, it justifies the inclusion of herd size as opposed to land. Conradie (2019) followed a similar total-farm approach when specifying a sheep production frontier for the extensive grazing areas.

Cows are expected to explain most of the observed milk production and cows are usually complements to fodder. Within the fodder category, roughage and concentrates are provided for. As explained before, these two important elements of dairy cows' diets are expected to be complements in production. Farm-produced pasture are a potential substitute for purchased roughage and fertiliser cost is used as a proxy for the pasture production process. Concentrates, purchased roughage and fertiliser are defined in value terms and are inflated to 2020 prices using the appropriate price indices from the Abstract of Agricultural Statistics published by the National Department of Agriculture (DAFF, 2019). The inputs measured in physical units require no inflating. The model should produce positive and significant coefficients on all the factors of production.

As mentioned above, the specification of the inefficiency model departed from the ideas in Qi *et al*. (2015) but like these authors substantial difficulty was experienced in getting these variables to work. Rainfall is both a weather condition and a primary input in rainfed agriculture, and therefore could either go in the frontier or in the inefficiency model. In Qi *et al.* (2015) rainfall was mostly insignificant in the frontier. There is still no consensus in the literature on how to model temperature in technical efficiency effects productivity models. In a Ricardian model of climate change, Gbetibouo and Hassan (2005) use "winter" and "summer" temperatures without specifying the months involved or whether these are minimums, maximums or averages. Levels and squared terms are included in their preferred model. Mendelsohn *et al.* (1994) selected just one reference month for each of the seasons of the year and worked with daily averages calculated from raw data. The four seasons are included separately in the Mendelsohn model. Qi *et al.* (2015) populated the inefficiency model with quarterly mean temperatures and the months included in the calculation varied from quarter to quarter depending on mean temperature, several of which were insignificant, while Dinar *et al.* (2007) combined temperature and rainfall in an aridity index that was used as a primary factor of production in a technical efficiency effects model developed to study the effects of extension on farm productivity. Recently, Mukherjee *et al*. (2013) and Key and

Sneeringer (2014) incorporated a temperature-humidity index (THI) in stochastic frontier models and found a significant negative effect on milk production.

In this study after much experimentation the best fit was obtained when annual rainfall was logged and treated as a basic factor of production in the frontier. Modelling summer and winter temperatures separately as average maximums and minimums produced results of very low face validity. Endless combinations of summer maximum, winter maximum, summer minimum and summer maximum temperatures were tried and rejected. As a last resort minimum and maximum temperatures were combined into average temperatures that were averaged across the year to identify cooler and hotter production seasons, but this also did not give the desired results. The final specification presented in Section 4 use only summer temperatures (January – March). In this model maximum and minimum temperatures are entered as two variables in the inefficiency submodel and this seems appropriate since the cow comfort zone $5 - 25°\mathrm{C}$ (Qi *et al.*, 2015) is rarely exceeded in winter.

The effects of heat stress depend on a number of factors, which were not included in this study due to data limitations. The available dataset did not allow us to control for physiological and climate factors such as the age and breed of the animal, humidity, solar radiation, air flow, and duration of exposure to heat, which can have an influence on the effects of heat stress on livestock productivity (Key & Sneeringer, 2014). Further, production and livestock management practices are also expected to alter the effect of heat stress. Individual farmers' adaptation mechanisms, such as the quantity and quality of feed, as well as the use of shade structures or cooling equipment could not be taken into account. In St-Pierre *et al.* (2003), the total cost of heat stress is conditional on the extent farmers spent to mitigate heat stress, ranging from no mitigation (suboptimal), spending until the marginal benefits of mitigation equal marginal costs (optimal), to complete mitigation (super-optimal). As a result, of limited information regarding specific management practices and animal characteristics, as well as the limited geographical region, the study may not be representative at the national level but still contributes to the understanding of the effects of heat stress on livestock productivity. Further, dairy operations are universally impacted by weather and climate and this study provides a novel analysis on this issue.

In the production function rainfall is expected to be a substitute for purchased roughage and a complement to concentrates. Higher maximum temperatures are expected to reduce cow productivity and cow productivity is not expected to be affected by higher summer minimum temperatures which fall within the cow comfort zone.

3.5 Results of the Customary tests of model specification

Once the climate model was finalised the usual specification tests could commence. Three tests are normally conducted to establish the presence of a frontier, check for Hicks neutral technical progress and/or convergence of efficiency scores, and to choose a functional form. Since the entire study is predicated on the existence of inefficiency effects, the frontier test was the first to be performed, and it was done on the simplest specification of the simplest functional form. Time trends were then added into the production function and inefficiency sub-model to conduct the second test. In test 3 the surviving model was formulated as Cobb Douglas and translog and in test 4 the specification of the inefficiency sub-model was refined.

All four questions are assessed using generalized likelihood ratio tests where the test statistic is $LR\ stat = -2[LLH_{restricted} - LLH_{unrestricted}]$. For these tests, the restricted model must be nested within the unrestricted model. A restriction is valid if imposing it makes no difference to the log likelihood value produced by the maximum likelihood restriction, but if the unrestricted model produces a better fit, resulting in a positive and significant LR test statistic, the restriction is rejected (Gujarti, 2003). These test results are presented in Table 3 and they should be read with the main statistical results in Table 4.

Table 3: Specification tests

	(1) Is this a frontier?	**(2) Progress and convergence**	**(3) Cobb Douglas or translog?**	**(4) Which temperatures?**
Hypothesis	$\gamma = \delta_i = 0$	$\beta_{20} = \delta_3 = 0$	$\beta_{ij} = 0 \vee i \neq j$	$\delta_2 = 0$
Restrictions	4	2	15	1
Critical value	8.761	5.138	24.384	2.706
LLH restricted	142.79	148.57	124.87	149.44
LLH unrestricted	148.57	149.78	148.57	148.57
Test statistic	11.56	2.416	47.40	-1.731
Conclusion	Reject	Fail to reject	Reject	Fail to reject

The log likelihood test in column (1) tests whether there is inefficiency, by comparing the ordinary least squares (OLS) model to the stochastic frontier model to confirm the existence of gamma, the one-sided inefficiency term. The OLS model restricts gamma to zero and thus is the restricted version of the stochastic frontier which allows gamma to take on any value. The log likelihood statistic of the OLS model was 142.24, while the production frontier's log likelihood statistic was 148.78. The test statistic has a mixed chi-squared distribution and a value of $LR = -2[142.79299 - 148.57456] = 11.56$. The critical value for 4 degrees of freedom - four being the number of omitted variables – at $p < 0.05$ is 8.761 (Kodde and Palm, 1986). The test confirms the existence of a best practice frontier as there is inefficiency present.

To test whether there is evidence of technical progress and convergence, we compare the restricted model which excludes the time trends from the frontier as well as the inefficiency module ($\beta_{20} = \delta_3 = 0$) to the full model. This is the second test reported on in Table 3. Since the critical value is larger than the test statistic, we fail to reject the null hypothesis and thus the restrictions are appropriate. Therefore, the time-trends, which capture technical progress and convergence, are dropped from the preferred specification.

Test 3 in Table 3 investigates functional form. The restricted model is Cobb Douglas and the unrestricted model is its second-order Taylor expansion, translog, which includes both the basic Cobb Douglas variables as well as the squares and cross products. The log likelihood statistic of the Cobb Douglas frontier was 124.87, while the translog frontier's log likelihood statistic was 148.57. The test statistic has a mixed chi-squared distribution and a value of $LR = -2[124.87177 - 148.57456] = 47.40$. The critical value for 15 degrees of freedom at $p < 0.05$ is 24.384 (Kodde and Palm, 1986). As this figure is lower than the log likelihood test statistic, the null hypothesis is rejected at the chosen level of significance. Therefore, the translog specification is favoured over the Cobb Douglas.

The final test reported on in Table 3 refines the specification of the inefficiency sub-model. Table 4 reveals that the translog specification produced an insignificant coefficient on summer minimum temperature (δ_2) and that the coefficient on gamma was insignificant too. This suggested that $\delta_2 = 0$ and that there would be no difference in maximum likelihood values between the restricted model in Appendix B and the result of the unrestricted model printed in Appendix A. The maximum likelihood values of 148.57 and 149.44 were indeed within 1% of each other, but contrary to expectations, the restricted model produced a larger value than the unrestricted model, hence rendering the test invalid. The fail to reject conclusion reported in Table 3 was based on the lack of difference between the two specifications' maximum likelihood values.

4. Results and discussion

4.1 Estimation results

The maximum likelihood estimates (MLE) of the translog specification and the Cobb-Douglas model are present in Table 4. As mentioned above, these estimates were produced with the stochastic frontier software package Frontier 4.1. The input and output files are printed in full in the appendix. When comparing the translog and Cobb Douglas specification it is clear the former has a higher maximum likelihood value, a higher mean efficiency score and higher returns to scale. Both models indicate the presence of increasing returns to scale, which is calculated by summing the elasticities of output with respect to the five inputs. For the translog model this is only possible because of the use of mean centred data. For the conventional inputs, some of the notable differences between the two models include; the stock of cows in milk make a 3% smaller contribution in the translog specification; the contribution of concentrates (fed to cows in milk) is also smaller, while the coefficients on roughage and rainfall are larger in the translog than the Cobb Douglas model. Fertiliser is also larger and significant at the $p \leq 0.05$ level in the translog specification, whereas it has an insignificant effect on milk output variation in the Cobb Douglas model.

As the translog specification is preferred to the Cobb Douglas, this section will focus on the output elasticities thereof. The dairy herd size was the main factor influencing output, which is consistent with several other papers that have a similar specification (Mukherjee et al., 2013; Qi et al., 2015; Key & Sneeringer, 2014). This indicates that output is most closely correlated to the number of cows in milk where a 1% increase in the number of cows will result in a 0.83% increase in the milk output. The second most important input is that of concentrates, with an output elasticity of 0.17 and is also significant at $p \leq 0.01$ in both models. This is followed by rainfall whose output elasticity is 0.11. The intermediate inputs roughage and fertiliser are the least important inputs, with output elasticities of 0.02 and 0.04, respectively. Although these coefficients are relatively small, they are still measured with a high level of precision.

