African Journal of Agricultural and Resource Economics Volume 12 Number 1 pages 62-84

The effect of rainfall variability on sustainable wheat production under no-till farming systems in the Swartland region, South Africa

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Abstract

Twenty years ago it was argued that rotational wheat production systems will reduce the economic risks to farmers and restore soil quality. Here we reflect on this assertion by analysing the evidence of a 12-year data window within a trial on a mixture of crop rotation systems at Langgewens Research Farm, South Africa. It was been found that production systems that include rotations with medics and/or medic-clover show some potential for improvement compared with wheat only, with a combination of the annual legume pasture with an added saltbush pasture showing the greatest improvement when taking into consideration the benefits from livestock production that are derived from pastures. Pastures are more resilient to changes in rainfall compared with wheat only. Planting pastures in alternate years also improves the yields from wheat, and this is beneficial in periods of low rainfall. Rotation systems on this farm that include lupin perform worse than the wheat-only model. Furthermore, when modelling the effect of drought on the system, the results of the multi- and rotation production systems actually improve.

Key words: wheat; Western Cape; rainfall; conservation agriculture; rotation

1. Introduction

The economy of the Swartland region in the Western Cape province of South Africa (see Map 1) has for long been based on wheat production (Arckoll 1998). Increased input costs and lower product price, as well as variable rainfall, were identified as increasing the economic risk to wheat farmers as many as two decades ago (Van Schalkwyk *et al*. 1995). Alternative crops and cropping systems have therefore been identified as potentially financially viable alternatives to the traditional wheat monoculture (Smit & Van Zyl 1998). These alternative crops include canola (Arckoll 1998) and lupins (Agenbag undated). Additionally, annual medic and/or clover pastures also have an important role to play in mixed wheat/livestock production systems. In Australia, the introduction of ley pastures in wheat-cropping areas since the late 1940s has successfully restored fertility and improved soil structure, so much so that grain yields have increased and hence reduced the economic risk associated with conventional mono-cropping production systems (Donald 1965; White *et al*. 1978).

Of particular importance to farmers seeking to reduce their risk is the concept of reduced input systems (Jordan *et al.* 1997), which involve the manipulation and integration of husbandry practices within crop management. Crop rotation is a key component in reduced input and integrated systems of production, with maximum use made of crops that contribute positively to soil fertility. Based on data from a five-year "less-intensive strategy" crop rotation experiment, Jordan *et al.* (1997) showed reduced overall yields of wheat and oilseed rape of up to 18%. However, production costs were also reduced by 32% and the overall profitability of crop production was maintained. There were substantial reductions in applied nitrogen (36%), herbicides (26%), fungicides (79%) and pesticides (78%) where "low-input" was compared to a conventional production strategy. The reason for this is that crops such as canola and lupins are ideally suited to rotation with wheat, as it is important (from a disease-prevention point of view) that neither canola nor lupins are planted on the same land more frequently than every third or fourth year. Not only do they provide suitable broad-leaf "break" crops in which grass weeds may be effectively controlled in wheat-production systems, but they also have the potential to improve soil structure (Arkcoll 1998) and, in the case of lupins, to provide nitrogen to the following wheat crop. Medic and medic/clover pastures contribute to soil organic matter and provide 40 to 100 kg of nitrogen per hectare annually to the soil profile, up to 40% of which is available to the subsequent crop (Ladd *et al.* 1983). Grass weeds may also be controlled effectively in the legume pasture, thus reducing costs in the production of the subsequent wheat crop.

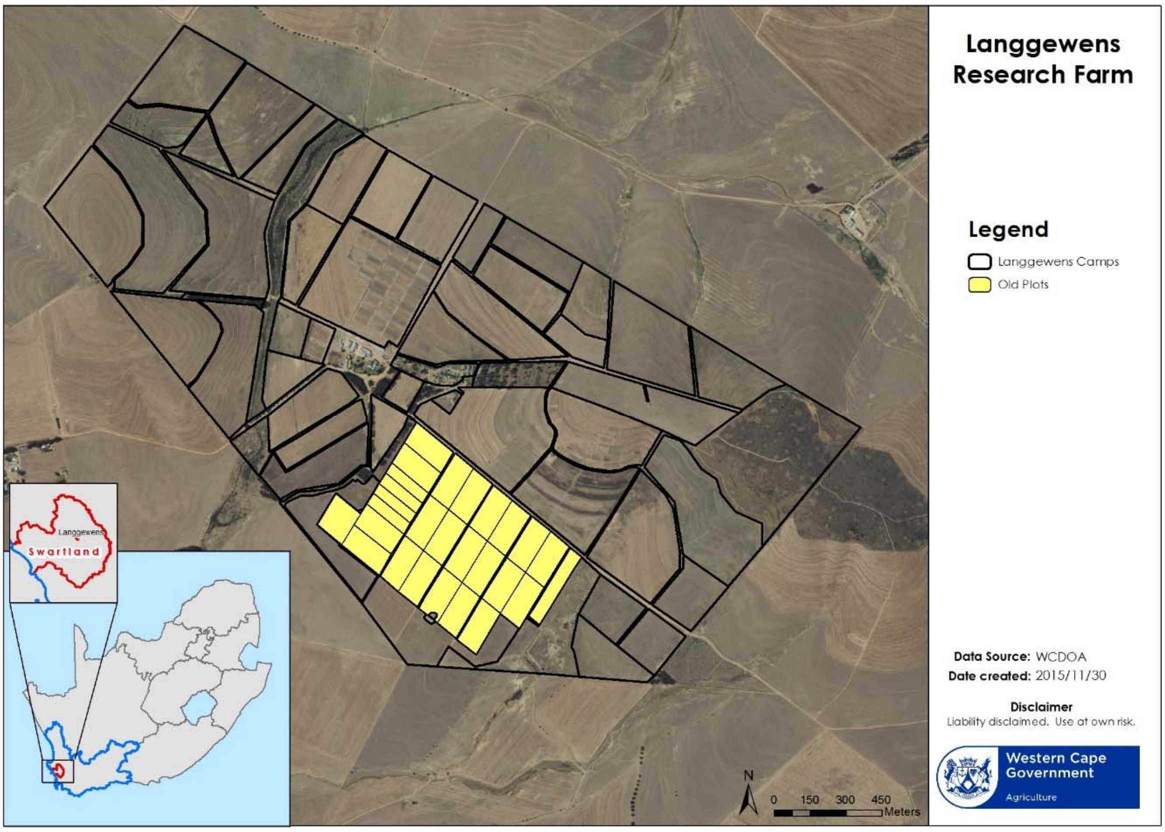
To date, no comprehensive evaluation has been conducted in the Western Cape to determine the long-term, on-farm potential of various crops and crop/pasture rotation systems. This study seeks to fill this gap by testing the validity of the recommendations made with respect to crop rotations and multi-cropping systems two decades ago. We therefore analysed the short- and long-term effects over a 20-year period (from 1996 to 2015) of eight of the most feasible crop and crop/pasture rotation systems identified through a series of discussions with local famers and industry. Open invitations were sent to possible participants, as well as directed invitations to leading farmers. Initial discussions were followed by more detailed discussions on the trial plans developed, until a final trial plan was decided on. These discussions were conducted to facilitate the improvement of sustainable wheat production, including the effects of rainfall variability. The minutes of these discussions are kept on file with the Western Cape Department of Agriculture, along with a detailed assessment report conducted by an independent firm (Urban-Econ) at the end of the 19th year of the trial. The assessment was done through one-on-one discussions with famers and members of the industry on the success of the trial and the way forward. The success of each rotation system was measured against i) the rotation system's influence on crop yield over time, and ii) an estimate of the system's net present value (NPV), which is a financial ratio indicating the net return, in real terms, over time. This assessment was conducted under both typical agricultural conditions as well as under drought conditions. A unique feature of this analysis is that the so-called externalities (uncompensated costs imposed on others, and therefore not reflected in the farmer's costs of production) are included in the analysis. These include positive externalities in the form of soil carbon storage, as well as negative externalities such as livestock enteric emissions, and emissions from fuel combustion and the use of chemicals on crops.

