PROFITABILITY OF PRECISION PHOSPHORUS APPLICATION ON A COMMERCIAL FARM IN THE HEIDELBERG DISTRICT, WESTERN CAPE

Ella Christina Hough

Submitted in accordance with the requirements for the degree
Philosophiae Doctor

In the
Faculty of Natural and Agricultural Sciences
Department of Agricultural Economics
University of the Free State

Promotor:

Dr W.T. Nell
(University of the Free State)

Co-promotor:
Dr N. Maine

Bloemfontein
May 2010

ACKNOWLEDGEMENTS

I hereby wish to express my sincere appreciation and thankfulness for the support and encouragement I received from my friends, family and certain institutions during the completion of my Ph.D. There are, however, a few persons and institutions I would like to mention in particular.

Firstly, I want to thank my family for their support and confidence in me at all times. Without their support and assistance it would have been much more difficult to complete my studies. A special word of appreciation goes to Jaco for his encouraging words and support.

I would also like to thank New Holland SA for the appropriation of funds for my studies.

Thanks to the staff members of the Elsenburg Agricultural Library who were always prepared to help me in my search for the appropriate literature.

I also want to thank the staff members of the Department of Agriculture: Elsenburg for their support during the period I was employed there.

My sincere thankfulness goes to Trompie and Michel Gildenhuys for allowing me to conduct experiments on their farm and to use the data of their farming business as a case study in the completion of my studies. I appreciate their willingness to answer all my questions.

The staff members of Technifarm at Swellendam and Moorreesburg were very kind in providing me with technical support, for instance with the printing of the required maps.

I want to address a special word of appreciation to Dewalene van der Merwe for her support and assistance with the GIS part of my studies, as well as to Marieta van der Rijst for her assistance in processing the data statistically. They played a vital role in the completion of my thesis.

I also want to thank the staff members of MKB, Moorreesburg, for allowing me to take study leave.

A special word of appreciation goes to Dr Wimpie Nell, my study leader, for all his assistance and support. Dr Nell expressed his confidence in me and inspired me to greater heights. Thank you also to Dora du Plessis for her advice and patience in dealing with my manifold questions. A special word of appreciation goes to Dr Ntsikane Maine for her advice and patience in dealing with all my queries, as well as the leadership she provided.

Last, but not least, I want to thank my Heavenly Father for the skills and knowledge I received from Him which I could apply in the completion of my studies. The Lord is my Saviour and succour in everything I do.

"People become really quite remarkable when they start thinking that they can do things. When they believe in themselves they have the first secret of success."

"If you want to get somewhere you have to know where you want to go and how to get there. Then never, never, never give up."

Norman Vincent Peale

"When we are motivated by goals that have deep meaning, by dreams that need completion, by pure love that needs expressing, then we truly live life."

Greg Anderson

ABSTRACT

Phosphorus (P) is an important nutrient required by every living plant and animal cell, and deficiencies in soils could cause a restriction on crop production. P is also a primary nutrient essential for root development and crop production, and are needed in the tissues of a plant where cells rapidly divide and enlarge.

Precision agriculture (PA) could assist the farmer in applying the prescribed amount of P to the part of the field where it is required. Variable rate technology (VRT) is therefore a tool that can help with the development of strategies for phosphate fertiliser management.

The main objective of this research is to determine the effect of precision P application on the profitability of PA on a commercial farm in the Heidelberg district in the Western Cape Province in South Africa.

The study was conducted in collaboration with Mr Gildenhuys (on-farm trials) in the Heidelberg district in the Western Cape, South Africa. Four fields, totalling 106 ha, were identified as research fields for the study. The main crops included in the study were wheat, canola and barley (third year). As many as five soil types were found in each field, which was divided into two halves. One half was planted by making use of VRT, and the other half was planted by conforming to the traditional farm management system or single rate (SR). The same crop was planted on both halves. Wheat, canola and barley were used in a crop rotation system.

The specific objectives were to determine the winter grain response to P on different soil types, the relationship with and effect of previous and current years' yields on the following year's P application and whether spatial econometric models are more accurate than traditional ordinary least squares (OLS) models in predicting the profitability impact of P on PA.

The results obtained show significant differences between OLS, spatial error (SER) and restricted maximum-likelihood (REML) models. All the measures of goodness of fit indicated an increase in fit from the OLS to the SER model, with the best fit being achieved with the REML model, implying that the use of this model resulted in more accurate estimates. Profit analysis based on the application of statistical models indicates that, on average, the VRT treatment resulted in higher profits than the SR treatment. It could not be established, based on this study, that yield response to fertiliser depends on a specific soil type, because some soil types delivered higher yields and profits during certain years and during others they performed considerably weaker. It can thus be concluded that yield responses and profits differ from year to year and also within the crop rotation system (wheat, canola and barley).

From the conclusions generated in hypothesis testing it is evident that the wheat crop yield response to P varied according to soil type. Over a three-year period, the VRT application of P lead to higher profitability compared to the SR application of P.

Key terms: Precision agriculture, variable-rate application, single rate application, profitability, spatial lag and error models, restricted maximum-likelihood model, phosphate, South Africa.

SAMEVATTING

Fosfate (P) is ‘n belangrike voedingstof wat deur elke lewende plant- en diersel benodig word en tekorte aan hierdie voedingstof in grond kan lei tot ʼn beperking van oeste. Fosfate is ook die hoofvoedingstof wat benodig word vir wortelontwikkeling en voedselproduksie. Dit word benodig in die weefsel van plante waar selle vinnig verdeel en groei.

Presisie-boerdery (PB) kan die boer help om die korrekte hoeveelheid P toe te dien in die gedeelte van die veld waar dit die meeste vereis word. Veranderlike-toedieningspeiltegnologie (VTT) is ʼn potensiële hulpmiddel vir die ontwikkeling van strategieë vir fosfaatbemestingbestuur.

Die hoofdoel van hierdie navorsing is om die uitwerking van presisiefosfaataanwending op die winsgewendheid van PB op ‘n kommersiële plaas in die Heidelbergdistrik in the Wes-Kaap Provinsie in Suid-Afrika te bepaal.

Die studie is in samewerking met mnr. Gildenhuys (proefneming op plase) in the Heidelbergdistrik in the Wes-Kaap in Suid-Afrika uitgevoer. Vier landerye wat gesamentlik 106 ha beslaan, is geïdentifiseer as navorsingsveld vir die studie. Die belangrikste gewasse wat by die studie ingesluit is, was koring, kanola en gars (derde jaar). In elke landery is soveel as vyf grondsoorte aangetref. Elke landery is in twee helftes verdeel. Die een helfte is beplant deur gebruik te maak van VTT, en die ander helfte is beplant deur gebruik te maak van die tradisionele plaasbestuurstelsel (ETT enkelpeiltoedieningstegnologie). Dieselfde gewas is op die twee helftes van die landerye geplant. Koring, kanola en gars is aangewend volgens ʼn oesrotasiestelsel.

Die spesifieke doelwitte van die navorsing was om die reaksie van wintergraan te bepaal met die toediening van P op verskillende grondsoorte, sowel as die verband tussen die huidige en vorige jare se oeste op die volgende jaar se toediening van P, en om te bepaal of ruimtelike ekonometriese modelle meer akkurate resultate lewer as die gewone kleinste kwadraatmodelle (GKK-modelle) in die voorspelling van die winsgewendheidsimpak van P op PL.

Betekenisvolle verskille is waargeneem tussen die resultate gelewer met GKK-, ruimtelike fout-modelle (RF) en beperkte maksimum voorkoms-modelle (BMV-modelle). Met die toepassing van maatreëls om die geskiktheid van die verskillende modelle, vanaf die GKK- tot die RF-modelle te bepaal, is bevind dat die akkuraatste skattings met die BMV-model verkry is en dit impliseer dat meer akkurate skattings met hierdie model gemaak kan word. ʼn Winsontleding is toegepas, gebaseer op die gebruik van statistiese modelle, wat aangedui het dat die veranderlike toedieningspeil- (VT-) behandeling groter winste gelewer het as die enkelpeiltoediening- (ET-) behandeling. Die navorsing kon nie bewys dat die grootte van oeste afhang van 'n spesifieke grondsoort in die landerye nie, omdat sekere grondsoorte groter oeste en beter produksie gelewer het gedurende sekere jare en gedurende ander jare swakker oeste opgelewer het. Daar kan dus afgelei word dat oeste en winste van jaar tot jaar en binne die oesrotasiestelsel (koring, kanola en gort) sal verskil.