Table 4: Final stochastic frontier production function with temperature effects

	Translog functional form				**Cobb Douglas**			
Variable names	**Coef**	**SE**	**t-ratio**		**Coef**	**SE**	**t-ratio**	
Constant	0.00	0.04	-0.09		6.14	0.36	17.01	***
Cows	0.83	0.04	19.76	***	0.86	0.04	23.00	***
Roughage	0.02	0.01	3.83	***	0.00	0.00	2.05	**
Concentrates	0.17	0.04	4.74	***	0.18	0.03	5.51	***
Fertiliser	0.04	0.02	2.17	**	0.03	0.02	1.50	
Rainfall	0.11	0.03	4.16	***	0.06	0.02	2.96	***
Cows x Cows	0.28	0.12	2.29	**				
Cows x Roughage	-0.01	0.01	-0.74					
Cows x Concentrates	-0.52	0.18	-2.82	***				
Cows x Fertiliser	0.04	0.07	0.53					
Cows x Rainfall	-0.04	0.09	-0.41					
Roughage x Roughage	0.00	0.00	3.12	***				
Roughage x Concentrates	0.01	0.01	1.43					
Roughage x Fertiliser	0.00	0.00	0.63					
Roughage x Rainfall	0.00	0.00	0.41					
Concentrates x Concentrates	0.16	0.08	2.00	**				
Concentrates x Fertiliser	-0.02	0.07	-0.33					
Concentrates x Rainfall	0.15	0.09	1.63					
Fertiliser x Fertiliser	-0.01	0.02	-0.44					
Fertiliser x Rainfall	-0.07	0.04	-1.71	*				
Rainfall x Rainfall	0.09	0.03	2.82	***				
Constant	1.47	0.55	2.70	***	2.48	2.24	1.11	
Mean summer max temperature	-0.06	0.02	-2.72	***	-0.13	0.12	-1.12	
Mean summer min temperature	0.00	0.01	0.21		0.04	0.03	1.31	
Sigma squared	0.02	0.00	4.26	***	0.06	0.04	1.62	
Gamma	0.33	0.25	1.30		0.81	0.13	6.44	***
Log likelihood statistic on frontier	148.57				124.87			
Log likelihood for mean response	142.79				117.26			
Average efficiency score	94.76%				91.95%			
Observations	206				206			

$*** \ p \leq 0.01$, $** \ p \leq 0.05$, $* \ p \leq 0.10$

Only one of the five square terms produced a coefficient that is not significant, which indicates a linear relationship between milk output and intermediate input fertiliser. Cows in milk are a non-linear input which interact with concentrates but is used in fixed proportions with fertiliser. In addition, milk output increases with additional cows, concentrates, and roughage. The negative sign on the interaction between cows and concentrates indicates that the two inputs are substitutes. Output and rainfall are non-linear and fertiliser and rainfall are substitutes, as expected. On the other hand, concentrates and rainfall are complements in production.

The inefficiency sub-model has two variables, namely mean summer maximum temperature and mean summer minimum temperature. Only the summer maximum temperature is significant at the $p \leq 0.01$ level in the translog specification. The negative sign on summer maximum temperature indicates that warmer days are beneficial for total factor productivity, and thus climate change is not yet a threat. A possible reason for the reduction in inefficiency is that, although higher temperatures are uncomfortable for the cow, they are conducive to pasture growth, except where there is significant water stress. Thus, better pasture growth results in more production from less bought feed (roughage and concentrates), which is the most expensive input on a dairy farm. Further, the highest temperatures are recorded in the Fish River region, which is where the most efficient/profitable farmers are located as they have not been heavily influenced by the drought due to a consistent supply of irrigation water. Dairy farmers are also very aware of the issues associated with heat stress and have become quite proficient at preventing cow distress by providing ample drinking water for cows, adjust cow diets and to provide evaporative cooling and adequate shade.

4.2 Variations in efficiency

This section takes a closer look at how technical efficiency (TE) varies over time, between production regions and in response to temperature. The average level of farm efficiency was 94%, with efficiencies varying between 82.0% and 99.1%. Since the estimates are predicated on the observations in the sample it is not possible to say if this performance is good or bad in relation to other studies, except that this is a relatively small sample and when know that larger samples would *ceteris paribus* result in lower efficiency scores.

4.2.1 By year and region

Figure 3 shows the distribution in efficiency levels over time. Mean efficiencies have gratifyingly steadily increased from 89.27% in 2012 to 96.14% in 2020 but it should be noted that there were only three participants in 2012. In some years there was more within group variation than in other years and it seems reasonable to attribute these performance differences to differences in growing conditions. For example, in 2014 all the observations were within nine percentage points of each other, varying from a low of 89.11% to a high of 99.11%. Except for 2020, when the lowest score on record was 93.8%, the 2014 production season was the year with the highest minimum efficiency level on record. According to Table 2 all three production regions were wetter than normal in 2014. In contrast 2018 and 2019 were more difficult production seasons, with a severe drought in Alexandria. The minimum score recorded in 2018 was 83.8% and almost one in five firms produced efficiency levels of less than 90%. In 2019 the minimum score fell to 82.5% and one in five firms were less than 90% efficient.

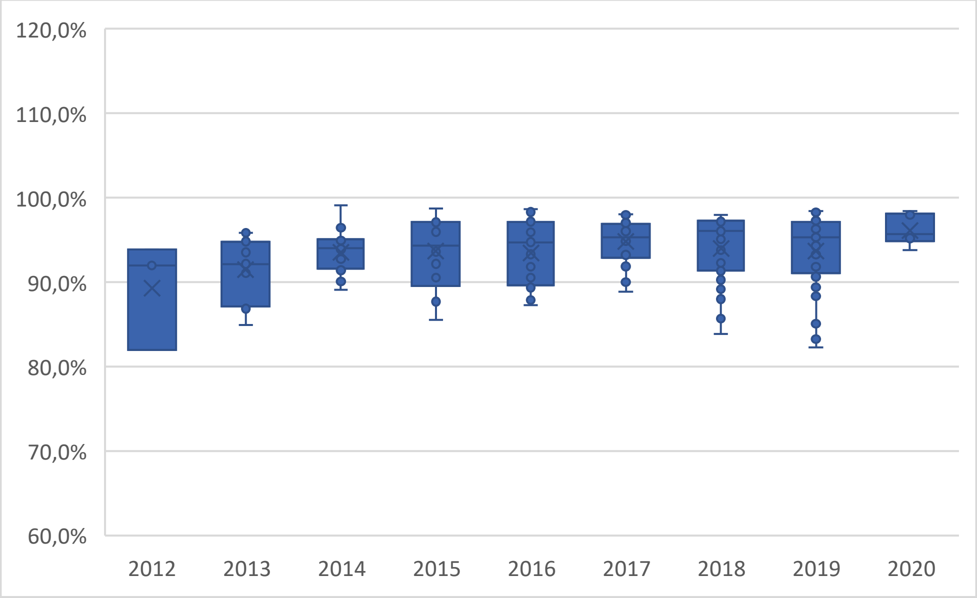

Figure 3: Efficiency differences by year

The data in Figure 3 sheds some light on the ability of Trace & Save to deliver technical progress for its members. With Trace & Save sharing a standard pasture management recipe for enhanced efficiency, the least efficient farms in the group stand to benefit most from catching up to the group's leaders. In the box-whisker plot above, median efficiency scores (indicated by the horizontal blue line in the blue box) and mean scores (indicated by the blue crosses) are expected to rise over time indicating a benefit to Trace & Save membership. While the trend may not be entirely statistically significant, there is some evidence of increasing technical efficiency in Figure 3. An Analysis of Variance (ANOVA) test was used to test the hypothesis that the groups all have the same mean. As the significance value of the F-test (0.084) is greater than 0.05, the null hypothesis that mean efficiency scores are equal across years cannot be rejected. In other words, the result indicates that the efficiency scores did not differ significantly from year to year. However, if one looks closely this impression is heavily influenced by the low mean value recorded in 2012 (89.27%) and the high mean value for 2020

(96.14%), but neither of these subsamples are representative of the group. In 2012 the group was just starting off and in 2020 only nine firms had filed by the time data was extracted and it would be reasonable to expect that firms that have been in the group longest would be the first to file. If 2012 and 2020 were disregarded, the technical progress trend for the remaining years is less obvious, which is unsurprising as it is highly unlikely that a single independent consulting company would be able to advance dairy production technology single-handedly. Other explanations could include the short timeframe of the study or the negative effects of the drought on most businesses.

Minimum and maximum values matter for convergence, and as explained, in this case the main mechanism for convergence is by weaker firms catching up to group leaders. Efficiency scores were the most tightly grouped in 2014, which also produced the highest maximum and highest minimum scores in the pooled sample. This was an exceptional year with above average rainfall in all three production areas (Table 2). In contrast data was widely dispersed in 2018 and 2019, where the minimum scores were 83.8% and 82.3% respectively. There are two possible explanations for the greater dispersal in these years, namely difficult growing conditions, especially in Alexandria, which was in the middle of a severe drought, or due to the inexperience of new group members. Close inspection shows that both firms recording the poorest performance in 2018 and 2019 had been in the group for at least five years, which lends more weight to the adverse weather argument.

Figure 4 provides a regional perspective. The author suspects that Oyster Bay, Humansdorp, Cradock and Cookhouse are doing better than the other areas due to their long-term relationship with Trace & Save employees dating back to years before the start of the Woodlands sustainability monitoring project. The wide dispersal amongst farmers in George is a case in point. These producers were only recently recruited into the group and the weakest among them had not yet been able to fully adopt all recommended practices. The few group members in Cookhouse and Cradock on the other hand had been in the group from the beginning and are now operating close to the frontier. The results of the ANOVA procedure confirm this hypothesis, suggesting that mean efficiency scores differed significantly between regions[2]. It is clear that, by promoting the efficient utilization of both novel and existing technologies and practices, Trace & Save employees improve farmers' know-how and managerial abilities.

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[2] Significance = 0.000

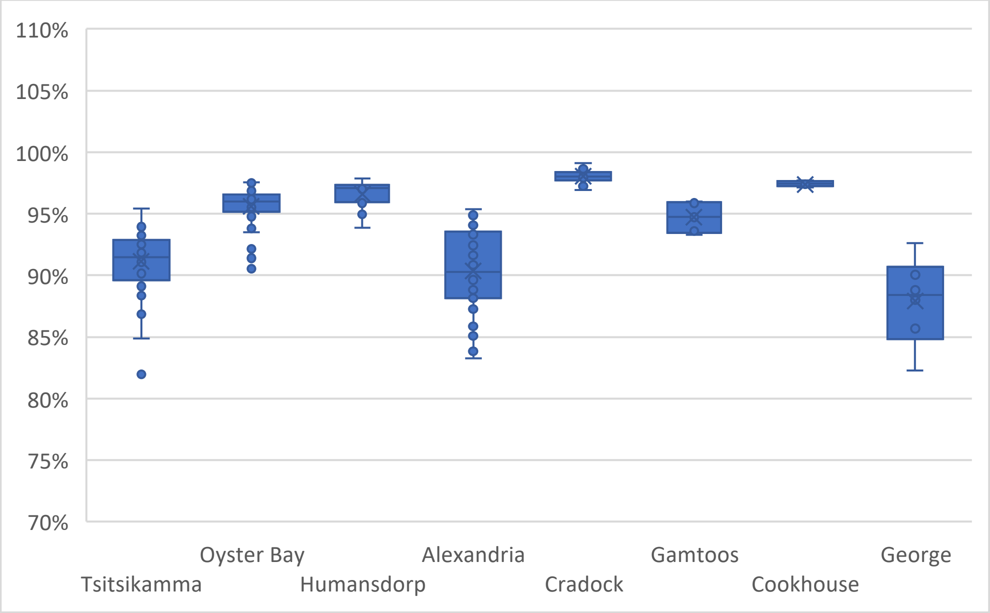

Figure 4: Efficiency differences by location

4.2.2 Efficiency differences by weather

The analysis of climatic effects is central to this paper. In the next figure (Figure 5) the climatic effects are captured as performance difference between coastal and inland farms, and in Figure 6 the correlation of efficiencies with summer maximum temperatures in the various years is shown. The inland production areas of Cradock, Cookhouse and Gamtoos are much hotter than the coastal production areas of Humansdorp, Oyster Bay, Alexandria, Tsitsikamma and George.