2. Materials and methods

2.1 Background

Langgewens Farm in the Swartland, the Western Cape Department of Agriculture's research farm, is situated in the heart of the western wheat-producing region of the province at 30°17′ S and 18°42′ E (see Map 1). The Swartland region has a typical Mediterranean climate, with hot dry summers and cool moist winters. Long-term ($n = 68$ years) average annual rainfall is 398.2 mm, of which ~80% falls during the period from April to September.

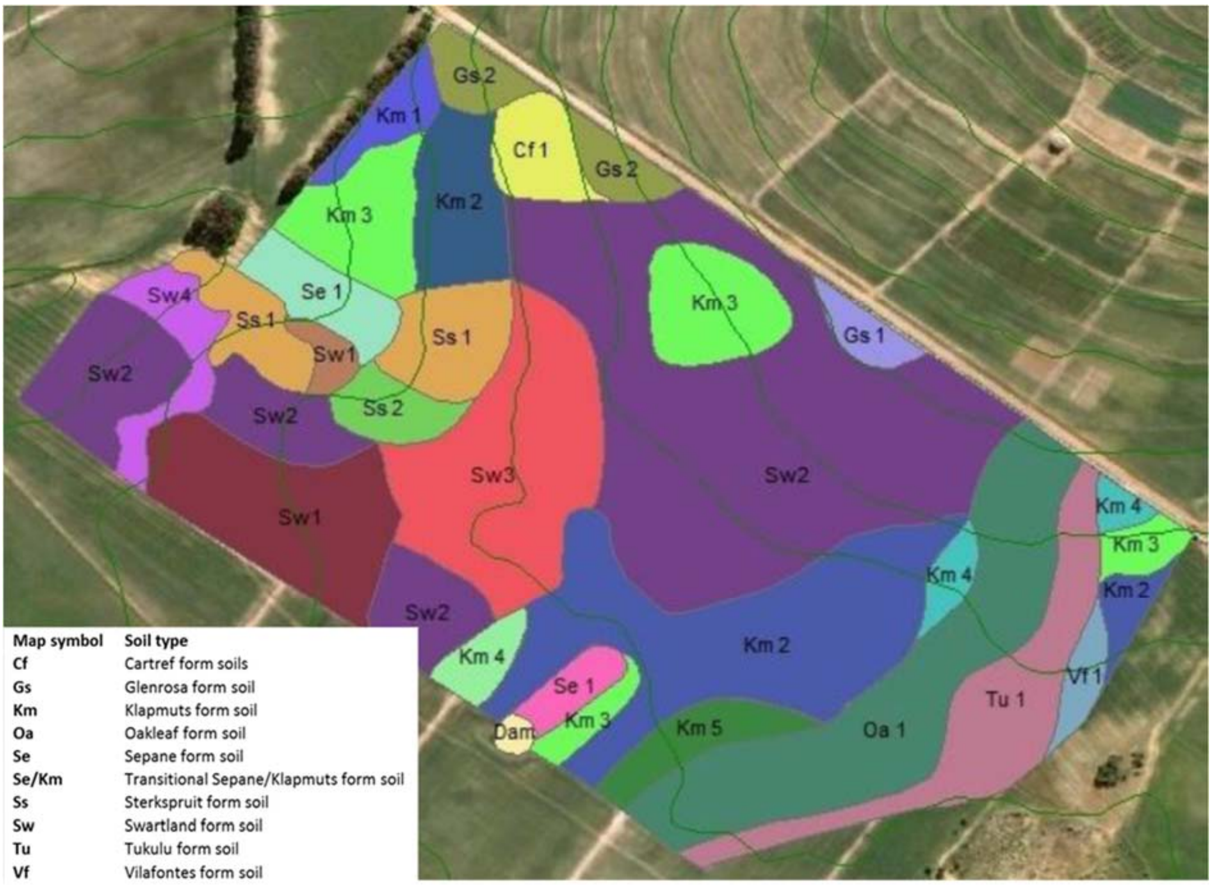
The trial on which this study is based started in 1996 and concluded in 2015. It included eight rotation systems (each taking four years to complete a full cycle), fully represented each year and replicated twice, in a randomised blocks design. The camp areas range in size from 0.5 ha to 2.0 ha, and include 38 camps planted to crops each year, 10 camps of medic pasture and a total of 66 sheep grazing on the respective pastures. From 1996 to the end of 2001, the trial was based on minimum tillage after the first autumn rains, using a scarifier (John Shearer), to a maximum depth of 120 mm, before planting the crops. No till was implemented in 2002 with the use of an AUSplow no-till seeder, and since then no disturbance of the soil has occurred before seeding the trial each year.



Map 1: Location of Langgewens farm

2.2 Soils and rainfall patterns

Nine soil forms and 24 soil families were identified during the survey of Langgewens farm. The majority of the experimental area is characterised predominantly by poorly drained soils, namely Swartland (Sw), Klapmuts (Km), Kroonstad (Ks), etc., which tend to remain wet for longer periods (Map 2). Soils are quite shallow throughout, making cereal production more dependent on continuous and well-dispersed rainfall, rather than total annual rainfall.



Map 2: Soil formations on Langgewens farm

The present soils have an average A-horizon depth of 200 mm to 400 mm, a sandy loam to loam texture and a stone content of 45%. As these soils tend to become waterlogged, the whole trial site was 'ridge and furrowed' prior to the start of the trial.

Historical rainfall patterns indicated a high degree of variability (Figure 1). Reducing farmer risk implies that production has to be sustainable within the context of such rainfall variability.

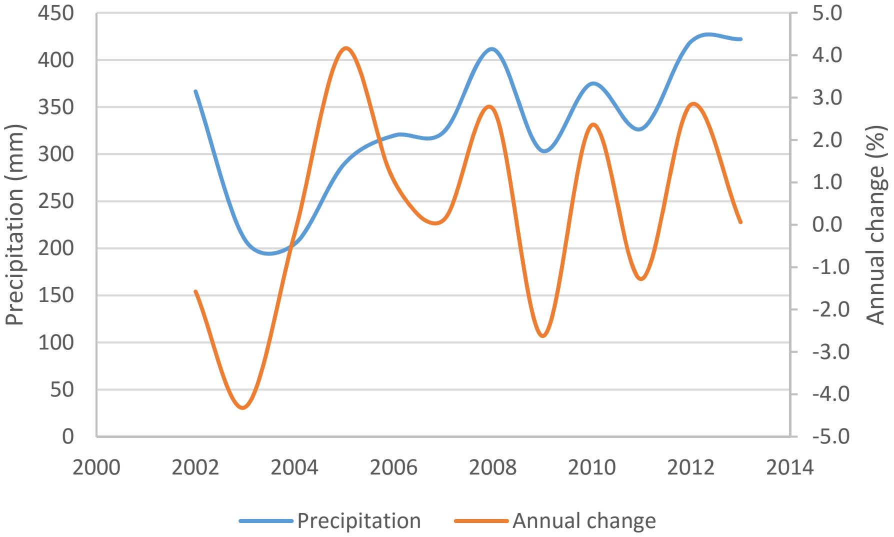


Figure 1: Total precipitation at Langgewens experimental farm (2001 to 2014)
Notes: precipitation shown above is for winter months only (April to September), since the crops modelled (wheat, lupins, canola) are winter crops in the Swartland region.

2.3 Data sources

The present model was developed for Langgewens experimental farm, where data was available for different production systems from 2002 to 2013 (in other words the 12 years that data on no-till farming was available). Eight rotation systems were modelled, which repeated themselves every four years. These are given in Table 1.