Met die hipotese-toetsing is tot die gevolgtrekking gekom dat die koringoesreaksie op P volgens grondsoort verskillende resultate opgelewer het. Oor ʼn driejaar-periode het die VT-aanwending van P tot beter winsgewendheid gelei in vergelyking met die ET-aanwending van P. Ruimtelike ekonometriese modelle het ook gelei tot meer akkurate skattings as wat met die GKK-modelle bereik is.

Sleutelterme: Presisie-boerdery, veranderlike-toedieningspeilaanwending, enkeltoedieningspeilaanwending, winsgewendheid, ruimtelike-vertraging- en foutmodelle, beperkte maksimum voorkoms-modelle, fosfate, Suid-Afrika.

TABLE OF CONTENTS

CHAPTER ONE: Introduction

CHAPTER TWO: Literature Review

CHAPTER THREE: Research Methods: On-farm trials

CHAPTER FOUR: Exploratory and descriptive statistics

CHAPTER FIVE: Statistical and profitability analysis

CHAPTER SIX: Summary and recommendations

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

During the twenty-first century there have been dramatic technological changes occurring in the agricultural sector, which are driven by certain important aspects. One of these drivers of change is technological improvements (Nell & Napier, 2009), as embodied in precision (information-intensive) agriculture. The above-mentioned changes are viewed as opportunities by some, but as threats by others (Boehlje, 2002).

Farming in-field management can, for instance, be modified by the utilisation of information about soil and crop variability. The technology of in-field variability management is called precision agriculture (PA) and it can be useful to all types of farmers (Elstein, 2003). The following can be quoted as an example of the aforementioned: According to Fiez, Miller and Pan (1994), variations in soil characteristics and yield potential can cause fertiliser requirements to vary widely within fields. The single rate application of fertiliser across a field will result in over-application in some areas and under-application in others. By varying fertiliser rates (variable-rate technology - VRT) within fields to match the site-specific needs, fertiliser misapplication can be eliminated. VRT is operated from a personal computer equipped with a geographic information system (GIS) and a navigation system such as a global positioning system (GPS). Khanna, Epouche and Hornbaker (1999) stated that in the traditional farm management systems, this kind of technology of in-field variability and the management of crop production systems have been lacking. In the traditional systems, farm managers rely on a uniform rate of application of inputs. According to Batte (2003), precision agriculture could assist the farmer in determining which factors are controllable.

Crop yields vary within fields and the degree of variability can be substantial. This can be caused by fixed or non-controllable characteristics (FC) and/or variable or controllable characteristics (VC). The VC encompasses nutrient availability, soil moisture, soil compaction, rooting depth, etc., while the FC includes, for instance, landscape position (Babcock & Pautsch, 1998). The farm manager has various responsibilities. One of the farmer's primary responsibilities is to make decisions regarding the economical efficient use of inputs to reach the goal of profit maximisation. Some factors can be controlled, for instance input use, while other factors, such as input prices, cannot be controlled. These uncontrollable factors introduce a great deal of uncertainty into the farm business (Powers, Dillon, Issacs & Shearer, 2003).

It is important to provide the correct nutrition in order to ensure good crops. Typical examples of such nutrients are phosphorus (P), nitrogen (N) and potassium (K). The P fertilisation of soils has always been traditionally viewed as important as it is the most immobile of major plant nutrients and can only be absorbed by plants in a soluble form. The average total P level of soils around the world is low (one-tenth to one-fourth of N and one-twentieth of K). P in the soil is present either as inorganically fixed phosphates, as organically fixed P, or as P dissolved in the soil. Only the latter form of P is available for use by plants. The P concentration in the soil solution is normally in the range of 0,3 to 1 ppm (approximately 0,3 to 1 kg of P_2O_5/ha). Non-labile P can range from 100 – 200 ppm (1 000 - 2 000 kg P_2O_5 in the upper 15 cm of 1 hectare of soil). The soluble sources of P are fertilisers and manure. When these soluble sources are added to soils, they are fixed (changed to unavailable forms), and these fixation reactions allow only a small fraction of the P in fertilisers and manure to be absorbed by plants in the year of application (Grego, 2001, Florida Institute of Phosphate Research, 2004 & Yara, s.a.).

P is an important nutrient required by every living plant and animal cell, and deficiencies in soils could limit crop yields. P is also a primary nutrient essential for root development and crop production, and is needed in the tissues of a plant where cells rapidly divide and enlarge. Plants that have P deficiency are often yellowish in colour

(Grego, 2001). Precision agriculture can play an important role in the application of the correct amount of P to the part of the field where it is specifically required.

The concept of using information about soil can be implemented by two somewhat different strategies that will be referred to as determining the soil potential and conducting a chemical analysis of the soil (Wollenhaupt & Buchholz, 1993). There are certain geographical differences that distinguish the agriculture in the Western Cape from that of the rest of South Africa. The soil types of the Western Cape are mainly described as "Soils with minimum development. Usually shallow on hard or weathering rock, with or without intermittent diverse soils" (Department of Agriculture: Western Cape, 2009). Genis (2009) stated that, according to Hoffman (2009), the soils of the Western Cape are shallow with little storing capacity for water and therefore very dependent on rainfall.

It has already been mentioned that precision agriculture could assist the farmer in applying the correct amount of P to the part of the field where it is required most. The mentioned process consists of two steps, namely soil sampling and the compilation of a soil analysis report. The yield potential for the Eastern Ruens part of the Western Cape is low (1,8 ton/ha) to medium (2,0 ton/ha) (ARC-guidelines, 2008). It is important to note that fertiliser prices increased between 300% and 400 % in the period of 2000 to 2008 (National Agricultural Marketing Council, 2009), while the local wheat price decreased from ZAR3 900,00 (July, 2008) to ZAR2 500,00 (May, 2009). The concept where input prices rise more than output prices is called the cost-price squeeze.

Fertiliser costs account for approximately a quarter of the variable costs of grain production (23 % of wheat production, 21 % of barley production and 27 % of canola production). Due to these high percentages, the role of PA becomes clearer as a tool to be used for the application of the correct amount of fertiliser to the part of the field where it is required. The research problem will focus on the price of agricultural inputs (seed, fertiliser, chemicals etc.) and the cost-price squeeze, as well as to determine how PA can play a role in improving the efficient use of P and therefore increasing the profitability of the farming businesses.

1.2 THE PROBLEM

It is a phenomenon in agriculture worldwide that the price of agricultural inputs increases faster over time than the price of outputs, which causes a cost-price squeeze. PA is one of the youngest technologies that could be applied to combat this trend and to improve the effectiveness of input management. Schoeman (2009) reported that the global economic slowdown and the recession in the United States of America for 2009 reflect the current global financial crisis. It is also true that projects undertaken in the agricultural sector in the near term will have to adjust to the aforementioned economic slowdown. The long-term growth in global demand for agricultural products caused the prices of many crops to remain well above the historical levels, but prices are not projected to reach the record highs of 2008 (the local wheat price in July, 2008, was ZAR3 975,00 per ton). However, a steady economic growth over the next couple of years will provide a more favourable demand situation. Countries in Africa and the Middle East will overall help with the gains in global grain trade. Schoeman (2009) is also of the opinion that food use of wheat is projected to show moderate gains, although feed use of wheat is projected to decline. Sub-Saharan Africa is an important growth market for wheat imports. Barley production will be boosted due to international demand for malting barley.

The appeal worldwide is to protect the natural resources against pollution and to minimise waste, where possible. According to Whitley, Davenport and Manley (2000) there has been (from 1990) an increase in attention to nitrate contamination of groundwater, in particular with regard to leaching associated with agricultural activities. Variable rate technology (VRT) is a potential tool that can help with the development of strategies for environmentally sound nitrogen fertiliser management (Whitley *et al.*, 2000). The same rule can be applied to precision application and runoff.

Traditional analyses and ordinary least squares (OLS) are unreliable when data are spatially correlated, for instance data obtained from yield monitors and site-specific data. Spatial regression analysis is one methodology that can overcome these limitations of traditional analyses (Griffin, Brown & Lowenberg-DeBoer, 2005).

Agriculture in South Africa is under pressure due to the rapid increase in production costs over the last couple of years (from 2005 onwards). The net average price of fertiliser increased nine percent between 2005 and 2006 and 200 % from August 2007 to August 2008. In 1995 the net average price of fertiliser was ZAR700,00 per ton, in 2006 ZAR2 100,00 per ton, in 2007 ZAR3 200,00 per ton and in 2008 ZAR9 800,00 per ton, with Maxifos fertiliser increasing with 248 % from August 2007 to August 2008, from ZAR3 200,00 per ton to ZAR11 125,00 per ton (Brink, 2008; Van Rooyen, 2007). Due to erratic weather conditions, a farmer must try to obtain the optimum yield with the lowest possible input cost. This is especially true for dry land (rain-fed) crop production. PA is the technology on the market that can help with identifying management zones (Stombaugh, Mueller, Shearer, Dillon & Henson, 2001) in a field to apply fertiliser only according to each management zone's potential and requirements, thus manipulating/reducing costs (Southern Precision Agriculture Association, s.a).