In Figure 5 observations are pooled by coastal and inland locations, a dummy variable set up to conduct a t-test of means for these two sub-samples. There is a small but statistically significant difference in efficiency between farms in the coastal belt and those in the interior, with inland farms having a higher level of efficiency on average regardless of rainfall. The t-test reported that the pooled sub-sample of 168 coastal farms were on average 92.9% efficient while the 38 observations for inland farms produced an average efficiency of 97.4%. The test statistic was $t = 7.41$ corresponding to a probability on the two-tailed t-test of $p \leq 0.000$, the highest level of significance. In previous discussions inland farms were said to be better than coastal farms because coastal farms are dependent on uncertain rainfall, and this is supported by Figure 5, but there is something else going on as well.

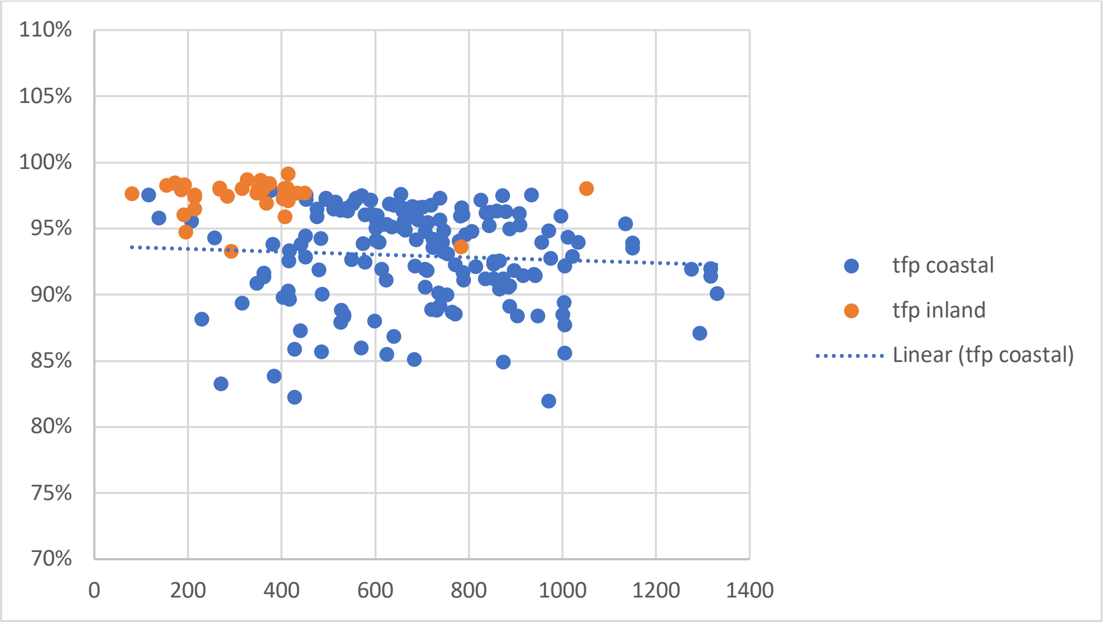

Figure 5: Efficiency differences by rainfall

Inland farms, indicated in orange, operate at high levels of efficiency regardless of whether they receive 200 millimetres of rainfall or 800 millimetres of rainfall and one can argue this is because irrigation makes up for the lack of rainfall along the Fish and Gamtoos Rivers. One could also argue, as was done above, that the difference is due to higher inland temperatures in the growing season which promote crop productivity. This would adequately explain the difference between orange and blue subsamples, but does not explain the distribution within the blue, coastal, subsample. Within the coastal subsample the spread of observations is rather large and the trendline is absolutely flat, suggesting that another factor might be at play.

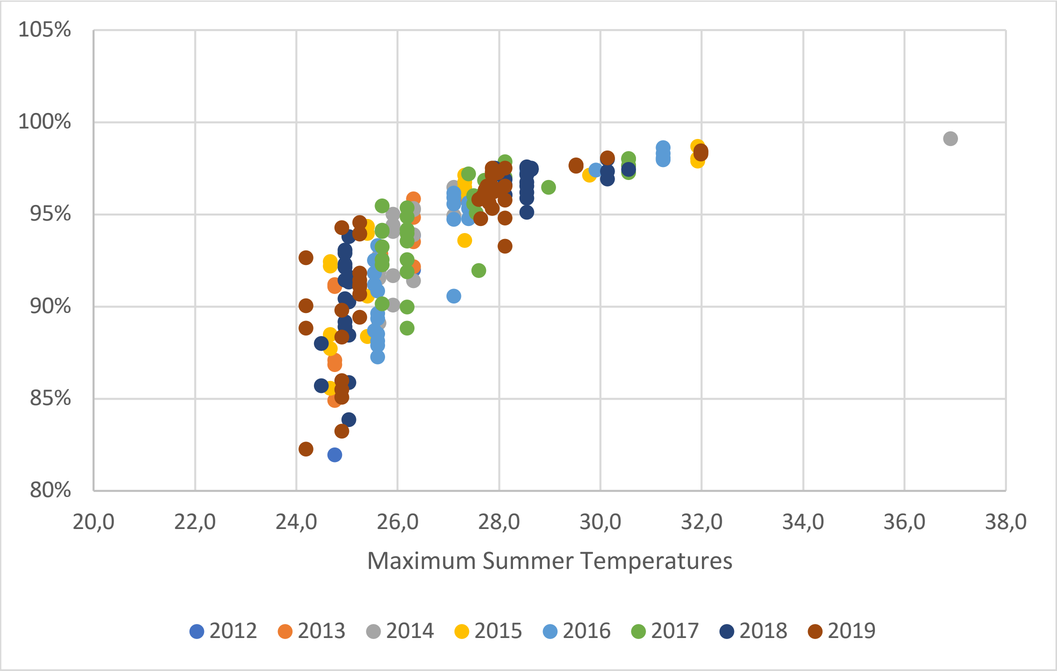

Figure 6: Efficiency differences by average daily maximum temperatures in January – March

In figure 6 efficiency scores are scattered against daily maximum summer temperatures with each year in a different colour. For example, observations for 2019 indicated in dark blue show that scores increase with increasing temperatures. It also shows a bigger range of scores at lower rather than higher temperatures, which indicates that inland farms which face hotter summers perform better than farms in the more humid coastal belt. Compared to 2019, 2013 was a cooler season, but within the 2013 cohort the same pattern is evident as in 2019. What these patterns mean is that farms in the Fish River area are more efficient than farms on the coast. The correlation coefficient of a pairwise correlation test between the maximum summer temperature variable and the estimated efficiencies was 0.7728 and significant at the highest level. Thus, there is a strong positive correlation between high summer temperatures and efficiency; that is, efficiency increases as temperatures increase. As argued above this could be because secure irrigation in Fish River area confers an advantage, or because higher summer temperatures result in greater crop growth. An alternative explanation would simply be that farmers on the Fish are systematically better managers than the much larger group of farmers who farm on the coast.

4.2.3 Relating efficiency to farm size

Galloway et al. (2018a) reported that the optimal scale of production involved a herd of 790 cows in milk on a milking platform of approximately 400 hectares. According to that analysis herds of 645 cows in milk face increasing returns to scale while herds of approximately 1200 cows in milk faced decreasing returns to scale. This detail on scale efficiency was made possible by the use of variable returns to scale Data Envelopment Analysis. The same level of detail is not possible with Stochastic Frontier Analysis, but it is possible to correlate efficiency scores with herd sizes *post hoc* and this was done in Figure 7.

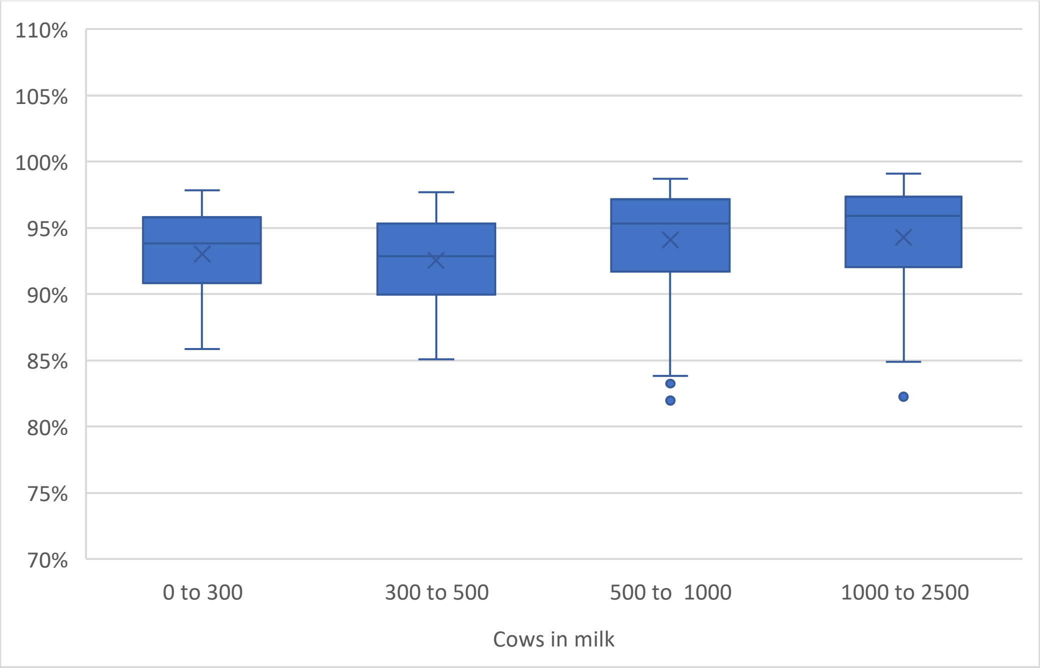

Figure 7: Efficiency differences by herd size

An ANOVA test of the pooled data classified by herd size reveals the difference in efficiency across herd sizes not to be statistically significant[3], although the spread in observed efficiencies increases for larger herds. This means that some managers of larger businesses struggle to produce good results, while others in the same size classes do very well. Since the current dataset did not include a proxy for management quality this matter could not be investigated further.