Table 1: The eight production systems and four-year rotational patterns for each system

System	Year 1	Year 2	Year 3	Year 4
A	Wheat	Wheat	Wheat	Wheat
B	Wheat	Lupin	Wheat	Canola
C	Wheat	Lupin	Wheat	Canola
D	Canola	Wheat	Wheat	Lupin
E	Wheat	Medics	Wheat	Medics
F	Wheat	Medic/clover	Wheat	Medic/clover
G	Medics	Wheat	Medics	Canola
H*	Wheat	Medic/clover	Wheat	Medic/clover

* With saltbush pastures

The model works from the camp level and then aggregates to the rotation level (using homogenous camps in that particular rotation), after which it aggregates up to the system level (A to H, in other words eight systems). Each rotation and each year has between two and four homogenous camps, resulting in each rotation having a total of between eight and 16 observations. An illustration of the level of disaggregation of the model showing a typical system with farm and rotation level disaggregation is shown in Figure 2.

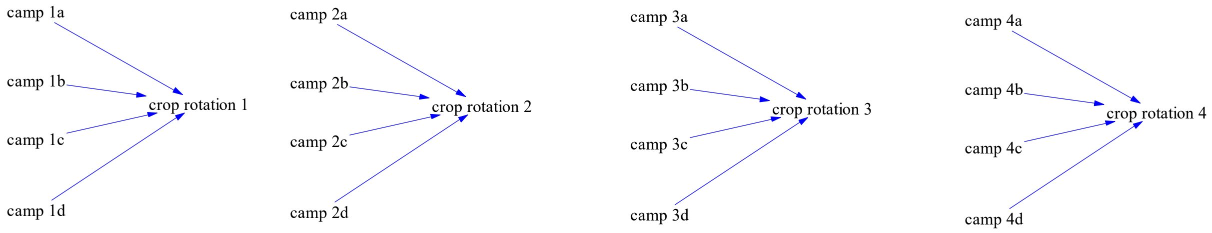


Figure 2: A typical system showing camp and rotation level disaggregation

Notes: each camp is homogenised around a particular rotation to ensure that the same crops are used to combine in each rotation.

The researchers at the experimental site also gathered information on carbon storage from 2001, and this was an important input into the externality component of the study.

Emission factors for enteric emissions from the different categories of sheep production (rams, breeding ewes, replacement ewes and lambs) were obtained from Du Toit *et al.* (2013). Du Toit *et al.* (2013) argue that nitrous oxide emissions from manure deposited by sheep are negligible, and therefore only report methane emissions from enteric and manure management. We found that, for the present study, methane from manure management also was low, therefore only enteric emissions are reported in the study.

Emission factors from diesel use were obtained from the South African National Emissions factors database for the energy sector (Department of Environmental Affairs [DEA] undated), whereas fertiliser, lime and dolomite emission factors were derived from Moeletsi *et al.* (2015). Unfortunately, no local emission factors for pesticides, herbicides and fungicides were available, so these data were obtained from Defra (2012). The emission factor for fertilisers was expressed as tCO_2/tN, and individual fertilisers whose units were not in ton/ha were converted from litres to tons using the relative density of that fertiliser. Furthermore, values expressed in tons carbon, tons methane and tons nitrous oxide were converted to tons carbon dioxide (CO_2) using the appropriate Global Warming Potential (GWP) conversion from the IPCC Fourth Assessment (IPCC 2007). CO_2 has been valued at R120/t (National Treasury 2013).

Financial data for each rotation and production system was derived from the experimental data collected at Langgewens research site from 2002 to 2013. A description of the data is given in Hardy *et al.* (2011a). A MICRO COMBUD was developed in Excel in conjunction with Dr Willem Hoffmann (Stellenbosch University) and Mr Louis Coetzee (Kaap Agri Graan). A description of the input data used for the financial model is given in Appendix Table 1 of Hardy *et al.* (2011b). The financial model generates gross margins for each of the crop rotation systems, as well as for the livestock component of the model (South African Mutton Merino and Döhne Merino sheep). The dataset is disaggregated down to the individual camp level, with details of specific crop inputs used (such as type and brand of fertiliser, pesticides, fungicides and herbicides), other input costs, such as mechanisation costs (sprayer, planter, spreader and tractor costs), labour costs, and how these costs have changed over time, yield data and prices of agricultural crops and values of livestock products. The basic input data for the model and a description of the assumptions are given in the supplementary material (Annexure 1)

2.4 Net present values

A number of different measures may be used to assess the financial performance of a model. These include benefit cost ratios, internal rate of return, cash flow return on investment and a number of other measures. In this model, the net present value (NPV) financial ratio was selected. The NPV calculates the present value of discounted benefits and costs over time, where B_t represents benefits in year t, C_t represents costs in year t, and $\frac{1}{(1+r)^t}$ indicates the discount factor (with r the discount rate):

$$NPV = \sum_{t=1}^{n} \frac{B_t - C_t}{(1+r)^t}$$

A project is deemed desirable if NPV > 0. Although this measure includes cash flow, which is important when assessing a farmer's ability to pay for converting to different crop rotations systems, as well as the impact of droughts, the advantage of the net present value ratio is that it is possible to also include (non-cash) externalities in the model, which is important in our study, as we wish to assess the total economic impact of different crop rotations. The methodology is well established for conducting natural capital economic feasibility assessments, including in the agricultural economics literature (e.g. Akinola *et al.* 2009; Herling *et al.* 2009; Rudi *et al.* 2010; Crookes *et al.* 2013; Blignaut *et al.* 2014; Crookes & Blignaut 2015), hence its use in the present study. The model also has the advantage of distinguishing between cash and non-cash revenues and costs (Bonabana-Wabbi *et al.* 2013). Two of the eight scenarios in the model are cash flow analyses, whereas the remaining six are cash and non-cash analyses.

2.5 Multivariate regression

Partial time series regression was undertaken to examine the relationship between rainfall and crop yields between 2002 and 2013 (n = 12 years). The effect of rainfall on yield was modelled for each crop within each system. A total of 23 regression equations were therefore estimated. Only winter rainfall data was used in the regressions to estimate the effect on crop yield.

2.6 System dynamics model

Modelling crop interactions with each other, as well as with climate, represents a complex system, and as such requires a modelling tool that is able to capture complexity. System dynamics modelling is one such tool. A conceptual model of the system is shown in Figure 3. The model comprises three components: 1) a financial model that models crop production for the various systems; 2) a climate model that models the interactions between crop yields and rainfall variability; and 3) an externality component that models the benefits of the different crop systems in terms of soil carbon storage, and emissions from soil management (fertilisers, herbicides, pesticides, fungicides), energy use (diesel), and livestock enteric fermentation.

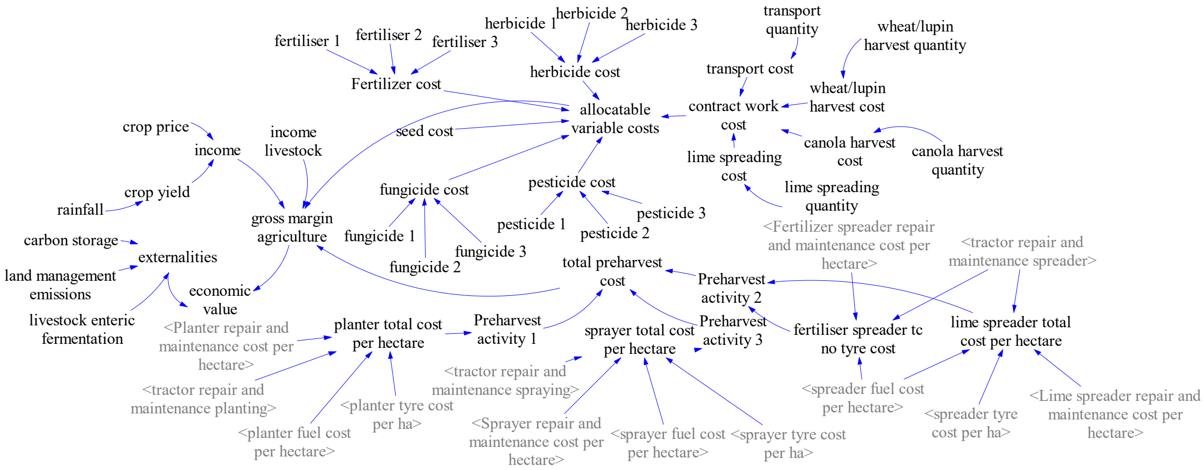


Figure 3: Stylised stock flow diagram for the model

Note: this is a stylised version of the model to show different components in the model and how they interact with each other. Not all elements are included.