According to Maine (2006), the use of fertiliser is influenced by many external factors, among which is the price thereof. Prior to 1984, in South Africa all prices and imports of fertiliser were controlled, but during 1984 the price control on fertiliser was lifted and that had serious financial implications for both the farmers and the fertiliser industry. Van Rooyen (2007) reported that there are three factors that will influence fertiliser prices and sales over the next couple of years. Firstly, there is the relationship between the price of fertiliser and the oil price. A decline in grain yields in 2005 and 2006 is the second factor. Thirdly, the production of bio-fuel is increasing in more countries. These three factors will lead to an increase in fertiliser costs and farmers should therefore find ways to manage their fertiliser applications, where PA can play an important role.

However, the question still remains unanswered whether the potential better application of fertiliser and the increase in potential returns are sufficient to cover the investment costs of PA. Wollenhaupt and Buchholz (1993) indicated that for new practices to be adopted widely, the practices must yield a financial benefit. In 2006, Maine, Nell, Alemu and Barker reported that the profitability of VRT has not been investigated in South African conditions. The potential increase in profitability is one of the main considerations by producers when thinking of adopting PA and the real challenge is to develop an appropriate strategy to maximise profitability for the producer (Maine, 2006), especially in the Western Cape.

1.3 MAIN RESEARCH OBJECTIVE

The main objective of this research is to determine the effect of precision phosphorus (P) application on the profitability of PA (precision agriculture) on a commercial farm in the Heidelberg district in the Western Cape Province in South Africa. Profit in this research is calculated by bringing into account the production cost, cost associated with PA as well as the interest cost for the precision equipment and fertiliser. A full description of the profit calculation formula will be discussed in Chapter 5.

1.3.1 Sub-research objectives

The sub-research objectives are to determine the impact of the following on the profitability of PA:

- Whether spatial econometric models are more accurate than traditional ordinary least squares (OLS) models in predicting the profitability impact of P on PA.
- To determine the variation of winter grain yield response to P on different soil types.
- To determine the profitability of precision P application.

1.3.2 Hypotheses

1. Spatial econometric models estimate the profitability of PA more accurately than the OLS models.
2. Winter grain yield response to P varies on different soil types.
3. There is a favourable statistical difference between the profitability of (variable rate) VRT and standard rate (SR) applications of P.

In the next section, there is a short description of the methodology used for this research, with a full description thereof in Chapter 3.

1.4 METHODOLOGY

The study was conducted in collaboration with Mr Gildenhuys (on-farm trials) in the Heidelberg district in the Western Cape, South Africa. Four fields, totalling 106 ha, were identified as research fields for the study. The main crops included in the study were wheat, canola and barley (third year). In each field as many as five soil types were found.

Each field was divided into two halves. One half was planted by making use of VRT, and the other half was planted by conforming to the traditional farm management system (SR). The same crop was planted on both halves. Wheat, canola and barley were used in a crop rotation system. The reason for using this design was that it was most suitable for the current farming operations. A full discussion of the methodology followed in the mentioned study is provided in Chapter 3.

1.5 VALUE OF THE STUDY

Hugo, Viljoen and Meeuwis (1997) stated that the continued existence of humans on earth is totally dependent on the resources that the environment can provide. Soil can be defined as the uppermost eroded layer of the earth's surface and is one of the more permanent and less changeable components thereof. It can, however, easily be damaged by incorrect use. The incorrect use of soils can be caused by over-utilisation, incorrect tilling methods or irrigation techniques. This is one of the greatest causes of desertification and the expansion of desert areas. PA technologies can help with better-informed decisions in soil management such as the improvement of soil pH management and better control of fertiliser applications. The likelihood of environmental benefits must also be kept in mind.

Precision agriculture also helps farmers to apply sustainable land management practices. The goal of sustainable agriculture is to improve the quality of life and the production of farmers by steering clear of negative changes in natural resources. It also has the potential to reduce the use of fertilisers and pesticides while maintaining sustainable land management (Coates, Horsburgh & Gleason, 2002). This kind of technology can also help to reduce nutrient losses in the environment by means of VRT, as only the correct quantities are applied to appropriate areas.

The profitability of agricultural production in South Africa is under pressure due to the cost-price squeeze phenomenon as mentioned earlier in this chapter. Precision agriculture can increase profit margins by more accurate fertiliser application and a potential decrease in per unit production costs as fertiliser is only applied according to the soil requirements as indicated by the chemical analysis. Spatial associations are present when working with yield monitor data and this study illustrates the importance of taking spatial variability into account in order to provide realistic estimates.

The collaboration between researchers and on-farm experimentation can contribute to the theory of agricultural management by providing greater insight into the value of PA. As PA is a capital intensive technology, it is important to balance the potential economic returns with environmental impact and the degree of risk involved (capital intensive). The sole purpose of this study is mainly to determine the profitability of precision P application in the Western Cape.

1.6 OUTLINE OF THE STUDY

This research addresses the question of whether the implementation of VRT with regard to fertiliser application in PA practices will be profitable. The research problem and the background to the problem, the objectives, methodology and value of the study are discussed in **Chapter 1.** In **Chapter 2** a literature review is done on PA applications and trends, as well as the benefits of PA. The international and national status of PA, as well as data analysis methods, is also discussed.

The research methodology is discussed in **Chapter 3**. The study area is discussed with specific emphasis on the climatic conditions and soil. The techniques and practices applicable to the trials are also discussed, like the production system of no-till. Focus on variable P application and the non-controllable variable, namely pre-planting rainfall, is also attended to. A full description of the surveyed data is also given.

In **Chapter 4** the exploratory and descriptive statistics are discussed, and in **Chapter 5** the focus is on the spatial econometric model which is used to analyse the research data, in order to determine the profitability of PA. In **Chapter 6,** the emphasis is on the results of the research. It is followed by a summary of results and some recommendations for future research.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

Swinton and Lowenberg-DeBoer (1998) reported that agriculture is becoming an industry based on knowledge, and that the ability to learn efficiently is a key factor in ensuring profitability in this sector. According to Gandonou, Stombaugh, Dillon and Shearer (2001), agriculture is increasingly becoming a computerised, information-based industry. The best example of this trend is the evolution of precision agriculture (PA). PA is an emerging technology that prescribes inputs based on site-specific soil and crop characteristics (Snyder, Schroeder, Havlin & Kluitenberg, 1996).

New intelligent technologies, lead by the utilisation of information technologies, are changing traditional production processes. These intelligent technologies, in combination with the determination of “position and time”, are much more complex than just dividing fields into management zones (Auernhammer, 2002). Khanna, Epouche and Hornbaker (1999) are of the opinion that the developments in computer, satellite and agricultural equipment technology enable farmers to undertake site-specific crop management instead of relying on whole-field management. This development enables farmers also to make more precise decisions about the application of inputs in order to avoid deficiencies and excesses in input-use. Snyder *et al*. (1996) stated that factors influencing crop yield can now be spatially measured, monitored and managed in order to ensure that inputs are only applied where they are most needed.