5. Limitations and further work

There are several significant limitations to this study that are worth commenting on. Firstly, farmers self-select into the sample by acquiring the services of Trace & Save. Even where Trace & Save offers a free service to the Woodlands Dairy's suppliers, farmers were under no

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[3] Significance = 0.071

obligation to join the group, at least not initially. The company builds resilience by assisting farmers with data collection and interpretation and by developing detailed fertiliser, irrigation and feed regimes for individual clients. The average level of productivity could be much lower in a random sample of dairy farms from the same area, especially under extreme conditions because farmers outside the Trace & Save group will not necessarily be aware of the extreme conditions or know how to respond to it appropriately. Thus, the sample is biased towards first movers, and therefore the results of this study are not fully representative of the industry. However, to determine how much lower the mean level of productivity in the area actually is, will require a proper random sample of all industry participants.

Secondly, it was found that inland locations perform much better than the coastal regions despite higher summer temperatures and much lower rainfall, which were both hypothesised to have a negative effect on productivity. Inland farms rely on irrigation to make up for a lack of rainfall, and irrigation is not included in the production function. There were no suitable proxies for irrigation in the dataset, irrigation costs or irrigation equipment is not available, and the best available proxy would be irrigated area. Land is currently excluded which prevents the use of this proxy. To come to grips with this problem a follow up study should investigate the viability of a per-cow production function. When irrigation is included, this extra input will penalise the performance of irrigated farms and might result in a different conclusion about the effects of temperature and rainfall. Good proxies for management quality could reveal that the coastal-inland difference has nothing to do with climate.

A third limitation revolves around missing variables as well as bad variables. In terms of missing variables, the dataset did not contain variables for labour or capital inputs, this study assumed they are used in fixed proportion to cows. This hypothesis needs to be checked with when a more detailed dataset becomes available. There were also a few problems which arose due to the climate data set. It was found that the results were quite sensitive to the specification of the climate variables, in particular temperatures, and this could be due to the incomplete specification of the frontier or the lack of information on management ability. Millimetres of rainfall per year is contained in the dataset made available by Trace & Save, however, it may be useful to obtain a measure of daily rainfall to check for the negative effects of sporadic droughts. Whereas rainfall data are farm-specific, temperature data was obtained from reference stations some of which have missing information in the summer maximum series.

The temperature data was also aggregated to maximum and minimum monthly temperatures which could potentially hide some of the more extreme temperatures.

6. Conclusion

The effect of heat stress on dairy farms and dairy productivity is a matter of growing concern as temperatures continue to rise. This study contributes to the production economics literature by exploring the effect of adverse weather on the productivity of pasture based dairy farms in the Eastern Cape. A stochastic frontier production function was developed to represent pasture-based milk production. The model considered cows in milk, expenditure on concentrates and roughage, fertiliser expenditure, rainfall and temperature variables. The hypothesis of technical progress was rejected and there was no evidence of catch-up of followers to leaders over the past eight years. The results show that inland farms have a slightly higher level of efficiency on average compared to coastal farms, which can be interpreted as a reflection of the benefits of having access to a reliable source of cheap irrigation water. It was found that warmer days are beneficial to output production and thus climate change is not yet a threat. It is hypothesized that warmer days are conducive to pasture growth, and that the farmers that take part in the Trace & Save program have adapted to deal with the heat stress caused by higher temperatures.

Although the farmers in the data set appear to be coping with the current climatic conditions, future productivity growth in dairy farming is likely to be hampered by increasing temperatures. Thus, research and extension efforts are needed to promote sustainable adaptation strategies. TFP analyses that incorporate climate effects, such as this study, may assist in highlighting areas where policymakers and stakeholders can target economic policy and public resources in order to improve productivity growth. The lack of technical progress as well as the variation of technical efficiencies between 82.0% and 99.1%, indicate that some farms do lag behind. Thus, identifying these farms and concentrating efforts towards improving farmer education and know-how may improve management efficiency, and thus possibly increase technical efficiency.

Dairy farming occurs throughout South Africa, however, the movement of dairy production has shifted increasingly towards pasture-based, coastal provinces, the highest concentration being in the Western Cape, the Eastern Cape and KwaZulu-Natal (MPO, 2020). This is in line with Meissner *et al.'s* (2013) and Williams *et al.'s* (2016) postulation that dairy cows on pasture systems on the southern parts of the east coast may be less likely to be affected by temperature increases. As the results indicate that the inland farms tended to have a slightly higher level of efficiency compared to the coastal farms, it may be necessary to direct training and education efforts towards these areas as the geographical shift towards the coast takes place.

The impacts of climate change on dairy production are difficult to establish and distinguish from other changes in the surrounding environment. The results show that some areas will benefit from increased temperatures, such as improved pastures and grazing, whereas others may suffer losses as temperatures exceed the cow's thermoneutral zone. Although mechanical cooling can be applied in some cases to mitigate the negative effects of heat stress, longer-term adjustments to nutrition and selecting breeds with a higher heat tolerance may be a more viable alternative.

A final point worth highlighting is that the temperature data available is not sufficient to provide a conclusive answer here. Therefore, it is important that South African agriculture invests more in collecting temperature data and doing research on its effects in productivity. In order to improve the adaptation of dairy cattle to their environments, location-specific and accurate weather data is required to enable improved analysis into the effects of climate change on dairy productivity and provide farmers with appropriate information for adaptation methods. To the authors knowledge, Trace & Save is already making steps in this direction by advising farmers to install their own weather stations as part of a bigger drive to improve irrigation efficiency.

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Appendix A: Table 4 Instruction and Output Files

Frontier 4.1 uses a three-file system; the first is the datafile, column 1 is farm identifiers, column 2 is the period; column 3 is the output. Data must be logged and demeanded.

A.1 Instruction file for Cobb Douglas model

```
2           1=ERROR COMPONENTS MODEL, 2=TE EFFECTS MODEL
b25-dt.txt        DATA FILE NAME
b25-ot.txt        OUTPUT FILE NAME
1           1=PRODUCTION FUNCTION, 2=COST FUNCTION
y           LOGGED DEPENDENT VARIABLE (Y/N)
62           NUMBER OF CROSS-SECTIONS
9           NUMBER OF TIME PERIODS
206           NUMBER OF OBSERVATIONS IN TOTAL
5           NUMBER OF REGRESSOR VARIABLES (Xs)
y           MU (Y/N) [OR DELTA0 (Y/N) IF USING TE EFFECTS MODEL]
2           ETA (Y/N) [OR NUMBER OF TE EFFECTS REGRESSORS (Zs)]
n          STARTING VALUES (Y/N)
           IF YES THEN     BETA0
                        BETA1 TO
                        BETAK
                        SIGMA SQUARED
                        GAMMA
                        MU            [OR DELTA0
                        ETA              DELTA1 TO
                                       DELTAP]

                        NOTE: IF YOU ARE SUPPLYING STARTING VALUES
                        AND YOU HAVE RESTRICTED MU [OR DELTA0] TO BE
                        ZERO THEN YOU SHOULD NOT SUPPLY A STARTING
                        VALUE FOR THIS PARAMETER.
```

A.2 Instruction file for translog specification

```
2            1=ERROR COMPONENTS MODEL, 2=TE EFFECTS MODEL
b23-dt.txt        DATA FILE NAME
b23-ot2.txt         OUTPUT FILE NAME
1            1=PRODUCTION FUNCTION, 2=COST FUNCTION
y            LOGGED DEPENDENT VARIABLE (Y/N)
62            NUMBER OF CROSS-SECTIONS
9           NUMBER OF TIME PERIODS
206            NUMBER OF OBSERVATIONS IN TOTAL
20           NUMBER OF REGRESSOR VARIABLES (Xs)
y            MU (Y/N) [OR DELTA0 (Y/N) IF USING TE EFFECTS MODEL]
2            ETA (Y/N) [OR NUMBER OF TE EFFECTS REGRESSORS (Zs)]
n            STARTING VALUES (Y/N)
            IF YES THEN    BETA0
                           BETA1 TO
                           BETAK
                           SIGMA SQUARED
                           GAMMA
                           MU           [OR DELTA0
                           ETA              DELTA1 TO
                                          DELTAP]

                           NOTE: IF YOU ARE SUPPLYING STARTING VALUES
                           AND YOU HAVE RESTRICTED MU [OR DELTA0] TO BE
                           ZERO THEN YOU SHOULD NOT SUPPLY A STARTING
                           VALUE FOR THIS PARAMETER.
```