There are a number of stock flow diagrams that model the interactions shown in the stylised model (Figure 3). For example, the stock flow diagram for livestock income, one of the components in the stylised model, is shown in Figure 4. A number of the model input parameters are provided in Annexure 1a.

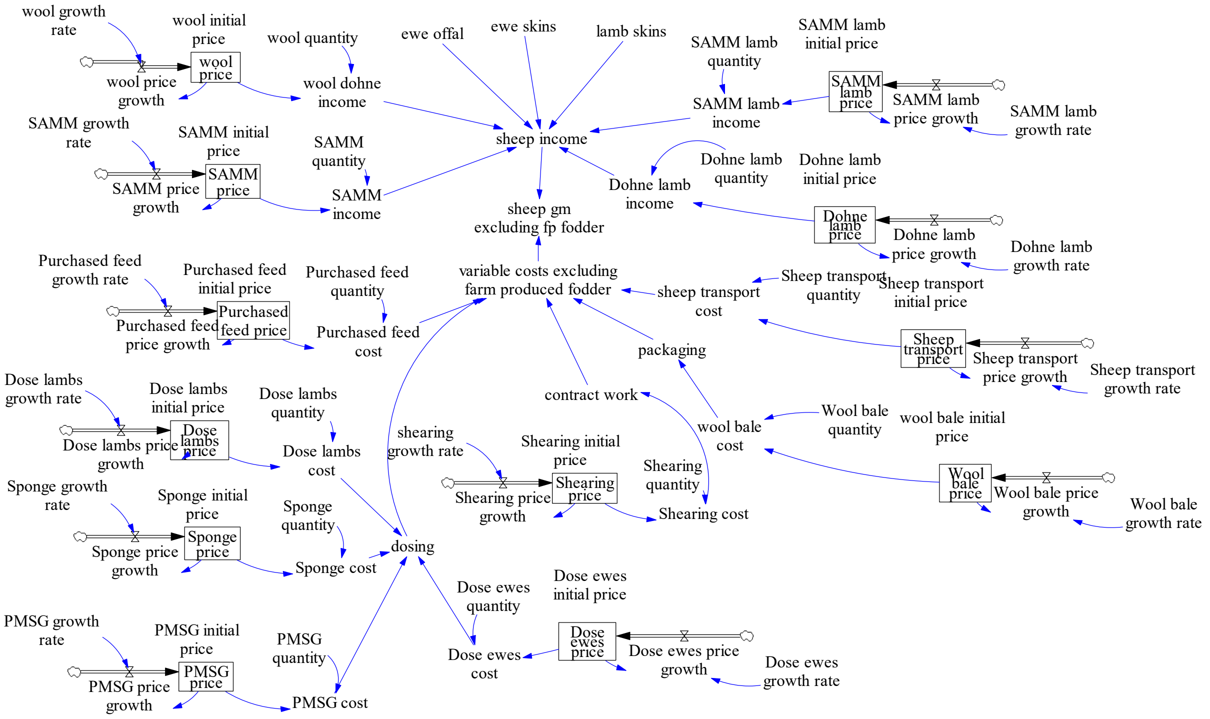


Figure 4: Stock flow diagram used to estimate livestock income

2.7 Model simulations

The baseline for the model is System A (wheat production only). System A was chosen as the control because that was what the average farmer was doing when the trials started. The first part of the trials, from 1996 to 2001, was based on minimum tillage and, from 2001 onwards, no till was employed. Each of the other systems is then compared with this system in order to ascertain whether or not it represents an improvement compared with wheat production only using a financial ratio (NPV).

The following eight simulations were modelled, representing different combinations of factors:

Simulation 1a: Static model, no externalities, no drought

The static model assumes that costs and prices are held constant. No externalities are included in the base model. Therefore, the first simulation assesses only the gross margins from crop production, as well as the gross margins from livestock production. This scenario would therefore represent a cash flow analysis. No drought is assumed. In other words, rainfall is modelled according to the mean precipitation between 2001 and 2014 (winter rainfall only).

Simulation 1b: Static model, with externalities

The same as simulation 1a, except that the net effect of CO_2 emissions is included in the model. The formula for determining the net effect of CO_2 emissions is as follows:

Net CO_2 storage benefit = Soil carbon storage - CO_2 emissions (fertiliser, pesticides, fungicides, diesel) - CO_2 emissions (enteric fermentation)

Simulation 1c: Static model, no externalities, drought

The same as for simulation 1a, except that a drought year is modelled by assuming that winter rainfall declines by one third compared with the mean.

Simulation 1d: Static model, with externalities, drought
The same as for simulation 1b, except that a drought year is modelled by assuming that winter rainfall declines by one third compared with the mean.

Simulations 2a to 2d: Dynamic model
Simulations 2a to 2d are identical to simulations 1a to 1d, except that the assumption that the costs and prices are static is relaxed and is assumed to follow historical trends. Scenario 2a represents a cashflow analysis, whereas scenarios 2b to 2d represent both cash and non-cash items.

In all cases, net present values (NPVs) for the eight different crop rotation systems are calculated, assuming a discount rate of 4%, which is the current real prime overdraft rate. This is an acceptable measure for private sector projects (Department of Environmental Affairs 2004). Since we are comparing systems B to H with system A, the NPV for system A is subtracted from each of the systems B, C, D, E, F, G and H respectively.

3. Results

3.1 Regression analysis

The results of the regression analysis for the effect of rainfall (independent variable) on crop yields (dependent variable) in the different rotations and systems (Table 2) indicate a significant positive relationship with rainfall for each of the crops and for each system ($p < 0.001$ for the coefficient with rainfall). The coefficient of precipitation indicates the amount by which the yield changes for one unit change in precipitation. For example, a 100 mm increase in precipitation increases wheat yields in System A by 0.8591 tons/hectare. For System B (wheat production combined with lupin and canola in the rotation), wheat yield increases are higher than for the wheat-only system (System A), increasing by 0.9445 tons/hectare per 100 mm increase in rainfall. These regression coefficients are then used as yield factors in the system dynamics (SD) model. Although this is a partial regression analysis, resulting in higher coefficients compared with a multi-factor environment, the partial analysis is deemed adequate in this context. The SD model is only concerned with the effect of rainfall on yield, as this is the most important factor affecting yield in a dryland annual cropping system (Van Duivenbooden *et al.* 2000). Other factors, such as fertiliser inputs, capital, labour and expertise, are therefore assumed to remain constant over time.

Table 2: Multivariate regression of the effect of precipitation on yields (dependent variable)

System/ rotation	Precipitation (mm)	Sig	Adj R^2	F	F sig
A	0.008591	***	0.788837	80.47275	***
B1	0.009445	***	0.842767	154.8537	***
B2	0.006266	***	0.719782	47.10623	***
B3	0.008915	***	0.820643	113.3669	***
B4	0.006232	***	0.628196	28.16059	***
C1	0.010723	***	0.853058	185.3131	***
C2	0.003885	***	0.801119	90.87817	***
C3	0.010427	***	0.837924	143.5672	***
C4	0.003389	***	0.759027	62.30196	***
D1	0.00674	***	0.666443	34.3332	***
D2	0.007493	***	0.646763	30.9323	***
D3	0.007025	***	0.744543	55.84982	***
D4	0.006368	***	0.550914	19.71108	**
E1	0.011291	***	0.880611	375.2305	***
F1	0.010545	***	0.874613	308.0469	***
G2	0.008938	***	0.779062	73.59656	***
G4	0.00835	***	0.748171	57.35684	***
H1	0.011583	***	0.882133	397.0447	***

Notes: *** sig $p < 0.001$; ** sig $p < 0.01$; only rotations where coefficients were significantly different from zero are shown

3.2 Net economic values

In the first set of radar graphs, net economic values for each of the rotations are provided without subtracting from System A. Figure 5 provides the results from the static model, whereas Figure 6 indicates NPVs for the dynamic model. In both Figure 5 and Figure 6, NPVs for all the model simulations are positive, indicating that polyculture is preferable to monoculture. Both figures also show that the model simulations that include externalities (s1b, s1d, s2b and s2d) actually improve NPVs for the cropping systems. This is because the net benefit of carbon storage in soils exceeds the damage cost of CO_2 emissions from livestock and chemicals use, although this effect is more pronounced in the static model (Figure 7), since the value of a unit of CO_2 is held constant in the model, even though agricultural prices and costs vary in the dynamic model.