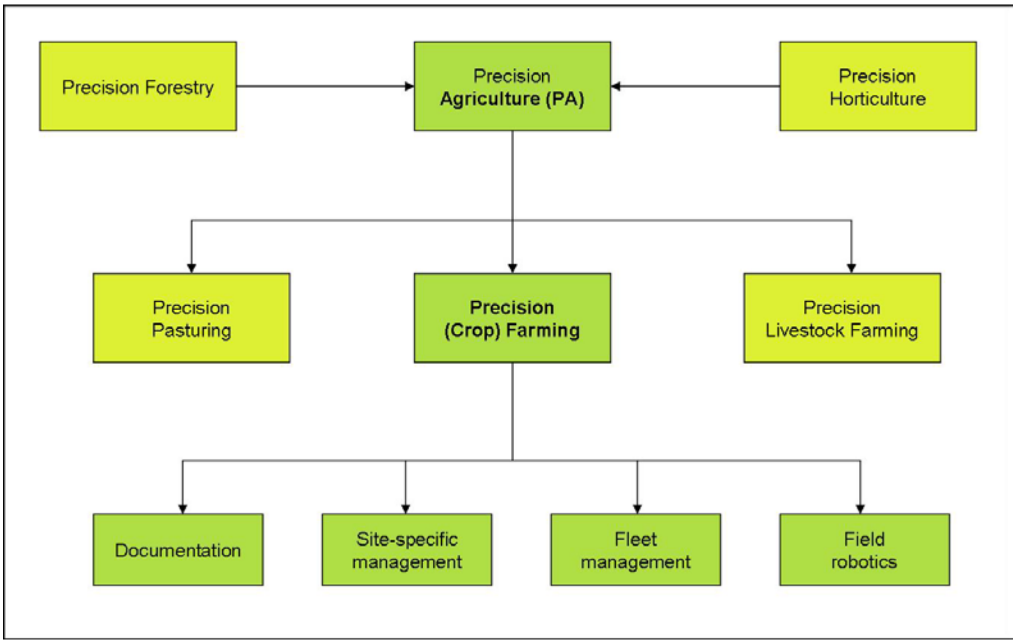
Larger-scale farmers normally adopt new technologies more quickly than smaller-scale farmers (Fountas, Pedersen & Blackmore, s.a.). The high cost of the existing equipment, farm size, land quality and farmer characteristics, such as existing levels of human capacity and technical skills, influence the benefits of the new technology and the rate and timing of adoption. When they are uncertain about the benefits of new technologies, farmers will rather adopt components one at a time, instead of a complete package in one step. Innovative farmers with prior technical skills may also be more likely to adopt complete packages. The adoption normally involves fixed investment in equipment, learning and land improvement. There are many different strategies to use when new technologies are adopted, but a lack of information about the benefits of new technologies is one of the factors hindering the adoption pattern. It is expected that adoption figures will rise over the next decade (Khanna *et al.*, 1999). The term "farm by the inch" is sometimes used to describe PA. In the following section, this term will be explained in more detail. There are various processes involved in applying PA, and some of these practices will be discussed. The benefits of PA, as well as the status of PA internationally and locally (in South Africa), will also be scrutinised.

2.2 BACKGROUND OF PRECISION AGRICULTURE

"Farm by the inch" is the term used to describe the method used when spatially referenced data about nutrient content and soil quality are captured, by means of computerised equipment. There are generally three dimensions involved, namely diagnostic and data management technologies, positioning technologies and application technologies. The first set of technologies helps with the generation of information and organisation with regard to the variability in a field. The second set attaches spatial dimensions to the information, and the third set enables farmers to apply the knowledge of the variability in soils in order to make managerial decisions (Khanna *et al.*, 1999).

According to Groenewald (1999) there are three basic requirements for precision agriculture (PA); firstly the fertilisation requirements of a field must be identified, secondly the precise geographic position of a field must be determined, and thirdly this geographic information must be linked to a control device, so that each action can be measured and adjusted. Such a management system would consist, according to Van Rooyen (2003), of three main components, namely a map of the farm and infrastructure, information about each action taken on the farm and a satellite image of the fields.

These three components form part of the PA system. In the following section, the concept of PA and precision farming will be illustrated. By using satellite maps and computer models, farmers can manage production inputs more effectively in order to produce a crop of a higher quality and with a higher yielding ability (Ag Fact Sheet, 2003). Figure 2.1 illustrates the position of precision crop farming within the total PA structure.



Source: Auernhammer (2002)

Figure 2.1: Illustration of precision agriculture

Figure 2.1 illustrates the differentiation in crop farming. The differentiation starts with information acquisition, continues with site-specific management and ends with machinery management, organisation and field robotics. PA is the technology that assists the farmer in recognising spatial boundaries, but also takes the equipment for yield recording and the variable application of agronomic input into account. The single greatest challenge is the combination of information from yield maps, crop performance records and soil analysis and characteristics in order to achieve the best PA. A practical strategy must be developed for the variable application of crop treatments for a particular field.

The variation in yield as a result of the variable application of treatments can be influenced by various factors. Table 2.1 shows which of these factors can be controlled and which cannot be controlled (Godwin, 2000).

TABLE 2.1: FACTORS INFLUENCING YIELD VARIATION

No control	***Possible control***
Soil-fixed characteristics (soil texture and soil structure) Climate Topography Hidden features	Available water Water-logging Nutrient levels pH levels Trace element levels Weed competition Pests and diseases

Source: Godwin (2000)

Table 2.1 shows that most of the soil-fixed characteristics such as soil texture and structure are not controllable. Available water can be controlled by applying different cultivation practices such as no-till. Nutrient, pH and trace element levels can be controlled by analysing the soils. Weed competition, pests and diseases can be controlled by implementing biological farming. PA can be used to address some of these issues by focusing only on those elements that are required by the soil.

According to Srinivasan (1998), PA should be viewed as the agricultural system of the 21st century. Precision agriculture is also called prescription farming, variable-rate technology (VRT) and site-specific agriculture. Conventional farming is based on uniform treatments across a field. The PA model differs from the conventional model therein that it involves the mapping and analysis of field variability. This model assists farmers in viewing their farms, crops and practices from an entirely new perspective. Farmers can now adjust input use and can make better production and management decisions. In order to apply PA, the following are required:

1. The ability to identify each field location,

2. The ability to capture, interpret and analyse agronomic data at an appropriate scale and frequency, and
3. The ability to adjust input use and farming practices in order to maximise benefits from each field location.

According to Roberts, English and Larson (2002), information about the differences in soil and other characteristics within a field are used to make management choices when PA is applied. Gold (1999) defined PA as a management strategy that employs detailed, site-specific information to precisely manage production inputs. Production inputs such as seed, fertiliser, chemicals, and so forth, should only be applied as needed and where needed for the most economic production.

Most farm fields contain more than two types of soil. Each type of soil has a different crop yield potential, as well as different nutrient-supplying capabilities. This difference in fertility levels between soils is the major cause of crop yield variability. The physical characteristics of various soils, together with the available water, largely explain yield variation between soils and fields. The boundaries of each soil unit can be identified by using a soil survey report. Fertiliser recommendations must then be made for each soil unit, based on soil test results, yield goals and fertiliser guidelines. The yield goals for each soil series is based on historical field records and grower experience (Carr, Carlson, Jacobsen, Nielsen & Skogley, 1991).

Lowenberg-DeBoer (1996a) is of the opinion that PA requires an investment of time and resources. This investment will have some short-term payoff, but its full capacities and main benefits will only be evident over the passage of time. The skills of the farmer and the employees will be a key factor in profitability. Economics change as technology changes, and almost every week new equipment and software are put on the market. The equipment and software can assist a farmer in collecting and using site-specific data. These new tools can have a considerable economic influence on a farming operation, but the understanding of the economics associated with these new tools is far from perfect.

PA technologies are being adopted relatively slowly, compared to other innovations. Profitability issues have constrained this adoption rate. Surveys of producers and agribusinesses showed that the application of PA technology is becoming standard practice in the United States of America (Lowenberg-DeBoer, 2003). Rilwani and Ikhuoria (2006) stated that the concept of PA is about doing the right thing, in the right way, at the right place, and at the right time. One of the greatest challenges in PA is linking spatial yield data to agronomic practices to explain and manage variability.

A production function describes the relationship that transforms inputs (resources) into outputs (commodities) (Snyder *et al.*, 1996). There are various factors that may influence the adoption rate and pattern of the practices when converting from conventional to PA techniques. Global positioning systems (GPS) and global information systems (GIS) are some of the equipment that can be used with a yield monitor to convert yield data from raw data into yield maps.

2.3 EQUIPMENT NEEDED

Davis, Casady and Massey (1998) reported that it is important to be familiar with the equipment needed for PA and these include hardware, software and recommended practices. According Queensland Government (1995-2010) the equipment needed will vary according to the situation of the specific farm which want to implement PA practices.

Farmers who engage fully in PA have yield monitors in their harvesters connected to a GPS system. These data is then transferred to a home/office computer where maps are produced showing paddock (zone) variations. Yield maps are normally produced over a number of years to document yearly variations. Soil tests can then be carried out to find the cause of these variations. Machinery using VRT can then be used to apply different input rates to a specific zone. This is achieved via a computerised map of various zones being programmed into a control module with GPS positioning and this is then linked to the equipment's VRT controller (Rainbow, s.a.).

2.3.1 Global positioning system (GPS)

There are a number of technologies which are used to fulfil the requirements of PA. Two of these technologies are GPS and GIS (Srinivasan, 1998). Khanna *et al.* (1999) regard GPS as a highly engineered technology that forms an important component of PA. English, Roberts and Sleigh (2000) reported that GPS uses technology that allows site-specified information to be collected by interfacing with satellites.

Farmers today use GPS to gather information on topography, soil, precipitation, drainage, chemical applications, irrigation and crop yields for every square metre of a field. This information is then downloaded onto a database called GIS. The latter program can be used to produce electronic maps (Coates, Horsburgh & Gleason, 2002).