A.3 Output file for Cobb Douglas model

```
Output from the program FRONTIER (Version 4.1c)


instruction file = b25-in.txt
data file =        b25-dt.txt


 Tech. Eff. Effects Frontier (see B&C 1993)
 The model is a production function
 The dependent variable is logged


the ols estimates are :

               coefficient     standard-error    t-ratio

  beta 0         0.59958240E+01  0.38429380E+00  0.15602187E+02
  beta 1         0.90726942E+00  0.39623374E-01  0.22897329E+02
  beta 2         0.25851735E-02  0.18588638E-02  0.13907278E+01
  beta 3         0.17914240E+00  0.35496636E-01  0.50467431E+01
  beta 4         0.17988398E-01  0.18461128E-01  0.97439322E+00
  beta 5         0.48739321E-01  0.21420774E-01  0.22753296E+01
  sigma-squared  0.19316253E-01

log likelihood function =   0.11726449E+03

the estimates after the grid search were :

  beta 0         0.61218024E+01
  beta 1         0.90726942E+00
  beta 2         0.25851735E-02
  beta 3         0.17914240E+00
  beta 4         0.17988398E-01
  beta 5         0.48739321E-01
  delta 0        0.00000000E+00
  delta 1        0.00000000E+00
  delta 2        0.00000000E+00
  sigma-squared  0.34624215E-01
  gamma          0.72000000E+00


 iteration =     0  func evals =     20  llf =  0.11920901E+03
    0.61218024E+01 0.90726942E+00 0.25851735E-02 0.17914240E+00 0.17988398E-01
    0.48739321E-01 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.34624215E-01
    0.72000000E+00
 gradient step
 iteration =     5  func evals =     42  llf =  0.12214152E+03
    0.61229317E+01 0.89700790E+00 0.27602617E-02 0.18413430E+00 0.14901582E-01
```

```
   0.51217940E-01 0.43836039E-03-0.17800919E-01 0.27868514E-01 0.38179838E-01
   0.71992228E+00
 iteration =    10  func evals =     65  llf =  0.12388076E+03
   0.62475745E+01 0.85965889E+00 0.33492948E-02 0.18533862E+00 0.22708464E-01
   0.51565121E-01 0.49280507E+00-0.31754638E-01 0.21711348E-01 0.39562877E-01
   0.77814642E+00
 iteration =    15  func evals =    153  llf =  0.12462184E+03
   0.61385516E+01 0.86136298E+00 0.35068691E-02 0.18321674E+00 0.26078679E-01
   0.59586458E-01 0.15293127E+01-0.78142984E-01 0.25876610E-01 0.41728237E-01
   0.73539351E+00
 iteration =    20  func evals =    260  llf =  0.12485587E+03
   0.61448601E+01 0.86221054E+00 0.35979119E-02 0.18226965E+00 0.25882749E-01
   0.58671010E-01 0.22965080E+01-0.12388918E+00 0.39765886E-01 0.57928012E-01
   0.80341339E+00
 pt better than entering pt cannot be found
 iteration =    23  func evals =    309  llf =  0.12487177E+03
   0.61423309E+01 0.86164878E+00 0.35982227E-02 0.18268302E+00 0.25522850E-01
   0.59407913E-01 0.24758855E+01-0.13388446E+00 0.42215696E-01 0.61398005E-01
   0.81489500E+00


the final mle estimates are :

              coefficient     standard-error    t-ratio

  beta 0         0.61423309E+01  0.36120213E+00  0.17005246E+02
  beta 1         0.86164878E+00  0.37465271E-01  0.22998600E+02
  beta 2         0.35982227E-02  0.17593395E-02  0.20452123E+01
  beta 3         0.18268302E+00  0.33184590E-01  0.55050558E+01
  beta 4         0.25522850E-01  0.16965806E-01  0.15043701E+01
  beta 5         0.59407913E-01  0.20101011E-01  0.29554689E+01
  delta 0        0.24758855E+01  0.22396857E+01  0.11054612E+01
  delta 1       -0.13388446E+00  0.11976954E+00 -0.11178507E+01
  delta 2        0.42215696E-01  0.32196413E-01  0.13111925E+01
  sigma-squared  0.61398005E-01  0.37791351E-01  0.16246576E+01
  gamma          0.81489500E+00  0.12654532E+00  0.64395505E+01

log likelihood function =   0.12487177E+03

LR test of the one-sided error =   0.15214545E+02
with number of restrictions = 4
 [note that this statistic has a mixed chi-square distribution]

number of iterations =     23

(maximum number of iterations set at :   100)

number of cross-sections =     62

number of time periods =      9
```

```
total number of observations =    206

thus there are:    352  obsns not in the panel


covariance matrix :

  0.13046698E+00  0.82111556E-02  0.11055826E-04 -0.10521975E-01 -0.52864261E-03
 -0.14752319E-02  0.10764078E-01 -0.48183510E-03  0.11673946E-03  0.52420165E-04
  0.12249305E-02
  0.82111556E-02  0.14036465E-02 -0.84112591E-05 -0.90408883E-03 -0.28101989E-03
  0.13102564E-03  0.60889111E-02 -0.28860010E-03  0.21563847E-04  0.44837443E-04
 -0.22358391E-03
  0.11055826E-04 -0.84112591E-05  0.30952754E-05 -0.12514100E-05 -0.19106091E-06
  0.50402634E-05  0.10711095E-03 -0.68410536E-05  0.28782682E-05  0.35363687E-05
  0.20373987E-04
 -0.10521975E-01 -0.90408883E-03 -0.12514100E-05  0.11012170E-02 -0.57872960E-04
 -0.29314762E-04 -0.88162163E-02  0.39021301E-03 -0.32414987E-04 -0.46350934E-04
  0.35313498E-04
 -0.52864261E-03 -0.28101989E-03 -0.19106091E-06 -0.57872960E-04  0.28783856E-03
 -0.11093581E-03  0.95270151E-03 -0.42574061E-04  0.11890907E-04 -0.12454168E-05
  0.45569470E-04
 -0.14752319E-02  0.13102564E-03  0.50402634E-05 -0.29314762E-04 -0.11093581E-03
  0.40405066E-03  0.62625900E-02 -0.19621496E-03 -0.61960709E-04 -0.19635426E-04
 -0.32399752E-03
  0.10764078E-01  0.60889111E-02  0.10711095E-03 -0.88162163E-02  0.95270151E-03
  0.62625900E-02  0.50161919E+01 -0.26509646E+00  0.56634764E-01  0.75323447E-01
  0.20452345E+00
 -0.48183510E-03 -0.28860010E-03 -0.68410536E-05  0.39021301E-03 -0.42574061E-04
 -0.19621496E-03 -0.26509646E+00  0.14344743E-01 -0.33442845E-02 -0.42393362E-02
 -0.11814791E-01
  0.11673946E-03  0.21563847E-04  0.28782682E-05 -0.32414987E-04  0.11890907E-04
 -0.61960709E-04  0.56634764E-01 -0.33442845E-02  0.10366090E-02  0.10814504E-02
  0.31832713E-02
  0.52420165E-04  0.44837443E-04  0.35363687E-05 -0.46350934E-04 -0.12454168E-05
 -0.19635426E-04  0.75323447E-01 -0.42393362E-02  0.10814504E-02  0.14281862E-02
  0.44459122E-02
  0.12249305E-02 -0.22358391E-03  0.20373987E-04  0.35313498E-04  0.45569470E-04
 -0.32399752E-03  0.20452345E+00 -0.11814791E-01  0.31832713E-02  0.44459122E-02
  0.16013719E-01


technical efficiency estimates :


   firm  year           eff.-est.

    14    1          0.75824646E+00
    46    1          0.91057318E+00
```

```
62     1          0.93333189E+00
 3    2          0.95326540E+00
 5    2          0.89129545E+00
 8    2          0.92011694E+00
14     2          0.86923056E+00
15     2          0.91202927E+00
26     2          0.78853493E+00
32     2          0.91114296E+00
49     2          0.95528608E+00
56     2          0.89942493E+00
61     2          0.91657796E+00
62     2          0.93867462E+00
 1    3          0.95389203E+00
 3    3          0.95170495E+00
 5    3          0.91215999E+00
10     3          0.97747848E+00
13     3          0.84203314E+00
14     3          0.92095182E+00
19     3          0.94281169E+00
23     3          0.93943960E+00
24     3          0.84648389E+00
26     3          0.85041786E+00
27     3          0.95815561E+00
31     3          0.91246688E+00
36     3          0.94342982E+00
42     3          0.93383954E+00
46     3          0.90150398E+00
56     3          0.92926975E+00
61     3          0.91241718E+00
62     3          0.93466701E+00
 2    4          0.90398388E+00
 3    4          0.95886749E+00
 5    4          0.94746233E+00
 6    4          0.93508091E+00
 8    4          0.94851358E+00
 9    4          0.94647610E+00
11     4          0.90893799E+00
20     4          0.93582423E+00
22     4          0.94019356E+00
24     4          0.86828579E+00
25     4          0.94636152E+00
26     4          0.87636422E+00
27     4          0.95374674E+00
36     4          0.81138496E+00
41     4          0.92442847E+00
43     4          0.94615725E+00
46     4          0.94031570E+00
47     4          0.85874799E+00
52     4          0.97780526E+00
61     4          0.88729305E+00
```

```
 62   4      0.94477073E+00
  3   5     0.95439868E+00
  4   5     0.82468605E+00
  5   5     0.92460018E+00
  6   5     0.93680630E+00
 10   5      0.96881571E+00
 11   5      0.94554283E+00
 13   5      0.75024572E+00
 20   5      0.95175121E+00
 22   5      0.93141298E+00
 23   5      0.92467485E+00
 24   5      0.84836777E+00
 25   5      0.93811980E+00
 26   5      0.89774339E+00
 27   5      0.94172994E+00
 28   5      0.95132635E+00
 32   5      0.83481778E+00
 36   5      0.81523079E+00
 38   5      0.88674298E+00
 39   5      0.91603914E+00
 43   5      0.94944813E+00
 46   5      0.93042607E+00
 47   5      0.84110541E+00
 49   5      0.94002975E+00
 52   5      0.97423926E+00
 54   5      0.83213334E+00
 61   5      0.86807225E+00
 62   5      0.95230690E+00
  1   6     0.97172427E+00
  3   6     0.96357345E+00
  5   6     0.95117051E+00
  6   6     0.92735475E+00
  8   6     0.95570857E+00
 10   6      0.96915084E+00
 11   6      0.94898080E+00
 13   6      0.65749584E+00
 19   6      0.93251638E+00
 21   6      0.95147117E+00
 22   6      0.92724362E+00
 23   6      0.94517163E+00
 24   6      0.92976657E+00
 25   6      0.95383087E+00
 26   6      0.95230591E+00
 27   6      0.95737193E+00
 32   6      0.92383150E+00
 36   6      0.88917771E+00
 38   6      0.92250565E+00
 39   6      0.85108096E+00
 41   6      0.92972176E+00
 43   6      0.95433575E+00
```