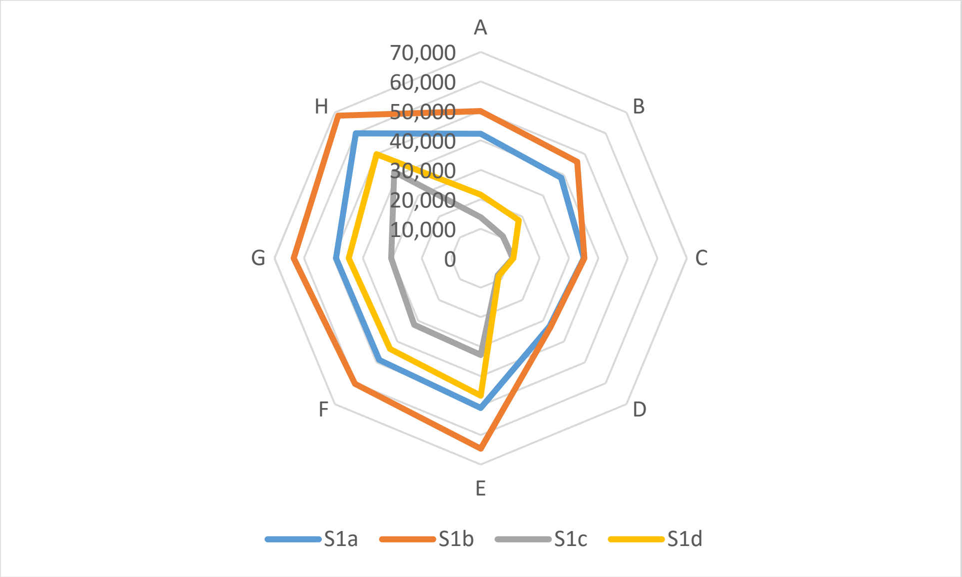


Figure 5: NPVs at the end of the model simulation, static model

Notes: all simulations are for the static model (prices and costs do not change over time). S1a – no externalities, no drought; S1b – all externalities, no drought; s1c – no externalities, drought; s1d – all externalities, drought

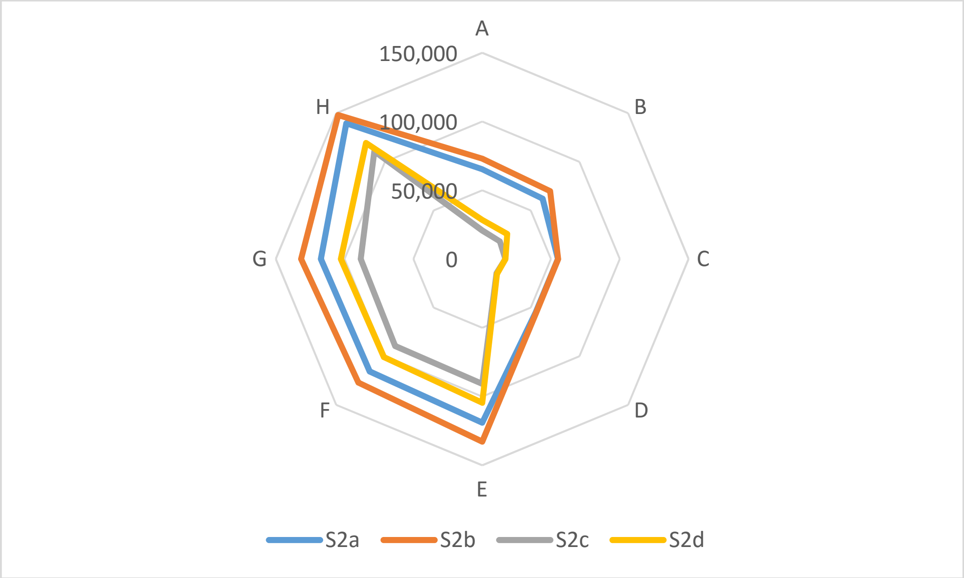


Figure 6: NPVs at the end of the model simulation, dynamic model

Notes: all simulations are for the dynamic model (prices and costs change over time). S2a – no externalities, no drought; S2b – all externalities, no drought; s2c – no externalities, drought; s2d – all externalities, drought

3.3 Net economic values compared with System A

In the final radar graph, Systems B through H are compared with System A (wheat only) in order to assess whether or not crop rotations are preferable from an economic perspective compared with monoculture. For simplicity, only those that included externalities are shown here. The radar graph for policy simulations without externalities is given in the supplementary material.

Figure 7 indicates that systems E to H resulted in positive NPVs compared with wheat-only production, whereas systems B to D resulted in negative NPVs compared with System A. Furthermore, when modelling the effect of drought on the system (S1d and S2d), NPVs for systems E to H actually improved vis-à-vis System A (monoculture) compared with no drought (S1b and S2b). This is because, although NPVs declined for all systems under drought conditions, they declined to a greater extent for the wheat-only simulation compared with systems E through H. This result held for both the static and the dynamic model.

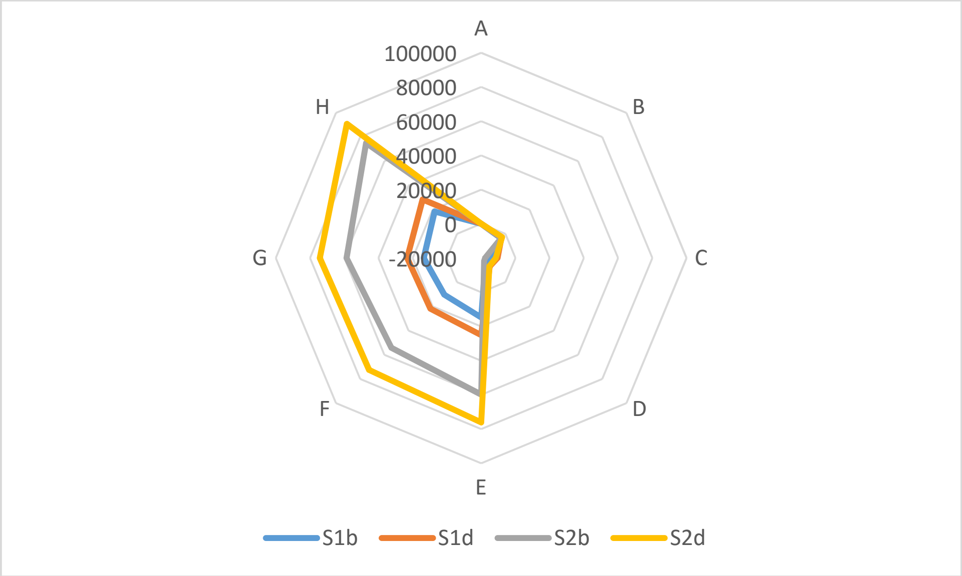


Figure 7: Radar graph comparing NPVs from alternative rotations with wheat-only rotations, all externalities

Notes: S1b – static model, all externalities, no drought; s1d – static model, all externalities, drought; S2b – dynamic model, all externalities, no drought; s2d – dynamic model, all externalities, drought

As Scenario 2d provides the best outcome from an NPV perspective, sensitivity analysis was conducted by varying rainfall. The results are provided in Annexure 2. Rainfall variability did not alter the outcome of the model, with positive NPVs remaining positive and negative NPVs remaining negative (compared to System A).

4. Discussion

This paper makes a contribution in at least four areas: Firstly, it provides an estimate of the effect of climate variability on wheat production in the Swartland. Secondly, it emphasises the importance of studying rain-fed agricultural systems. Thirdly, it assesses the impact of different crop rotations on profitability, and finally, it provides a way of dealing with agricultural risk, particularly as it relates to droughts. Each of these three contributions will now be elaborated on with reference to the literature.