2.3.2 Global information system (GIS)

According to Srinivasan (1998), GIS is a computerised data storage system. It can be used to manage and analyse spatial data relating to crop productivity and agronomic factors. Gandonou *et al.* (2001) stated that the usage of GIS involves the analysis of multiple layers of data. Crop yield mapping and soil-related characteristics are very important data, and many farmers see them as an entry level into PA. By using these data, it becomes possible to establish a clear overview of the nutrient availability over the entire field. Variable-rate application is made possible by this spatially detailed soil fertility data, and nutrient application levels can now be varied spatially within the field.

2.3.3 Home computer and software

According to Queensland Government (1995-2010) the first component necessary for VRT is a personal computer. Rainbow (s.a.) stated that although considerable random-access memory (RAM) is required for PA most late model home computers can be used. The software must be carefully selected as this will enables the yield data to be accessed from the yield monitor. PA software tools help to manage detailed spatial information and one such product is the Ag Leader Advanced Farming Software System which enabled the researcher to identify soil sampling points within management zones, by using a system of coordinates.

2.3.4 Maps

The raw data must be processed and cleaned before going any further with the use of this data. A basic map can be compiled with many software packages (SSToolbox, ArcGIS etc). These maps can then be used to make certain decisions and this is where VRT equipment plays a role (Rainbow, s.a.).

2.3.5 Variable Rate (VRT) equipment

According to Rainbow (s.a.) VRT equipment enables farmers to reduce inputs in a cost-effective way on areas that are clearly unprofitable as this can reduce overlapping/underlapping of fertiliser application and chemical spraying. PA farming equipment includes yield monitors, variable-rate controllers, spreaders, air carts for bulk seed and fertiliser handling, seeders, planters and sprayers (Nell, Maine & Basson, 2006). By adding a task controller to the VRT equipment the rate change process can be automated. The task controller is used to capture yield data which is again being used during the planting process to direct VRT application of inputs from the processed yield data and application maps. The application rates or the product can be changed according to prescription maps. PA enables farmers to move from macro to micro management of production. Macro management looks at field level average, and micro management looks at grids or management zones.

2.4 METHODS USED TO IDENTIFY MANAGEMENT ZONES

A number of methods have (according to McCann, Pennock, Van Kessel & Walley, 1996) been developed to subdivide research sites into units with similar productive potential, namely (1) detailed soil surveys, (2) extensive sampling programs and (3) the collection of topographic data. Srinivasan (1998) stated that the development of management zones can help with the independent treatment of each unit. Two common methods used are intensive grid soil sampling and mechanical yield monitoring for at least three to four years. Grid soil sampling as application to identify management zones will be discussed in the next section.

2.4.1 Grid soil sampling

According to Frick (2003), soil classification can be done by a soil surveying specialist in order to identify various zones within a field, as well as to determine the potential yield for each zone. Soil sampling can be done on a grid basis. Grid soil sampling is used to divide several subunits according to the soil characteristics, and this can also determine yield. Each unit is treated differently.

The grid soil-sampling technique is therefore one of the strategies used to identify management zones. The soil test data are summarised and nutrient management maps are created (Wollenhaupt & Buchholz, 1993). The accuracy of the map depends upon the sample size. The optimal sample size increases when using a VRT fertiliser program, as farmers using a VRT strategy will only sample a portion of the field rather than the entire field (Pautsch, Babcock & Breidt, 1998). Grid soil sampling consists of samples being collected every 1 ha (100 x 100 m) as explained by Thrikawala, Weersink, Kachanoski and Fox (1999), or every 2 to 3 acres or 0,8094 to 1,2141 ha, as reported by Wollenhaupt and Buchholz (1993). The norm in South Africa is to collect soil samples every 1 ha (100 x 100 m), as confirmed by Burger (2009). According to the study of Wollenhaupt and Buchholz (1993) for Montana, Minnesota, North Dakota and Missouri, different grid samples were used (49 ft, 148 ft and 246 ft). Although grid sampling (49 ft) could produce significantly higher yields, the extra costs of soil sampling and analysis caused it to have the lowest net return. Variable-rate returns were US$1,21 per acre lower than in the case of the single-rate approach. The cost of this concept of farming will need to be offset against increased yield or lower fertiliser expense due to less fertiliser being applied.

Thrikawala *et al.* (1999) stated that intensive sampling is necessary to obtain a map that differentiates between fertility levels in a field. This technique is called fertility mapping. The maps are created by using map-making software. Rehm, Lamb, Davis and Malzer (1996) reported that those who collect soil samples will choose the size of the grid cell and this will have a major impact on the cost of following this approach. The economical size of the grid cell will depend on the field situations, although some researchers have shown that fertiliser will be applied more accurately if smaller grid cells are used for making fertiliser recommendations. The extra cost involved in doing grid sampling and scepticism on the level of variability which occurs within fields are some of the factors that influence the question whether grid sampling is cost-effective or not (Lenz, 1996). According to Fleming, Westfall and Wiens (s.a.), the use of grid soil sampling to generate accurate VRT maps may not always be feasible because of the time and expense required. The variations in soil fertility that are identified by the sampling, allows the farmer to identify different "management zones" in a field and this technology can be used to develop VRT application maps.

Several potential benefits of precision soil sampling (grid sampling) exist and this is one of an array of PA tools available to ensure that nutrients are used more efficiently in agriculture. Areas of nutrient deficiencies and excesses within fields can be identified and lime and fertiliser use can be increased by directing applications to specific sites (zones) (Crozier & Heiniger, 1998). The main purpose of grid soil sampling is the creation of a detailed map of a field and this allows the farmer to identify areas (zones) in which a unique management practice will be conducted. The main challenge of this practice is the cost, but the cost can be spread over a rotation period, as the farmer only needs to do sampling intensively before one crop in order to create management units (zones). In subsequent years only a few samples can be taken in order to verify the spatial patterns of soil nutrients (Staben, Ellsworth, Sullivan, Horneck, Brown & Stevens, 2003). The use of yield monitors and yield maps to identify management zones will be discussed in the next section.

2.4.2 Yield monitors and yield maps

A second method used to identify management zones is to use yield maps. It is probably important that yield maps of a minimum of three years should be used. When data from the yield monitor are normalised by creating yield maps, a true picture of yield variability emerges, and from this picture management zones can be developed and deficiencies can be corrected. This yield map can then be used to identify and manage production problems in future scenarios (Reichenberger, 2003). Farmers realise that yields are highly variable and often seize the opportunity to tailor their management style to a much more site-specific approach. The information obtained from this technology can continually be upgraded (Doerge, 2002).

Precise information about yields is essential in the spatial database of any grain farmer's land and a yield monitor can be the point of entry to ownership of PA technology. The interpretation and usage of yield maps is a key step in the development of precision management skills. It is important that the mapping data be stored in a format that can be used in the next generation of software and for this reason, raw yield data should be retained (Lowenberg-DeBoer, 1996a).

According to Johannsen, Arvik and Berglund (1996), one can literally measure yield on the go by equipping combines with other harvesting equipment are coupled to a GPS. The compilation of a yield map will assist the farmer in determining variation throughout a field. Appropriate software is necessary to conduct this action. On the yield monitor the combined position from latitude and longitude readings taken every few seconds, can be indicated. Yield and moisture maps can also be created by using this technology. If these maps are used appropriately, they could constitute a valuable management tool. According to Grisso, Alley, Phillips and McClellan (2009), a yield monitor measures and records information such as crop mass, moisture, area covered and location. The required yield data is automatically calculated by using the aforementioned variables. The data extracted must be combined with mapping software in order to produce a colourful map showing variations in grain yield and moisture. The data generated from the maps must be incorporated into the decision-making, analysis and the overall planning process of the farm operation. However, it should be kept in mind that a yield map showing the spatial distribution of crop yield (zones) may raise more questions than it will answer, as it does not reveal what caused the variations and this can become a source of frustration rather than a source of information. A yield map is only of value when it leads to management decisions or validates management practices. Yield variability can be grouped into two areas, namely variability caused by producer management practices and naturally occurring variables. The producer must use the data in decision-making processes. The following steps are taken during the decision-making process:

1. Data collection;
2. Data interpretation;
3. Decision making;
4. Implementation of a plan; and
5. Evaluation.

The yield monitor is involved in the first and last steps of this process, and the yield map is involved in the second step. The following question should be answered by the producer: What strategy should be used to implement management practices based on a yield map? In the variable-rate application of agronomic inputs, this kind of technology is also used (English, Roberts & Sleigh, 2000).