46	6	0.94422611E+00
47	6	0.82649272E+00
49	6	0.95560609E+00
50	6	0.95052203E+00
52	6	0.96472813E+00
54	6	0.89007733E+00
55	6	0.94066242E+00
56	6	0.95144436E+00
57	6	0.93942775E+00
61	6	0.92603998E+00
62	6	0.96283860E+00
1	7	0.96891040E+00
3	7	0.96987687E+00
5	7	0.93948314E+00
6	7	0.94440209E+00
7	7	0.96544555E+00
8	7	0.95486269E+00
11	7	0.91707909E+00
13	7	0.64764846E+00
16	7	0.95400588E+00
21	7	0.95158089E+00
22	7	0.95129084E+00
23	7	0.90736690E+00
24	7	0.84558458E+00
25	7	0.93710925E+00
26	7	0.95631247E+00
27	7	0.94682612E+00
32	7	0.92112788E+00
33	7	0.86614121E+00
36	7	0.74284932E+00
37	7	0.97473647E+00
38	7	0.90829942E+00
39	7	0.88397499E+00
40	7	0.97021909E+00
41	7	0.90793767E+00
42	7	0.94080058E+00
43	7	0.94218057E+00
44	7	0.94181875E+00
46	7	0.94365875E+00
48	7	0.97034853E+00
49	7	0.95198754E+00
51	7	0.86263208E+00
52	7	0.96428634E+00
54	7	0.89538697E+00
55	7	0.92345241E+00
56	7	0.95653452E+00
57	7	0.93279113E+00
58	7	0.95867997E+00
59	7	0.93779565E+00
61	7	0.94825258E+00

```
62    7       0.95235238E+00
 1    8       0.97047987E+00
 3    8       0.96848452E+00
 5    8       0.92038392E+00
 6    8       0.87796568E+00
 7    8       0.96739956E+00
 8    8       0.95339646E+00
10    8       0.95937083E+00
11    8       0.84475542E+00
12    8       0.93276979E+00
16    8       0.94112017E+00
17    8       0.91344945E+00
18    8       0.79182705E+00
21    8       0.94161585E+00
22    8       0.93790866E+00
23    8       0.93445084E+00
24    8       0.81920436E+00
25    8       0.96776792E+00
26    8       0.96153371E+00
27    8       0.95522137E+00
29    8       0.92103451E+00
30    8       0.95812706E+00
32    8       0.86218201E+00
33    8       0.85489990E+00
34    8       0.91977978E+00
35    8       0.89306600E+00
36    8       0.73804519E+00
38    8       0.86850932E+00
39    8       0.95265329E+00
40    8       0.96705862E+00
41    8       0.94749819E+00
42    8       0.93381862E+00
43    8       0.97296717E+00
45    8       0.94403427E+00
46    8       0.93627588E+00
48    8       0.96277528E+00
49    8       0.95718619E+00
50    8       0.93805061E+00
51    8       0.77133828E+00
53    8       0.95464740E+00
55    8       0.92330211E+00
56    8       0.95620398E+00
57    8       0.93276684E+00
58    8       0.94013438E+00
59    8       0.92439363E+00
60    8       0.96228833E+00
61    8       0.95953316E+00
62    8       0.95902430E+00
 6    9       0.92878104E+00
10    9       0.97399743E+00
```

```
    22     9          0.93307709E+00
    39     9          0.84391223E+00
    52     9          0.94970754E+00
    59     9          0.93427465E+00


 mean efficiency =    0.91951799E+00


summary of panel of observations:
(1 = observed, 0 = not observed)

  t:   1   2   3   4   5   6   7   8   9
   n
   1   0   0   1   0   0   1   1   1   0   4
   2   0   0   0   1   0   0   0   0   0   1
   3   0   1   1   1   1   1   1   1   0   7
   4   0   0   0   0   1   0   0   0   0   1
   5   0   1   1   1   1   1   1   1   0   7
   6   0   0   0   1   1   1   1   1   1   6
   7   0   0   0   0   0   0   1   1   0   2
   8   0   1   0   1   0   1   1   1   0   5
   9   0   0   0   1   0   0   0   0   0   1
  10   0   0   1   0   1   1   0   1   1   5
  11   0   0   0   1   1   1   1   1   0   5
  12   0   0   0   0   0   0   0   1   0   1
  13   0   0   1   0   1   1   1   0   0   4
  14   1   1   1   0   0   0   0   0   0   3
  15   0   1   0   0   0   0   0   0   0   1
  16   0   0   0   0   0   0   1   1   0   2
  17   0   0   0   0   0   0   0   1   0   1
  18   0   0   0   0   0   0   0   1   0   1
  19   0   0   1   0   0   1   0   0   0   2
  20   0   0   0   1   1   0   0   0   0   2
  21   0   0   0   0   0   1   1   1   0   3
  22   0   0   0   1   1   1   1   1   1   6
  23   0   0   1   0   1   1   1   1   0   5
  24   0   0   1   1   1   1   1   1   0   6
  25   0   0   0   1   1   1   1   1   0   5
  26   0   1   1   1   1   1   1   1   0   7
  27   0   0   1   1   1   1   1   1   0   6
  28   0   0   0   0   1   0   0   0   0   1
  29   0   0   0   0   0   0   0   1   0   1
  30   0   0   0   0   0   0   0   1   0   1
  31   0   0   1   0   0   0   0   0   0   1
  32   0   1   0   0   1   1   1   1   0   5
  33   0   0   0   0   0   0   1   1   0   2
  34   0   0   0   0   0   0   0   1   0   1
  35   0   0   0   0   0   0   0   1   0   1
  36   0   0   1   1   1   1   1   1   0   6
```

37	0	0	0	0	0	0	1	0	0	1
38	0	0	0	0	1	1	1	1	0	4
39	0	0	0	0	1	1	1	1	1	5
40	0	0	0	0	0	0	1	1	0	2
41	0	0	0	1	0	1	1	1	0	4
42	0	0	1	0	0	0	1	1	0	3
43	0	0	0	1	1	1	1	1	0	5
44	0	0	0	0	0	0	1	0	0	1
45	0	0	0	0	0	0	0	1	0	1
46	1	0	1	1	1	1	1	1	0	7
47	0	0	0	1	1	1	0	0	0	3
48	0	0	0	0	0	0	1	1	0	2
49	0	1	0	0	1	1	1	1	0	5
50	0	0	0	0	0	1	0	1	0	2
51	0	0	0	0	0	0	1	1	0	2
52	0	0	0	1	1	1	1	0	1	5
53	0	0	0	0	0	0	0	1	0	1
54	0	0	0	0	1	1	1	0	0	3
55	0	0	0	0	0	1	1	1	0	3
56	0	1	1	0	0	1	1	1	0	5
57	0	0	0	0	0	1	1	1	0	3
58	0	0	0	0	0	0	1	1	0	2
59	0	0	0	0	0	0	1	1	1	3
60	0	0	0	0	0	0	0	1	0	1
61	0	1	1	1	1	1	1	1	0	7
62	1	1	1	1	1	1	1	1	0	8
	3	11	18	21	27	33	40	47	6	206