With regard to the effect of climatic conditions on wheat production, our linear regression model found that climate variability had an effect on production in all of the crop rotation systems in the model. In their econometric evaluation of wheat production in the Swartland, Niebuhr and Van Zyl (1990) also found that climate had a significant effect on production. Their climate variable was based in a drought index, in contrast to our study that utilised precipitation. Their model was a much more extensive evaluation of the impacts of climate variability on wheat production, but our results show that even parsimonious models can provide a reasonably good explanation of the variation in yield data.

The second contribution of our article is to the literature of rain-fed agricultural systems. Troskie *et al*. (2000) found that the price of wheat in particular was important in determining the profitability of rain-fed wheat systems in the Western Cape. They found that an free-on-bard (FOB) price of wheat of $140/ton ensured positive profits in 95% of wheat-growing areas, compared with 59% for an FOB price of $100/ton (ceteris paribus). Conradie *et al*. (2009) measured the efficiency of agricultural production in a number of areas, including the Swartland. They found that growth in efficiency was moderate in the rain-fed areas of the Swartland, and most of this growth was driven by the Piketberg region, where there is wheat production, but increasing amounts of more valuable crops, namely apples, pears, peaches and table grapes. The Western Cape is an important wheat-growing area, given its historical (1986 to 1996) stability of production compared with the rest of South Africa (Troskie *et al.* 2000), and a study of the profitability of rain-fed systems such as those in the Swartland therefore is important.

A number of other articles (in addition to our own) have considered the effect of crop rotations on wheat returns. In their study of wheat production in the Mossel Bay area, Smit and Lombard (1996) found that climatic instability emphasised the importance of developing crop rotational systems involving mixed pasture/livestock/grain farming. The work that is most closely aligned to ours is that of Hoffmann and Laubscher (2002), who also conduct an assessment of the effects of different crop rotations on profitability in the Middle Swartland. Like our study, they modelled eight rotation systems with data from the Langgewens research farm. They used the internal rate of return measure as the financial ratio. This earlier work also found that a combination of medics/livestock and wheat rotation would be more beneficial than wheat monoculture only. Our study utilises more recent (2002 to 2013) data from this study site, and since no-till planting was initiated in 2002 it is important to assess whether or not the findings from this earlier work still hold under a no-till regime. Conservation agriculture, which includes no till, is an alternative system that promotes sustainable and climate-smart agricultural intensification, through which farmers can attain higher levels of productivity and profitability (i.e. 'green prosperity') while improving soil health and the environment (Blignaut *et al.* 2015). Hoffmann's (2010) study of the effect of crop rotations on profitability was more broad-based than ours, considering wheat-growing areas beyond the Swartland as well. Our study shows that the findings from this earlier work still hold under a no-till regime, but also expand on earlier work by including externalities in the financial assessment to incorporate the potential broader societal effects of farming.

Visagie and Ghebretsadik (2005) emphasise the complex interrelationships that characterise crop-livestock interactions in mixed farming systems in the Swartland. These authors address this complexity through the incorporation of risk in their model. Nowers and Van Zyl (1991) also modelled risk in their dynamic linear programming model of wheat production in the middle Swartland. Risk in these two models is defined as the sum of the expected negative deviations of the solution results of a given target return. Mahlanza *et al.* (2003) developed a static model to assess the benefits of organic wheat production over conventional wheat production. However, they included a sensitivity analysis of key variables, in particular the price of wheat, as a means of taking into consideration risk.

The main focus of these approaches is to assess financial risk, defined as the expected variability in gross income, which is important, but not the only consideration. It is also important to consider the effect of risk caused by climate variability on the profitability of rain-fed agricultural systems. Although the effects of climate variability on production have been considered previously, our approach is novel in that a system dynamics model is developed to assess this effect. System dynamics modelling is an appropriate tool for modelling complex systems involving agricultural land utilisation and conversion (see, for example, Jogo & Hassan 2010). The supplementary material (Annexure 2) provides a demonstration of the risk assessment potential of the model by using Monte Carlo simulation to investigate the effect of rainfall variability on the different rotation systems.

5. Conclusion

Under conditions of rainfall variability, the rotation that included medics and/or medic-clover showed improvement compared with wheat only. Medics with saltbush pastures showed the greatest improvement after taking into consideration the grazing benefits of pastures. Pastures are more resilient to changes in rainfall compared with wheat only. Planting pastures in alternate years also improved the yields from wheat, which is beneficial in periods of low rainfall. This conclusion validates the recommendations made earlier (Van Schalkwyk *et al*. 1995; Smit & Van Zyl 1998) about the introduction of multi- and rotational cropping production systems to reduce the economic risks of farmers and, in the process, to restore soil quality.

Carbon storage was higher for the pasture crops, representing an improvement compared with wheat production only. Including other externalities, such as CO_2 emissions from fertilisers, herbicides and pesticides, further favours systems E to H compared with the wheat-production systems, even when the CO_2 emissions from enteric fermentation in sheep production are included.

It is important to emphasise that, while wheat/pasture rotations are favoured using a financial objective (taking into consideration also positive and negative externalities), other rotations, such as those that include lupins or canola, may be favourable when compared with other objectives (for example weed control, disease suppression and soil nutrient retention). Further analysis is therefore required to consider other potential benefits of these crops.

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Annexure 1

1. Basic input data

Constant	Value	Unit
period lambs kept on farm	5/12	dimensionless
dolomite emissions factor	0.13	dimensionless
density per litre bortrac	0.001353	ton/litre
NO_2 GWP	298	dimensionless
limestone emissions factor	0.12	dimensionless
density per litre coptrel	0.001523	ton/litre
density per litre nitro 24	0.00128	ton/litre
carbon GWP	3.67	dimensionless
proportion decline in rainfall due to drought	0.33	dimensionless
lambs enteric	3.62	kg/head/year
replacement ewes enteric	6.21	kg/head/year
breeding ewes enteric	8.07	kg/head/year
rams enteric	14.7	kg/head/year
GWP methane	25	dimensionless
herbicide emission factor	0.0576102	kg/Rand
convert kg to tonnes	0.001	ton/kg
density per litre	0.000832	ton/litre
diesel emission factor	3.38	dimensionless
pesticide emission factor	0.0735288	kg/Rand
fungicide emission factor	0.0576102	kg/Rand
fertiliser emission factor	0.027	dimensionless
Dohne lamb initial price	36.56	Rand/kg
Dose lambs initial price	1.81	Rand/lamb
Sponge initial price	16.21	Rand/item
Dose ewes initial price	49.15	Rand/ewe
PMSG initial price	14.08	Rand/ewe
Shearing initial price	5.29	Rand/head
Sheep transport initial price	3.83	Rand/head
wool initial price	43.59	Rand/kg
Purchased feed initial price	2.15	Rand/kg
SAMM initial price	37.21	Rand/item
SAMM lamb initial price	35.61	Rand/kg
wool bale initial price	90.97	Rand/bale
soil bulk density conversion	3 500	ton/hectare
value of unit CO2	120	Rand/ton
discount rate	0.04	1/Year
initial rainfall	334.5	mm
initial tyre cost 74 kw tractor	4 000	Rand
initial tyre cost 86 kw tractor	6 000	Rand
spreader work width	10	m
sprayer work width	12	m
spreader speed	14	km/hour
efficiency	0.85	dimensionless
planter work width	3.3	m
lifespan of tyres	12 000	km
conversion to metres	1 000	m/km
sprayer speed	5.8	km/hour
planter speed	5.5	km/hour
conversion to hectares	10 000	m*m/hectare
high usage proportion	0.6	dimensionless
use per kW hr high	0.3	litre/(kW*hour)
initial fuel price	7.41	Rand/litre
tractor power high	86	kW
tractor power medium	74	kW