2.5 VARIABLE FERTILISER APPLICATION

Doerge (2002) is of the opinion that the advantages of the variable application of crop inputs are generally limited to in-field benefits and the profits may be higher with high-yielding and high-value crops. Swinton and Lowenberg-DeBoer (1998) examined nine university field research studies of variable-rate (VRT) fertiliser applications, by applying standard minimum cost assumptions to all studies where selected cost items had been omitted. The findings were that high-value crops (sugar beet) that responded to VRT fertilisation, tended to do so more profitably than low-value crops (wheat, barley and corn). The cost savings from reduced fertiliser application were much less important. According to Griffin, Lowenberg-DeBoer, Lambert, Peone, Payne and Daberkow (2004) sugarbeet recorded the highest benefits from VRT with 100 %, followed by corn at 81 % and wheat at 60 % when a literature review covering more than 200 studies were done.

Doerge (2002) further mentions that the costs and benefits of using this system can easily be measured in controlled field experiments and the profitability of PA can therefore be calculated directly (Section 2.5.2). According to Maine *et al.* (2006), the standard rate of fertiliser application for individual cropping systems in South Africa is gradually being replaced by PA advice, based on the soil mineral nitrate of nitrogen (N) and phosphorus (P). Lowenberg-DeBoer and Erickson (2010) reported that PA is mostly adopted for its ability to increase the efficiency of inputs such as fertilisers, while still maintaining crop productivity.

There are three different approaches to VRT, namely the low-tech approach (manual application of VRT), the medium-tech approach (grid soil sampling, soil maps and management zones) and the high-tech approach (yield monitor, task controller and VRT equipment). For this study the focus will be on the high-tech approach as this approach incorporates GIS, GPS and computer-activated fertiliser spreaders. Soil data and historical yield data are incorporated to produce a fertiliser rate map and this map is tagged to GPS coordinates and is downloaded into a task controller. This allows the farmer to automatically adjust the fertiliser rate in accordance to the digital rate map (Soluhub, Van Kessel & Pennock, 1996).

2.5.1 Nitrogen

N, P and potassium (K) are the three main nutrients applied by farmers in their fertiliser program where N is the most mobile nutrient of the three. According to a study conducted by Fiez, Miller and Pan (1994), the N requirements may vary widely within various fields due to variations in soil characteristics and yield potential. These variations are due to differences in yield potential, soil N status, mineralisation and the efficiency of fertiliser use. Misapplication of fertiliser can be reduced by varying the application rates to match the site-specific needs. One way of doing this is to vary the fertiliser rates by soil type or intensively grid sampled soils or to use soil test results to divide fields into uniform areas, called management zones. The field is divided according to soil type or by using soil sampling according to grid coordinates, and then the fields are divided into units of equal productivity and N requirements. The net return may increase when the fertiliser rate has been calculated for each landscape position within a field. Wheat yields and soil fertility status within fields may vary greatly, and therefore variable fertiliser management should be highly advantageous. Deberten (1986) used the following formula to indicate the optimum economic yield. Optimum economic yield occurs at the point where marginal revenue equals marginal cost:

$$df(\chi) \text{ (wheat price)} = d\chi \text{ (N price)}$$

Only the cost of N is taken into consideration. $f(\chi)$ is a polynomial function relating grain yield to χ, which is the N supply.

The degree of economic benefit will depend on the levels of over- and under-application and the yield responses to the fertiliser which will determine the results of misapplication (Zeilinga, 2004). When planning variable-rate fertiliser applications, there are important factors to consider such as knowledge of all parameters and the variability of fields with regard to site-specific N requirements. It is important to note that in the case of fields in which yields drop rapidly when N is under-applied and in which yields rise only slightly or decline when N is over-applied, the economic benefit will be greater (Fiez *et al.*, 1994). Although adequate N is essential for optimum crop production, applying excess N can have serious environmental consequences. Nitrogen, in the form of nitrates, is extremely soluble in water and will be carried down below the root zone as the water drains. However, it is important to note that this may increase the potential for ground water contamination (Herbert, Hashemi, Chickering-Sears & Weiss, s.a.).

2.5.2 Phosphorus

P promotes growth in plants and animals and thus the importance of P cannot be over-emphasised in agriculture. Deficient P can cause low yield and poor quality of crops and pastures. Rock phosphate provides the P element in a N, P and K fertiliser mix to ensure good growth in plants (Florida Institute of Phosphate Research, 2004).

According to a study undertaken by Robinson (2005) near Cleveland, Mississippi, it was found that in some areas in farm fields the plants were stunted and these areas also did not yield well. By adding a yield monitor to a combine, the problem areas were identified. Soil samples indicated very low levels of P and the decision was taken to try a pre-plant application of Triple Super P. Satisfying the soil's P needs by applying chicken manure can cost the producer US$12,00 per pound of P applied. By applying the variable rate of P, the yield showed increases. This fact emphasizes the importance of addressing the specific sites where the problems are experienced.

In another study undertaken in order to compare VRT and uniform-rate (SR) P fertilisation, it was found that P could be a major yield-limiting nutrient for some producers in many regions. VRT has the potential to reduce costs in areas where SR fertilisation would over-apply fertiliser and to increase yield where fertiliser would be under-applied, but it seldom increased net returns because of increased costs of soil sampling and fertiliser application. VRT resulted in better P nutrient management because between 12 % and 41 % less fertiliser was applied and soil-test P variability was reduced compared with the SR fertilisation method (Wittry & Mallarino, 2004).

In Denmark, the use of yield maps, as a predictor of the amounts of agrochemicals and fertilisers to be applied, was found unsuccessful. Soil maps are more beneficial for use in making decisions on crop management. Animal manure can also be applied site-specifically and this may decrease the risks of nutrient losses (NJF, 2002).

The ultimate success of VRT is, according to Solohub, Van Kessel and Pennock (1996), dependent upon the economic advantage of implementing this technology into a farm-based management plan. There are four factors that control the profitability of such an approach: (1) the value of the commodity, (2) the savings in fertiliser costs, (3) the change in crop yield and (4) the cost associated with implementation.

According to Le Roux (2008) and Venter (2008), one big challenge of P applications is that the analysis methods are not sorted out and that there is no correlation between different methods. When P is applied to the soil, it is immobile and the crop will only benefit from the application in the next season. This next section will focus on the different benefits of PA and more emphasis will be placed on the management benefits and the profitability of PA.

2.6 BENEFITS OF PRECISION AGRICULTURE

Arnholt (2001) reported in his study that PA has the potential to be both an output-increasing and cost-reducing technology. Farmers may be able to lower the unit costs of production by increasing input efficiency or by increasing yields.

2.6.1 Marketing tool

Yield monitors provide information regarding crop yields and farmers have passionate interest in this field. Taylor (1998) reported that the installation of yield monitors on combines to gather yield data can be used as a marketing tool. The yield monitors can also be used to find problem areas in a field. If the yield readings are mapped, the information can be used to market the product accordingly. Yield monitoring can also help farmers to become better managers of their operations. It allows farmers to view their overall management system from a more "whole-farm" perspective (Doerge, 2002). The grain mass and harvested area can be measured on a load-by-load or field-by-field basis and this allows a farmer to get instantaneous readings in the fields of accumulated grain weight, harvested area and average yield (Shearer, Fulton, McNeill, Higgins & Mueller, s.a.). After documenting all the applicable information, the farmer can proceed to market his grain by signing contracts.

2.6.2 Management benefits

PA has the advantage that growers can plan ahead and manage problems such as water stress, soil compaction, diseases and pests more effectively. This process can be started by keeping accurate farm records and then establishing a database of all inputs and actions on the farm. These technologies can contribute to agronomic research, as well as improve farm management by variable fertiliser applications (Srinivasan, 1998). According to Gandonou *et al.* (2001), the main advantage of PA is that it allows farmers to spatially manage fields using GIS. A major off-farm advantage of precision technologies is the reduction in the level of polluting residuals (Thrikawala *et al.*, 1999). According to Nell *et al.* (2006), PA is a complementary process consisting of different kinds of management practices including environmental management. Oriade, King, Forcella and Gunsolus (1996) also reported that PA has the potential to reduce pesticide use and cost, as only certain portions of a field are treated with herbicides instead of the entire field. There is a growing interest in this kind of research due to the prospects of reducing herbicide costs, controlling costs and reducing attendant health hazards.

Farmers using the technologies of PA would benefit greatly in many ways, according to Roberts *et al.* (2002).

1. An agricultural workforce that is upgraded, well trained and informed and is capable of calibrating, operating and maintaining equipment.
2. Agribusiness personnel that are well trained and well informed and can give accurate technical advice.
3. Standardised equipment and software.
4. Training for agricultural labourers, agribusiness personnel and owner-operators that are up to standard with the technologies of PA.
5. Digitised soil maps available on the Internet for farmers to download and overlay on other field maps.