A.4 Output file for translog specification

```
Output from the program FRONTIER (Version 4.1c)

instruction file = b23-in.txt
data file =        b23-dt.txt

 Tech. Eff. Effects Frontier (see B&C 1993)
 The model is a production function
 The dependent variable is logged

the ols estimates are :

               coefficient     standard-error    t-ratio

  beta 0       -0.72350381E-01  0.28035959E-01 -0.25806280E+01
  beta 1        0.84185137E+00  0.40260673E-01  0.20910017E+02
  beta 2        0.26172955E-01  0.69359274E-02  0.37735336E+01
  beta 3        0.17060105E+00  0.35077791E-01  0.48635062E+01
  beta 4        0.34455739E-01  0.18328228E-01  0.18799274E+01
  beta 5        0.84760173E-01  0.25239788E-01  0.33581967E+01
  beta 6        0.24889942E+00  0.13092400E+00  0.19010986E+01
  beta 7       -0.59146569E-02  0.73817384E-02 -0.80125528E+00
  beta 8       -0.44841703E+00  0.19738819E+00 -0.22717521E+01
  beta 9        0.15863407E-01  0.71753161E-01  0.22108304E+00
  beta10       -0.11438995E+00  0.93751388E-01 -0.12201414E+01
  beta11        0.23520704E-02  0.73935314E-03  0.31812543E+01
  beta12        0.96730767E-02  0.66153988E-02  0.14622061E+01
  beta13        0.23841923E-02  0.33671491E-02  0.70807446E+00
  beta14        0.78335518E-03  0.40109949E-02  0.19530196E+00
  beta15        0.11641851E+00  0.87243199E-01  0.13344135E+01
  beta16        0.39454868E-02  0.72877805E-01  0.54138386E-01
  beta17        0.20490041E+00  0.95232182E-01  0.21515879E+01
  beta18       -0.10673734E-01  0.22915636E-01 -0.46578387E+00
```

```
  beta19        -0.52379853E-01  0.47408659E-01 -0.11048583E+01
  beta20         0.84073900E-01  0.34707720E-01  0.24223400E+01
  sigma-squared  0.16220099E-01

log likelihood function =   0.14328819E+03

the estimates after the grid search were :

  beta 0         0.16240866E-01
  beta 1         0.84185137E+00
  beta 2         0.26172955E-01
  beta 3         0.17060105E+00
  beta 4         0.34455739E-01
  beta 5         0.84760173E-01
  beta 6         0.24889942E+00
  beta 7        -0.59146569E-02
  beta 8        -0.44841703E+00
  beta 9         0.15863407E-01
  beta10        -0.11438995E+00
  beta11         0.23520704E-02
  beta12         0.96730767E-02
  beta13         0.23841923E-02
  beta14         0.78335518E-03
  beta15         0.11641851E+00
  beta16         0.39454868E-02
  beta17         0.20490041E+00
  beta18        -0.10673734E-01
  beta19        -0.52379853E-01
  beta20         0.84073900E-01
  delta 0        0.00000000E+00
  delta 1        0.00000000E+00
  delta 2        0.00000000E+00
  sigma-squared  0.22415003E-01
  gamma          0.55000000E+00
```

```
iteration =     0  func evals =     20  llf =  0.14357641E+03
   0.16240866E-01 0.84185137E+00 0.26172955E-01 0.17060105E+00 0.34455739E-01
   0.84760173E-01 0.24889942E+00-0.59146569E-02-0.44841703E+00 0.15863407E-01
  -0.11438995E+00 0.23520704E-02 0.96730767E-02 0.23841923E-02 0.78335518E-03
   0.11641851E+00 0.39454868E-02 0.20490041E+00-0.10673734E-01-0.52379853E-01
   0.84073900E-01 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.22415003E-01
   0.55000000E+00
gradient step
iteration =     5  func evals =     46  llf =  0.14476054E+03
   0.15849861E-01 0.83962008E+00 0.23768633E-01 0.16980422E+00 0.31553662E-01
   0.83564568E-01 0.24936974E+00-0.75591371E-02-0.44815217E+00 0.16890745E-01
  -0.11435074E+00 0.21317044E-02 0.10461280E-01 0.22037226E-02 0.82492062E-03
   0.11630544E+00 0.43924366E-02 0.20451601E+00-0.98110376E-02-0.52633806E-01
   0.83504925E-01 0.65283782E-03-0.85861189E-02 0.13772597E-01 0.22903277E-01
   0.55012862E+00
iteration =    10  func evals =     63  llf =  0.14493423E+03
   0.12136392E-01 0.83436852E+00 0.24971399E-01 0.17412024E+00 0.32873383E-01
   0.83128213E-01 0.24913192E+00-0.69593479E-02-0.44836429E+00 0.20609921E-01
  -0.11285587E+00 0.22612161E-02 0.10450006E-01 0.17252805E-02 0.88800896E-03
   0.11557095E+00 0.49963642E-02 0.20235857E+00-0.11480694E-01-0.57784563E-01
   0.76992948E-01 0.39167944E-02-0.10112609E-01 0.15730907E-01 0.23389033E-01
   0.55137231E+00
iteration =    15  func evals =     82  llf =  0.14517666E+03
   0.12281891E-01 0.81212960E+00 0.25761107E-01 0.19096342E+00 0.35879430E-01
   0.81891644E-01 0.24205826E+00-0.61371090E-02-0.45174728E+00 0.30601310E-01
  -0.99067052E-01 0.23505891E-02 0.98575160E-02 0.14431980E-02 0.11611209E-02
   0.11874821E+00 0.15729578E-02 0.18899729E+00-0.11337129E-01-0.60690208E-01
   0.79155308E-01 0.25092278E-01-0.11142744E-01 0.16758927E-01 0.23163830E-01
   0.55892852E+00
iteration =    20  func evals =    102  llf =  0.14668703E+03
   0.57143617E-01 0.81127425E+00 0.24316819E-01 0.19688333E+00 0.31812276E-01
   0.86312955E-01 0.26098529E+00-0.58431547E-02-0.47572661E+00 0.31048012E-01
  -0.32136801E-04 0.23012707E-02 0.84289024E-02 0.11312493E-02 0.17736030E-02
```

```
   0.12796707E+00 0.51419028E-02 0.89123114E-01-0.14083149E-01-0.67872906E-01
   0.71691296E-01 0.47989761E+00-0.23496512E-01 0.12669907E-01 0.25605058E-01
   0.76760863E+00
 iteration =    25  func evals =    122  llf =  0.14712430E+03
   0.41743201E-01 0.81245998E+00 0.26022021E-01 0.19030069E+00 0.33245978E-01
   0.99864610E-01 0.25682813E+00-0.61284957E-02-0.48362241E+00 0.53994339E-01
  -0.30140172E-01 0.24596157E-02 0.89764038E-02 0.10946758E-02 0.21514258E-02
   0.13741791E+00-0.16238744E-01 0.11847775E+00-0.13152350E-01-0.67135166E-01
   0.83968859E-01 0.72157243E+00-0.29268262E-01 0.80880929E-02 0.22803613E-01
   0.68891584E+00
 iteration =    30  func evals =    157  llf =  0.14858480E+03
   0.10693335E-01 0.82477000E+00 0.24236045E-01 0.17346276E+00 0.39966369E-01
   0.11293673E+00 0.27297118E+00-0.45420208E-02-0.50915172E+00 0.41271371E-01
  -0.38487784E-01 0.21611493E-02 0.83904689E-02 0.15128917E-02 0.20607595E-02
   0.16016018E+00-0.22157084E-01 0.14240272E+00-0.92321919E-02-0.71253352E-01
   0.91416225E-01 0.11861408E+01-0.45378728E-01 0.24084061E-02 0.19201607E-01
   0.46133599E+00
 pt better than entering pt cannot be found
 iteration =    34  func evals =    207  llf =  0.14898002E+03
  -0.53162577E-02 0.83520630E+00 0.23222524E-01 0.16654755E+00 0.38479412E-01
   0.11160106E+00 0.27426943E+00-0.47254201E-02-0.51060740E+00 0.39707766E-01
  -0.39100080E-01 0.20472758E-02 0.85432643E-02 0.20564999E-02 0.17386154E-02
   0.16357517E+00-0.25398479E-01 0.14564377E+00-0.95766822E-02-0.71186492E-01
   0.89837667E-01 0.14922211E+01-0.57339780E-01 0.22045052E-02 0.16557441E-01
   0.31325334E+00


the final mle estimates are :


              coefficient     standard-error    t-ratio


  beta 0       -0.53162577E-02  0.39689793E-01 -0.13394521E+00
  beta 1        0.83520630E+00  0.40880016E-01  0.20430675E+02
  beta 2        0.23222524E-01  0.60330626E-02  0.38492098E+01
  beta 3        0.16654755E+00  0.34093894E-01  0.48849673E+01
```

```
  beta 4        0.38479412E-01  0.17355329E-01  0.22171526E+01
  beta 5        0.11160106E+00  0.26347308E-01  0.42357672E+01
  beta 6        0.27426943E+00  0.12164256E+00  0.22547161E+01
  beta 7       -0.47254201E-02  0.71499403E-02 -0.66090344E+00
  beta 8       -0.51060740E+00  0.18138785E+00 -0.28150032E+01
  beta 9        0.39707766E-01  0.69727015E-01  0.56947462E+00
  beta10       -0.39100080E-01  0.91288270E-01 -0.42831439E+00
  beta11        0.20472758E-02  0.65251266E-03  0.31375265E+01
  beta12        0.85432643E-02  0.62407129E-02  0.13689565E+01
  beta13        0.20564999E-02  0.32473722E-02  0.63328125E+00
  beta14        0.17386154E-02  0.38558497E-02  0.45090331E+00
  beta15        0.16357517E+00  0.79558418E-01  0.20560385E+01
  beta16       -0.25398479E-01  0.69751242E-01 -0.36412942E+00
  beta17        0.14564377E+00  0.88471121E-01  0.16462295E+01
  beta18       -0.95766822E-02  0.19575561E-01 -0.48921622E+00
  beta19       -0.71186492E-01  0.42010868E-01 -0.16944780E+01
  beta20        0.89837667E-01  0.31668045E-01  0.28368555E+01
  delta 0       0.14922211E+01  0.51304221E+00  0.29085738E+01
  delta 1      -0.57339780E-01  0.18489301E-01 -0.31012412E+01
  delta 2       0.22045052E-02  0.97635292E-02  0.22578979E+00
  sigma-squared  0.16557441E-01  0.35879161E-02  0.46147793E+01
  gamma          0.31325334E+00  0.21780828E+00  0.14382068E+01

log likelihood function =   0.14898002E+03

LR test of the one-sided error =   0.11383661E+02
with number of restrictions = 4
 [note that this statistic has a mixed chi-square distribution]

number of iterations =     34

(maximum number of iterations set at :   100)

number of cross-sections =     62
```

```
number of time periods =      9

total number of observations =    206

thus there are:    352  obsns not in the panel

covariance matrix :

  0.15752797E-02 -0.13552868E-03 -0.11419856E-03  0.10025619E-03 -0.47841942E-04
  0.69750626E-04 -0.41396096E-03  0.19413503E-04  0.68569447E-03  0.16863960E-03
  0.85206651E-03 -0.11360136E-04 -0.18052334E-04 -0.14071794E-04  0.93804792E-05
 -0.41859797E-03  0.43820629E-04 -0.89401375E-03 -0.10154999E-03 -0.12570734E-04
 -0.20102702E-03 -0.81306718E-02  0.35232232E-03  0.12014262E-04  0.77617464E-04
  0.61186420E-02
 -0.13552868E-03  0.16711757E-02 -0.76907546E-04 -0.10335116E-02 -0.34446225E-03
  0.34840384E-04 -0.46822666E-03 -0.21061489E-04  0.12711814E-02  0.12822167E-04
 -0.19689593E-03 -0.84857500E-05  0.25392856E-04  0.11683585E-04 -0.29429018E-04
 -0.63984643E-03 -0.78141288E-04  0.35154378E-03 -0.78738722E-04  0.17426163E-03
 -0.41497195E-04  0.45715090E-02 -0.13703698E-03 -0.89533363E-04 -0.38371550E-04
 -0.30139450E-02
 -0.11419856E-03 -0.76907546E-04  0.36397845E-04  0.16979796E-04  0.26010517E-04
  0.24139365E-04 -0.29238043E-04 -0.69218291E-05 -0.31110561E-04  0.18479172E-04
 -0.69407465E-04  0.37462454E-05  0.29525456E-05  0.14816565E-05  0.12821212E-05
  0.30072584E-04 -0.51972792E-06  0.76497387E-04  0.39633752E-05 -0.28338265E-05
  0.30404533E-04 -0.15018473E-03  0.21405591E-05  0.62672824E-05  0.50365440E-06
  0.83547632E-04
  0.10025619E-03 -0.10335116E-02  0.16979796E-04  0.11623936E-02 -0.25000986E-04
 -0.25008336E-04  0.86328637E-03  0.25408492E-04 -0.16097375E-02 -0.10738936E-03
  0.53043099E-03  0.28337798E-05 -0.18914577E-04 -0.13262823E-04  0.19350545E-04
  0.66772239E-03  0.35828252E-03 -0.71066867E-03 -0.41531528E-04 -0.75029581E-04
 -0.12287399E-03 -0.40727448E-02  0.11527251E-03  0.81326924E-04  0.18294996E-04
  0.16928240E-02
 -0.47841942E-04 -0.34446225E-03  0.26010517E-04 -0.25000986E-04  0.30120743E-03
```

```
-0.93686453E-04 -0.16695024E-04 -0.12591107E-05  0.15978373E-04 -0.73022176E-04
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technical efficiency estimates :


   firm  year             eff.-est.
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 3   2      0.94995639E+00
 5   2      0.87617190E+00
 8   2      0.91192798E+00
14   2       0.87335593E+00
15   2       0.92703220E+00
26   2       0.85340269E+00
32   2       0.93090494E+00
49   2       0.95946065E+00
56   2       0.93839375E+00
61   2       0.91226607E+00
62   2       0.96120777E+00
 1   3      0.96655635E+00
 3   3      0.95544681E+00
 5   3      0.92919579E+00
10   3       0.99186252E+00
13   3       0.94283340E+00
14   3       0.92339175E+00
19   3       0.94592559E+00
23   3       0.92188242E+00
24   3       0.92037717E+00
26   3       0.89609471E+00
27   3       0.95159680E+00
31   3       0.90515282E+00
36   3       0.94380060E+00
42   3       0.95445433E+00
46   3       0.91875971E+00
56   3       0.94156645E+00
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62   3       0.95210445E+00
 2   4      0.91008131E+00
 3   4      0.97276518E+00
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25    4         0.98216730E+00
26    4         0.88661784E+00
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 3    5         0.96391660E+00
 4    5         0.91365097E+00
 5    5         0.92756030E+00
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24    5         0.88364537E+00
25    5         0.98146444E+00
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27    5         0.93587939E+00
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33    8          0.88991774E+00
34    8          0.95683923E+00
35    8          0.88534300E+00
36    8          0.83767625E+00
38    8          0.89886499E+00
39    8          0.96779458E+00
40    8          0.97428908E+00
41    8          0.98427233E+00
42    8          0.96547725E+00
43    8          0.98563820E+00
45    8          0.92088059E+00
46    8          0.96430660E+00
48    8          0.96682946E+00
49    8          0.96569309E+00
50    8          0.95946571E+00
51    8          0.82511146E+00
53    8          0.96744096E+00
55    8          0.91338261E+00
56    8          0.96517474E+00
57    8          0.91452832E+00
58    8          0.96303141E+00
59    8          0.95081724E+00
60    8          0.96062291E+00
61    8          0.94018405E+00
62    8          0.97300620E+00
 6   9          0.96223553E+00
10    9          0.98507094E+00
22    9          0.95852548E+00
39    9          0.94366956E+00
```

```
    52    9          0.98151956E+00
    59    9          0.95602889E+00

 mean efficiency =   0.94030528E+00

summary of panel of observations:
(1 = observed, 0 = not observed)

  t:   1   2   3   4   5   6   7   8   9
   n
   1   0   0   1   0   0   1   1   1   0   4
   2   0   0   0   1   0   0   0   0   0   1
   3   0   1   1   1   1   1   1   1   0   7
   4   0   0   0   0   1   0   0   0   0   1
   5   0   1   1   1   1   1   1   1   0   7
   6   0   0   0   1   1   1   1   1   1   6
   7   0   0   0   0   0   0   1   1   0   2
   8   0   1   0   1   0   1   1   1   0   5
   9   0   0   0   1   0   0   0   0   0   1
  10   0   0   1   0   1   1   0   1   1   5
  11   0   0   0   1   1   1   1   1   0   5
  12   0   0   0   0   0   0   0   1   0   1
  13   0   0   1   0   1   1   1   0   0   4
  14   1   1   1   0   0   0   0   0   0   3
  15   0   1   0   0   0   0   0   0   0   1
  16   0   0   0   0   0   0   1   1   0   2
  17   0   0   0   0   0   0   0   1   0   1
  18   0   0   0   0   0   0   0   1   0   1
  19   0   0   1   0   0   1   0   0   0   2
  20   0   0   0   1   1   0   0   0   0   2
  21   0   0   0   0   0   1   1   1   0   3
  22   0   0   0   1   1   1   1   1   1   6
  23   0   0   1   0   1   1   1   1   0   5
  24   0   0   1   1   1   1   1   1   0   6
```