Constant	Value	Unit
medium usage proportion	0.45	dimensionless
use per kW hr medium	0.35	litre/(kW*hour)
"86 kw tractor growth rate"	1.76	1/year
"86 kw tractor initial price"	664 743	Rand
tractor lifespan	12 000	hour
"tractor R&M ratio"	1.2	dimensionless
implement lifespan	2 500	hours
"implement R&M ratio"	0.3	dimensionless
"74 kw tractor initial price"	538 649	Rand
"74 kw tractor growth rate"	1.76	1/Year
lime spreader initial price	115 640	Rand
planter growth rate	1.33	1/Year
fertiliser spreader growth rate	1.33	1/Year
lime spreader growth rate	1.33	1/Year
fertiliser spreader initial price	64 200	Rand
planter initial price	558 723	Rand
sprayer initial price	118330	Rand
sprayer growth rate	1.33	1/Year
canola harvest initial price	427.73	Rand/hectare
transport initial price	47.7	Rand/ton
lime spreading initial price	107.16	Rand/ton
"wheat/lupin harvest initial price"	300.05	Rand/hectare
duett initial price	163.02	Rand/litre
cyperphos initial price	108.98	Rand/litre
sluggim initial price	18.24	Rand/kg
mospilan initial price	0.7	Rand/gram
endosulphan initial price	55.86	Rand/litre
mollxide initial price	39.33	Rand/kg
methosan initial price	125.4	Rand/kg
topaz initial price	621.3	Rand/litre
gallant super initial price	279.3	Rand/litre
broadstrike initial price	4 696.8	Rand/kg
buctril DS initial price	70.68	Rand/litre
biodew initial price	68.4	Rand/litre
lontrel initial price	168.44	Rand/litre
glyphosate initial price	32.83	Rand/litre
simazol initial price	50.16	Rand/litre
kerb initial price	333.45	Rand/kg
atrazine initial price	35.06	Rand/litre
aramo initial price	269.04	Rand/litre
paragone initial price	41.95	Rand/litre
triflurex initial price	56.43	Rand/litre
dash initial price	58.14	Rand/litre
"0.1.1. (28) initial price"	5 895	Rand/ton
gypsum initial price	585.73	Rand/ton
amiplus S initial price	4 962.42	Rand/ton
bortrac initial price	46.33	Rand/litre
calcitic lime initial price	329.46	Rand/ton
coptrel initial price	110.58	Rand/litre
dolomitic lime initial price	421.58	Rand/ton
MAP initial price	6 053.12	Rand/ton
alpha magic initial price	6 070.44	Rand/ton
kysan initial price	3 508.07	Rand/ton
nitro 24 initial price	4.1	Rand/litre
turbo 39 APS initial price	4 853.04	Rand/ton

Notes: Only selected constants are shown, as some constants are too complex to display

2. Assumptions

2.1 Farm implements

Prices of new machinery increased for most machinery between 2010 and 2012. For example, the list price of a 215 hp tractor in 2012 was $215 000. A comparably sized tractor in 2010 had a list price of $181 500 (http://farmindustrynews.com/farm-equipment/machinery-cost-estimates-2012-and-2013). This equates to an annual increase of 8.84%, or 133% over 10 years (lifespan of implements). Assume new implements are purchased every 10 years. Although this is an extremely crude measure of estimating price increases, it does mirror the historical change in prices in South Africa, where the tractor price index more than doubled over the ten years between 2001 and 2010 (Grain SA 2013).

2.2 Tractors

Tractor prices increased by 8.84% per annum between 2010 and 2012. This equates to 176% over 12 years (lifespan of a tractor). Assume a new tractor is purchased every 12 years.

Future price changes will depend on interest rates, as high interest rates will increase costs, while low interest rates reduce costs (http://farmindustrynews.com/farm-equipment/machinery-cost-estimates-2012-and-2013). Future price changes are therefore highly uncertain.

2.3 Breeding ewe stocking rate

Treatments E, F, G – 2 Dohne and 2 SAMM
Treatment H – 2.25 Dohne and 2.25 SAMM
Sheep data capture from 2009 – Langgewens

2.4 Replacement ewe stocking rate

25% per annum ewe-replacement strategy
Sheep data capture from 2009 – Langgewens
Systems E, F, G: 4*0.25 = 1 ewe/ha; System H: 4.5*0.25=1.125

2.5 Lamb stocking rate

Lambing percentage, all treatments: 150%
Stocking rate: Systems E, F, G: 4 breeding ewes/ha*1.5 = 2.5; System H: 4.5 breeding ewes/ha*1.5 = 2.81

2.6 Herbicide emissions factor

We use the emissions factor for other chemicals (in Defra 2012) as a proxy for the emissions factor of herbicides in the study (= 0.76 kg Co_2 eq/GBP) converted to 2010 kg CO_2 eq/Rand

2.7 Fertiliser emission factor

Direct – 0.01; Indirectly deposited – 0.01; Indirect leaching/runoff – 0.007 (Moeletsi *et al.* 2015). Total emissions factor is sum of direct, indirect and leaching/run-off.

2.8 Density per litre diesel

As of 2010, the density of petroleum diesel is about 0.832 kg/L
(Wikipedia: Diesel fuel; accessed 17 November 2015)

3. Results

3.1 Net economic values compared with System A

a. No externalities (S1a, S1c, S2a, S2c)

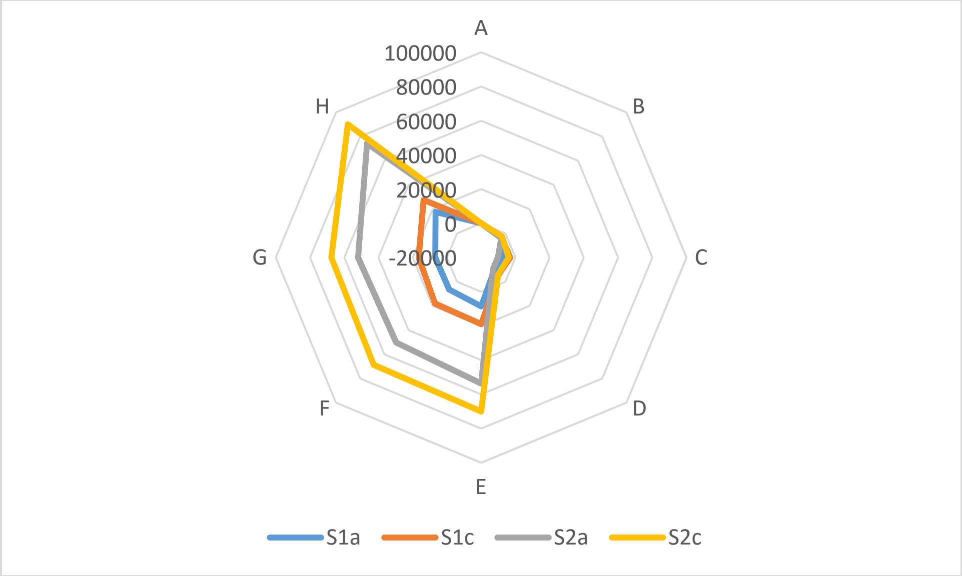

Figure A1: Radar graph comparing NPVs from alternative rotations with wheat only rotations, no externalities

Notes: S1a – static model, no externalities, no drought; s1c – static model, no externalities, drought; S2a – dynamic model, no externalities, no drought; s2c – dynamic model, no externalities, drought

3.2 Monte Carlo simulation

Monte Carlo simulation is conducted to examine the sensitivities of rainfall variation in the model that provided the best policy outcome from a net present value perspective (Annexure 2). The mean and standard deviation for the Monte Carlo simulations follow the historical data discussed in the main document. The 'plumes' are relatively narrow for the dynamic model, indicating that NPVs are not sensitive to rainfall variability. By contrast, in the static model (not shown), 'plumes' are broader, but rainfall variability still does not affect model outcomes: those systems that have a positive NPV continue to have a positive NPV in comparison with System A, and those systems with a negative NPV continues to have a negative NPV in comparison with System A.