The use of yield monitors can also have some on- and off-farm opportunities and Table 2.2 shows the different opportunities. The opportunities will, however, vary from farm-to-farm and from farmer-to-farmer (Doerge, 2002).

TABLE 2.2: ON- AND OFF-FARM OPPORTUNITIES USING MONITORS

Type of Profit Opportunity	*Examples*
In-field, real-time benefits during harvesting	• Collect on-farm testing results, of yields with little or no disruption of the harvest operation; • Facilitate on-the-go grain moisture decisions, e.g. "Should grain go to the drier or to town?" and • Use real-time yield information to capture early-season contracts or marketing premiums when yields exceed expectations.
On-farm benefits	• Create detailed field and load yield summaries; • Evaluate the effects of variable soil nutrient and pH levels on crop yield; • Evaluate hybrid consistency within a field in time and space. Develop a historical spatial data base.
Off-farm benefits	• Offer custom yield mapping services to other farmers; • Custom harvesters can offer yield mapping services or better document acreage and productivity; • Provide "trace-back" records for food safety; • Develop spatial management skills and familiarity with spatial data bases in preparation for future generations of precision farming tools.

Source: Doerge (2002)

Table 2.2 indicates that the list of benefits is not exhaustive and that every farmer may experience these benefits differently due to site-specific differences in farm characteristics, local marketing opportunities and managerial expertise.

Khanna *et al.* (1999) reported that site-specific technologies offer the potential for environmental, financial and economic benefits. Adrian, Norwood and Mask (2005) also reported that the potential benefits of PA include reducing production costs, increasing yields and protecting the environment. Maine (2006) is of the opinion that in developing countries such as South Africa, environmental benefits have little or no value to farmers and the reason is that environmental legislation is not yet well-developed and consumers are less concerned about the environment.

Auernhammer and Muhr (1991) reported that crop production techniques and systems need to be reconsidered due to the increase in concern about environmental pollution.

PA is a method of improving agricultural efficiency while meeting environmental goals. The efficiency can be improved by reducing the use of chemicals. More precise application of fertilisers and other agricultural inputs can be achieved as application is based on the inherent yield capability and the available nutrients of the soil in a small area. The potential for pollution problems can be reduced as fertiliser is only applied in the exact amount needed. The more precise placement and application of agricultural inputs are clearly consistent with conservation and environmental goals (Christensen & Krause, 1995). By using PA technologies the hope exists to reduce the adverse environmental impact of farming by applying farm chemicals only where needed and in the appropriate amount and thus reducing the potential for pollution (Project Proposal S-283, 1998). The high environmental cost as a result of the intensification of agricultural production and increase in food production over the last few decades have resulted in the launch of several directives by the European Union and the State of Baden-Wurttemberg (Southwest Germany) in order to overcome this problem. The aim is to reduce the loss of N to groundwater from agricultural sources. If a farmer has a management plan and the N threshold value is below 45 kg N/ha, then he will receive a compensation of 165 € per ha. Uniform N application may result in over- and under-fertilisation. Over-fertilisation may increase the probability of nitrate leaching, and under-fertilisation may limit yield. Producers defined the optimum N as the rate that maximises profit. In the study conducted, the compensation creates an economical stimulus for the farmer to stay within the limits of environmental legislation (Link, Graeff, Batchelor & Claupein, 2006). The literature review regarding the main focus of this study, namely precision phosphorus application and the profitability of PA, will be discussed in more detail in the next section.

2.6.3 Profitability of precision agriculture

2.6.3.1 Overview

Before a new technology can be considered, the potential returns that this technology can generate will be one of the main factors influencing the adoption. Other factors that will be considered are capital and learning cost (Swinton, 2004). Some economic studies have found that PA is unprofitable. It is reported by Gandanou *et al.* (2001) that out of 17 studies, 30 % found PA to be unprofitable and 35 % had mixed results. The slow rate of adoption may be linked to low profit potential. PA is mainly adopted on large farms, due to high equipment costs, and it is important to identify what size of farm is required to justify the investment in PA equipment versus the alternative of custom hiring. Griffin and Lowenberg-DeBoer (2008) also reported that 234 articles were reviewed by Griffin during 2004 and, although the results were not consistent, 90 % presented losses or benefits and 68 % reported positive benefits from some sort of PA technology. Lowenberg-DeBoer (1996a) is also of the opinion that it is important that the investment costs must be brought into account as focus is often placed on changes in crop input costs, such as fertiliser or herbicide. The capacity to use PA profitability must be developed, because these kinds of technologies are profitable in some cases, but often the technologies fail to cover all additional costs in the production of bulk commodities like wheat. The low profitability in bulk commodities may be due as much to management problems as to technology. The long-term profitability of PA technology depends on the development of management systems which are site-specific. The performance of a generic decision support system will be enhanced by data from a specific farm. The inputs applied must be linked with yields harvested on specific sites and the pooling of data may help farmers to realise the full benefit from PA.

The relatively slow adoption of PA has raised questions about the farm level benefits of this technology. The economic feasibility of a practice can be evaluated by three generally grouped methods, namely unsubstantiated reports (articles or reports that provide lump-sum numerical estimates, without supplying detailed information about changes in costs and revenue), rough partial budgets (generally providing a table demonstrating changes in costs caused by the addition or practice of a technology compared to standard operating expenses) and partial budgets (documenting most costs) (Lambert & Lowenberg-DeBoer, 2000).

In the following two sections, greater focus will be placed on case studies in which profitability was examined, as well as the methods used to determine profitability.

2.6.3.2 Case studies

Clay, Carlson, Chang, Clay, Malo, Ellsbury and Lee (2003) demonstrated the approach for evaluating the impact of grid distance on spatial analysis and profitability. Soil samples from the 0 to 15 cm depth were collected from a 30 by 30 m grid in May 1995. This resulted in more than 650 sample points. Soil samples were also collected from a 60 by 60 m grid (180 samples) and from a 90 by 90 m grid (60 samples). The field used was 65 ha large with no-till production system. The potential profitability associated with different sampling approaches could be estimated for grid-sampled fields. The cost of the soil samples for the 60 by 60 m grid was US$3 600,00 and for the 90 by 90 m grid was US$1 200,00. The cost was US$20,00 per sample. The total investment cost was US$5 817,00 (US$1 017,00 for fertiliser, US$200,00 for application cost, and US$3 600,00 for soil samples) for the 60 by 60 m grid and US$3 428,00 (US$1 028,00 for fertiliser, US$1 200,00 for application cost, and US$1 200,00 for soil samples) for the 90 by 90 m grid. The net return was US$4 656,00 for the 60 by 60 m grid, and US$4 584,00 for the 90 by 90 m grid. These conditions resulted in a net loss of US$1 162,00 for the 60 by 60 m grid and a net profit of US$1 156,00 for the 90 by 90 m grid. The investment in using variable-rate equipment was greater than the expected economic return in some treatments.

Swinton and Lowenberg-DeBoer (1998) reported that the measuring of the profitability of yield mapping (and other ways of monitoring outputs) is more difficult than in the case of variable-rate inputs. The calculation of net present value (NPV) gives the most reliable measure of profitability from an investment such as yield mapping. Better recommendations must be made from the data collected and these recommendations could help farmers to be more profitable. The following are needed:

1. A list of the costs and revenues of the investment for each year;
2. The maximum number of years relevant to the investment; and

3. The rate of return (discount rate), if money had not been put into this investment.

The Ohio trials by Batte (1999) revealed that the range of soil P for the uniform application is 26 to 76 pounds per acre, and for the VRT application the range is between 33 to 70 pounds per acre. Environmental damages are also lower with the VRT application. However, it is also true that most farmers will not necessarily consider the environmental costs and benefits when making the PA adoption decision.

In South Africa, one farmer's yield with dryland maize increased from 2,5 – 3,5 ton/ha to 5,0 – 9,0 ton/ha. This is due to the variation in seed and fertiliser. One of the farmers who has already adopted PA practices, reports an increase of up to 47 % in yields and input cost reductions as high as 68 % (Van Rooyen & Jordaan, 2002). On-farm trials as a method to determine the profitability of PA will be discussed in the following section. Some of the first on-farm trials with yield monitors were conducted in 1999 in Purdue, United States of America (Griffin & Lowenberg-DeBoer, 2008).