25	0	0	0	1	1	1	1	1	0	5
26	0	1	1	1	1	1	1	1	0	7
27	0	0	1	1	1	1	1	1	0	6
28	0	0	0	0	1	0	0	0	0	1
29	0	0	0	0	0	0	0	1	0	1
30	0	0	0	0	0	0	0	1	0	1
31	0	0	1	0	0	0	0	0	0	1
32	0	1	0	0	1	1	1	1	0	5
33	0	0	0	0	0	0	1	1	0	2
34	0	0	0	0	0	0	0	1	0	1
35	0	0	0	0	0	0	0	1	0	1
36	0	0	1	1	1	1	1	1	0	6
37	0	0	0	0	0	0	1	0	0	1
38	0	0	0	0	1	1	1	1	0	4
39	0	0	0	0	1	1	1	1	1	5
40	0	0	0	0	0	0	1	1	0	2
41	0	0	0	1	0	1	1	1	0	4
42	0	0	1	0	0	0	1	1	0	3
43	0	0	0	1	1	1	1	1	0	5
44	0	0	0	0	0	0	1	0	0	1
45	0	0	0	0	0	0	0	1	0	1
46	1	0	1	1	1	1	1	1	0	7
47	0	0	0	1	1	1	0	0	0	3
48	0	0	0	0	0	0	1	1	0	2
49	0	1	0	0	1	1	1	1	0	5
50	0	0	0	0	0	1	0	1	0	2
51	0	0	0	0	0	0	1	1	0	2
52	0	0	0	1	1	1	1	0	1	5
53	0	0	0	0	0	0	0	1	0	1
54	0	0	0	0	1	1	1	0	0	3
55	0	0	0	0	0	1	1	1	0	3
56	0	1	1	0	0	1	1	1	0	5
57	0	0	0	0	0	1	1	1	0	3
58	0	0	0	0	0	0	1	1	0	2

59	0	0	0	0	0	0	1	1	1	3
60	0	0	0	0	0	0	0	1	0	1
61	0	1	1	1	1	1	1	1	0	7
62	1	1	1	1	1	1	1	1	0	8
	3	11	18	21	27	33	40	47	6	206

Appendix B: Models for specification tests

B.1 Ordinary Least Squares (OLS) output

```
the ols estimates are :

               coefficient     standard-error    t-ratio

  beta 0       -0.73753352E-01  0.28134295E-01 -0.26214750E+01
  beta 1        0.84322925E+00  0.40432227E-01  0.20855375E+02
  beta 2        0.26150651E-01  0.69623415E-02  0.37560139E+01
  beta 3        0.16900813E+00  0.35264467E-01  0.47925899E+01
  beta 4        0.34655732E-01  0.18363902E-01  0.18871661E+01
  beta 5        0.85278431E-01  0.25313396E-01  0.33689052E+01
  beta 6        0.25139284E+00  0.13278097E+00  0.18932896E+01
  beta 7       -0.65607417E-02  0.74064925E-02 -0.88580954E+00
  beta 8       -0.44654350E+00  0.19936581E+00 -0.22398198E+01
  beta 9        0.14608744E-01  0.72250615E-01  0.20219543E+00
  beta10       -0.11410995E+00  0.95211122E-01 -0.11984939E+01
  beta11        0.23537651E-02  0.74163568E-03  0.31737484E+01
  beta12        0.10137335E-01  0.66439436E-02  0.15258010E+01
  beta13        0.25375567E-02  0.33727774E-02  0.75236412E+00
  beta14        0.72220250E-03  0.40209322E-02  0.17961072E+00
  beta15        0.11413651E+00  0.87658545E-01  0.13020580E+01
  beta16        0.25904242E-02  0.73385390E-01  0.35298909E-01
  beta17        0.20834628E+00  0.96369961E-01  0.21619422E+01
  beta18       -0.92719475E-02  0.22936633E-01 -0.40424187E+00
  beta19       -0.54021458E-01  0.47442547E-01 -0.11386711E+01
  beta20        0.85531976E-01  0.34843111E-01  0.24547744E+01
  sigma-squared  0.16298270E-01

log likelihood function =   0.14279299E+03
```

B.2 Model with time trends in the frontier and the inefficiency module

```
the final mle estimates are :

               coefficient     standard-error    t-ratio

  beta 0       -0.60639767E-02  0.43625762E-01 -0.13899990E+00
  beta 1        0.84096635E+00  0.40553326E-01  0.20737297E+02
  beta 2        0.21187534E-01  0.70997937E-02  0.29842465E+01
  beta 3        0.15705642E+00  0.36471963E-01  0.43062233E+01
  beta 4        0.41031057E-01  0.16781165E-01  0.24450660E+01
  beta 5        0.12276749E+00  0.26539918E-01  0.46257675E+01
  beta 6        0.24486546E+00  0.12135429E+00  0.20177733E+01
  beta 7       -0.34252549E-02  0.71475509E-02 -0.47922078E+00
  beta 8       -0.45901059E+00  0.18524580E+00 -0.24778462E+01
  beta 9        0.49325345E-01  0.69307978E-01  0.71168351E+00
  beta10       -0.52110423E-01  0.94013170E-01 -0.55428855E+00
  beta11        0.18833274E-02  0.73357449E-03  0.25673295E+01
  beta12        0.70741480E-02  0.63117148E-02  0.11207965E+01
  beta13        0.23696148E-02  0.32356609E-02  0.73234339E+00
  beta14        0.10637245E-02  0.38581063E-02  0.27571156E+00
  beta15        0.13856425E+00  0.83389746E-01  0.16616461E+01
  beta16       -0.33649112E-01  0.68203582E-01 -0.49336282E+00
  beta17        0.14915236E+00  0.89795882E-01  0.16610155E+01
  beta18       -0.93150449E-02  0.20241894E-01 -0.46018642E+00
  beta19       -0.66246871E-01  0.42953950E-01 -0.15422766E+01
  beta20        0.97932682E-01  0.33562297E-01  0.29179374E+01
  beta21       -0.20669081E-03  0.77232143E-02 -0.26762278E-01
  delta 0       0.15832059E+01  0.53690558E+00  0.29487604E+01
  delta 1      -0.59049746E-01  0.18079404E-01 -0.32661335E+01
  delta 2       0.39906191E-02  0.98133347E-02  0.40665270E+00
  delta 3      -0.14335117E-01  0.16271539E-01 -0.88099328E+00
  sigma-squared  0.16374079E-01  0.37590265E-02  0.43559359E+01
  gamma          0.30322217E+00  0.22460475E+00  0.13500257E+01

log likelihood function =   0.14978250E+03

LR test of the one-sided error =   0.11580591E+02
with number of restrictions = 5
 [note that this statistic has a mixed chi-square distribution]
```

B.3 Model without mean summer minimum temperature variable

```
the final mle   estimates are :


              coefficient     standard-error    t-ratio


  beta 0        0.17101251E+00  0.30019440E-01  0.56967257E+01
  beta 1        0.80046782E+00  0.38355810E-01  0.20869533E+02
  beta 2        0.27245367E-01  0.61031529E-02  0.44641463E+01
  beta 3        0.18373793E+00  0.36020954E-01  0.51008624E+01
  beta 4        0.39854298E-01  0.17039289E-01  0.23389649E+01
  beta 5        0.85531945E-01  0.25289372E-01  0.33821301E+01
  beta 6        0.21730246E+00  0.12672690E+00  0.17147304E+01
  beta 7       -0.61493449E-02  0.70855332E-02 -0.86787327E+00
  beta 8       -0.41947790E+00  0.18594917E+00 -0.22558740E+01
  beta 9        0.39768088E-01  0.71096636E-01  0.55935259E+00
  beta10       -0.62662447E-01  0.91416548E-01 -0.68546066E+00
  beta11        0.25745614E-02  0.64053385E-03  0.40193995E+01
  beta12        0.10015853E-01  0.62717060E-02  0.15969902E+01
  beta13        0.25624573E-03  0.32860980E-02  0.77978725E-01
  beta14        0.20399112E-02  0.35430931E-02  0.57574304E+00
  beta15        0.81035085E-01  0.79456805E-01  0.10198634E+01
  beta16        0.19957772E-01  0.71383382E-01  0.27958569E+00
  beta17        0.14989236E+00  0.90414505E-01  0.16578353E+01
  beta18       -0.17059389E-01  0.19723573E-01 -0.86492384E+00
  beta19       -0.29876351E-01  0.39716774E-01 -0.75223509E+00
  beta20        0.62920550E-01  0.32116645E-01  0.19591259E+01
  delta 0       0.55375579E+00  0.21678963E+00  0.25543463E+01
  delta 1      -0.12149611E-01  0.81604365E-02 -0.14888433E+01
  sigma-squared  0.19374197E-01  0.51038542E-02  0.37959933E+01
  gamma          0.99999999E+00  0.10881694E+00  0.91897456E+01

log likelihood function =   0.14944000E+03
```

```
LR test of the one-sided error =   0.13294032E+02
with number of restrictions = 3
 [note that this statistic has a mixed chi-square distribution]
```