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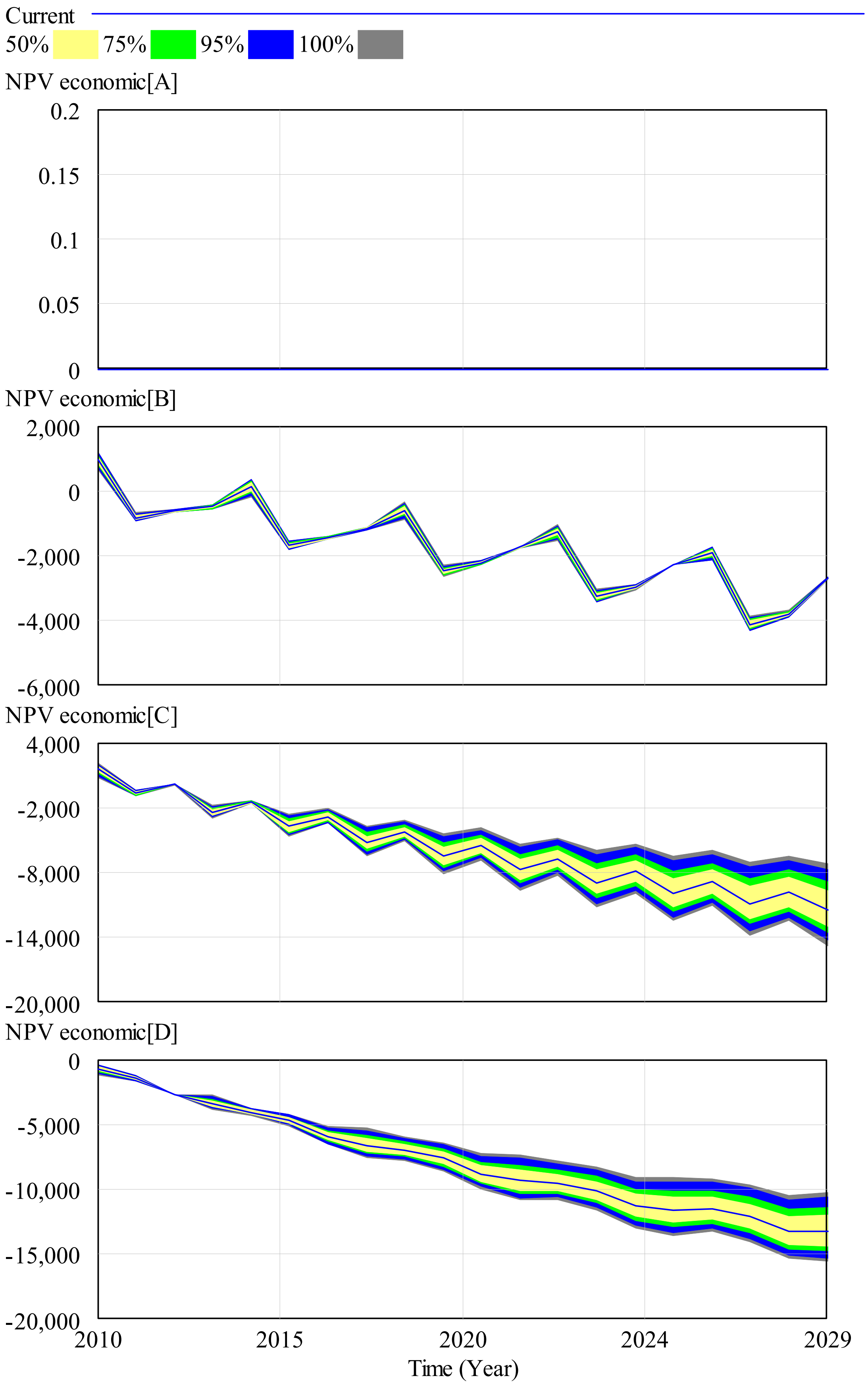
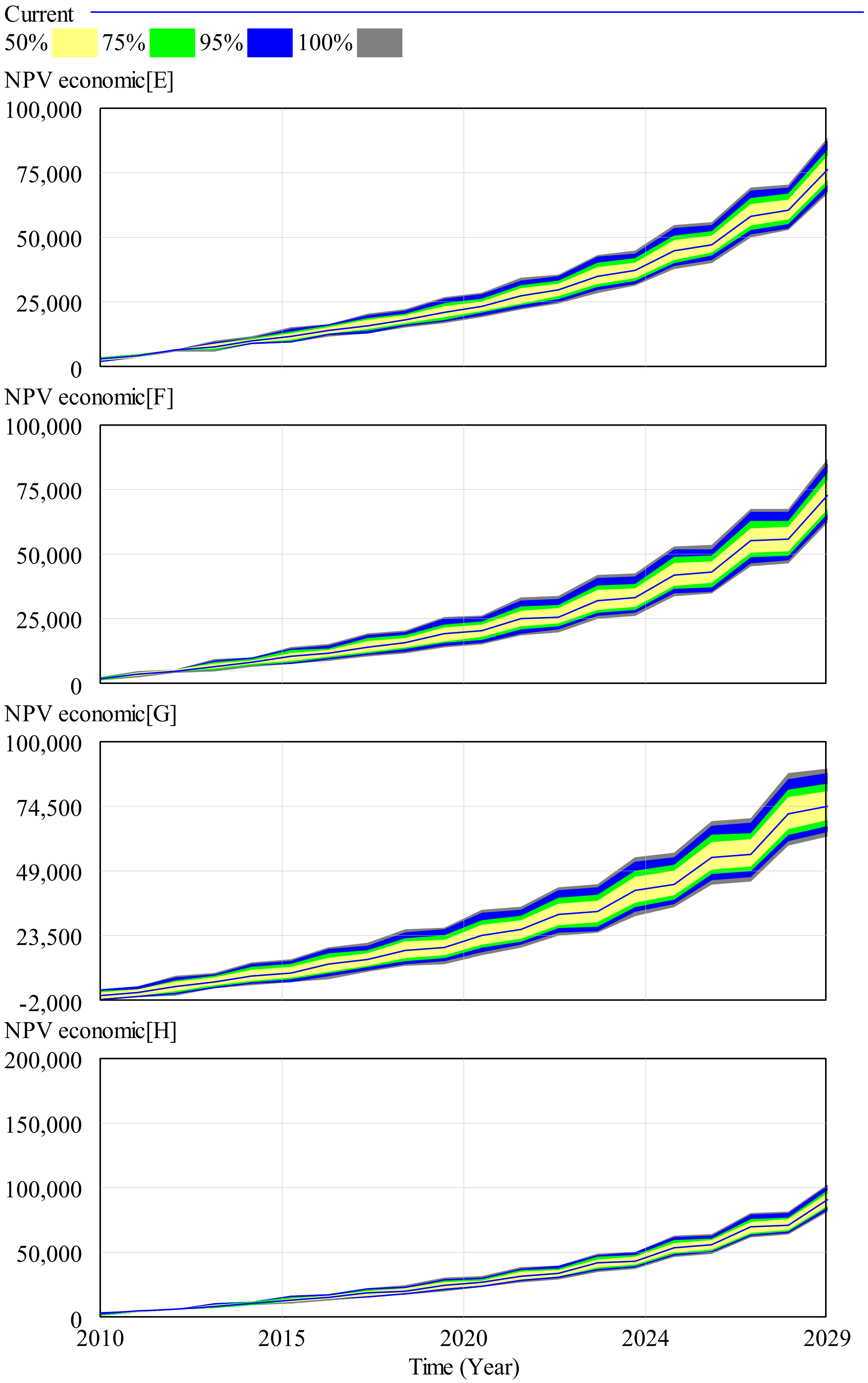
Annexure 2: Monte Carlo simulation for dynamic model, with drought, all externalities




Current
50%
75%
95%
100%
NPV economic[E]
100,000
75,000
50,000
25,000
0
NPV economic[F]
100,000
75,000
50,000
25,000
0
NPV economic[G]
100,000
74,500
49,000
23,500
-2,000
NPV economic[H]
200,000
150,000
100,000
50,000
0
2010
2015
2020
2024
2029
Time (Year)