2.6.3.3 On-farm trials in South Africa and the benefits

Frick (2003) reported that the market for PA in South Africa is rapidly growing. According to Pretorius (2000), one farmer started to use a yield monitor on one of his combines in 1998 and it was linked to a GPS. The data were used to compile yield maps. The yield maps showed a difference in yield of between 2,0 and 15,0 ton/ha with the same cultivation practices and fertilisation program. The fertilisation program was designed for 6,0 ton/ha, however, some parts of the land were over-fertilised and other parts were under-fertilised. By using PA technology, the possibility of over- and under-fertilising may be minimised. PA is only a management aid, and additional expert advice is important for the compiling of yield maps, as well as determining the correct type of software to be used in order to achieve the best benefits. All the information gathered from the yield monitor may be downloaded onto a GIS database that can produce yield maps. Matela (2002) mentioned that some farms in the Western Cape, South Africa, have already used yield monitors since 2001.

A maize farmer near Nigel started to adjust his farming practices in 1980 by looking at the potential of the soil. Soil maps were compiled, and the soils were classified according to their potential, namely as high, medium or low. A 58 ha field was divided into halves of low and high potential. According to the soil map, the land must have been divided into four zones. Before the division took place, the average yield was never higher than 3,5 ton/ha. After the division, the lowest potential soil long-term average increased to 3,6 ton/ha over a 10 year period and the highest potential soil increased to 6,1 ton/ha. Each division had been treated to reach its full potential, and adjustments regarding cultivation, cultivars and fertiliser had been made (Pretorius, 2001). This is an example of the type of PA technology that will definitely ensure an increase in the yielding of crops.

Maine (2006) studied the effect of variable-rate treatment of N on expected maize yields in the Bothaville region. The management zones were chosen according to yield data gathered over three years and the yield potential was determined. Four zones were identified, namely the low potential zone (less than 3 ton/ha), the medium potential zone (3-4 ton/ha), the high potential zone (4-5 ton/ha) and the very high potential zone (>5 ton/ha). The findings were that the VRT treatment effect in Zones 1, 2 and 3 was close to zero in years one and three. In year two, the treatment effect was statistically positive in all the zones. For Zone 4, the VRT effect was substantial and also positive in all the years.

According to Burger (2010) two research projects are currently the main focus in South Africa on the benefits of PA. The first project started in 2005 and the project investigate the effect of overlaying yield data from the yield monitor with the chemical and physical soil maps to identify homogeny areas within a specific field. The next project was undertaken during 2008 and 2009 and the main focus was to investigate the differences between soil analyses conducted in South Africa, compared to soil analyses from the same soil samples sent to USA. The results of these two projects will be published the next year. More focus will now be placed on econometric methods and the results obtained will be used to determine profitability.

2.6.3.4 Econometric methods and results

Lowenberg-DeBoer (2003) reported that variable-rate application of fertiliser was the first PA technology to be commercialised. Most of the data were automatically available and this was one of the reasons why the most economic studies focused on this technology. Partial budgets may be used to determine profitability, but the results could be difficult to interpret, due to differences in experimental design and assumptions about included costs. Scattered studies have dealt with the economics of techniques other than variable-rate application.

According to Swinton and Lowenberg-DeBoer (1998), the estimation of the varying cash costs is the easiest part of a partial budgeting analysis. The cost of gathering information is seriously underestimated. The available information is often useful for more than one year. Information-related costs include: grid soil sampling, laboratory analysis, purchasing digitised soil maps, software, yield mapmaking and the training needed to understand soil or yield maps.

Gandonou *et al.* (2001) recommended that profitability must be determined on a farm-by-farm basis and that individualised analyses for each farm were required. Partial budgets may be used to compare the costs of two alternative decisions and is the common economic tool for assessment of the profitability of PA. The two alternatives analysed are "custom hire" versus "purchase of PA equipment". The related equation is the point where ownership costs are equivalent to custom hiring costs. The following formula is used for these calculations:

$$TFC + TVC*A = CH*A$$

TFC is the total fixed cost of ownership of PA equipment; TVC is the total variable costs associated with operating owned PA equipment; CH is the custom hired rate and A is the total area of land on which PA is practiced. Algebraically solving A results in:

TFC/(CH – TVC) = A

Break-even analysis can be coupled with the partial budgets to develop a widely applicable decision tool. The potential benefits and cost deductions are offset by the additional costs incurred to engage in PA technology. Fixed and variable costs form part of engaging in this technology. The results show that only larger farms find it more profitable to invest in the equipment of PA. The VRT of a single product results in a break-even point of 430 ha. The break-even acreage for VRT decreases as more products are applied to the same ground (from 430 ha for a single product to 359 ha for more than one product). This decrease in break-even area is justified by the fact that the usage of the equipment over multiple operations reduces fixed cost. Wide variations in the break-even base line are possible.

The study conducted by Babcock and Pautsch (1998) scrutinised the development of a model to estimate the potential value of switching from uniform to variable fertiliser rates. The two key issues involved in the developing of a model for production decisions under variable-rate technology (VRT) is first to choose a functional relationship between yields and fertiliser levels, and secondly the selection of a field attribute that can be used to guide fertiliser rates.

Returns (price x yield x acreage), variable costs (such as grid sampling, mapping, remote sensing, fertiliser and pesticide), fixed costs (such as depreciation, interest on investment and development of human capital) and profit (returns minus costs) may be used as parameters to determine the impact of PA technology. How big or small the impact is will depend on the specific farming situation (Batte, 1999). Lowenberg-DeBoer (1996b) is of the opinion that the primary motivation for investment in precision farming is long-term profits from increased efficiency. Farmers must try to balance the costs of data collection, analysis and implementation with the benefits of PA. PA creates a need for economic information about profit potential and the primary opportunity is the chance for agricultural production economics to be profitable (Lowenberg-DeBoer, 1996b).

Thrikawala *et al.* (1999) found that the question surrounding the increase in gross returns and reduction in fertiliser expenses is sufficient to cover the additional investment costs of VRT. Profits are higher with the VRT method and this method recognises that there are areas in the field requiring more fertiliser than what is applied according to the constant rate approach. Larger farms normally adopt PA technologies earlier and the profits achieved on these farms are expected to be higher (Srinivasan, 1998). A study by the United States Department of Agriculture found that larger farm acreage is associated with higher probability of adopting PA, but the highest probability of adoption is at the relatively modest farm size of 660 ha (Lowenberg-DeBoer, 2003).

2.6.3.5 Econometric models

There are two variable-rate models that can be used, namely the Plug-in Method and the Bayesian Method. The first model is equivalent to assuming that the producer no longer over-fertilises to prevent yield losses. The second model assumes that producers account for estimation risk. If a producer strictly fertilises according to an estimated map, then the plug-in approach is used. When using the Bayesian approach, producers improve or update their beliefs about the mean and variance of nitrogen fertiliser, after each sample. Under the Bayesian approach, marginal returns over fertiliser costs and marginal environmental benefits decline as the sample size increases. The level must be determined where the cost of sampling and additional VRT costs will be too high and the profit from a single-rate (SR) fertiliser program will then exceed that of a VRT fertiliser program (Pautsch *et al.*, 1998). It is important to remember, however, that this study is conducted in South Africa and therefore more emphasis will now be placed on the South African context and the associated benefits.

2.6.3.6 The profitability of precision agriculture in the South African context

Gouws (2002) made use of an example for dryland production and found that after the soil samples were taken, the recommendation for lime application was 3 ton/ha. On 8 ha, too much lime would have been applied if soil samples had not been taken and the cost of the lime application would have been ZAR4 880,00 on the 8 ha. With the pH map, lime only has to be applied to certain areas and this results in a saving in cost of ZAR1 380,00 on the 8 ha. Another example of how PA can increase the profitability, is where maize cultivated under irrigation had a yield of 14 ton/ha, while the average yield was only 10 ton/ha. On some areas only 6 ton/ha was harvested according to the yield data. With the use of PA, the weak areas in a conventional land could be identified and this could result in a saving of 15 % on cultivated land, although the average tonnage increased.

In the next two Sections (2.7 and 2.8) the status and some of the reasons why PA was adopted internationally and in South Africa will be discussed.

2.7 PRECISION AGRICULTURE INTERNATIONALLY

PA is a fast growing technology and studies have already been undertaken in the United States of America (USA), Latin America such as Argentina, Uruguay, Brazil and also Canada, Europe, Australia, Japan, Malaysia, Asia and developing countries such as Nigeria.

Murakami, Saraiva, Ribeiro, Cugnasca, Hirakawa and Correa (2007) reported that PA is a relatively new management concept introduced in the mid-1980s. The use of PA techniques and equipment is increasing, but the rate of adoption has slowed down compared to the mid- and late 1990s. The next section will focus on the international status of PA. A study of the situation with regard to farmers in Denmark showed that they are generally optimistic about PA, but a major problem has been the difficulty of verifying the economic and environmental gains.

2.7.1 International status

The adoption of yield monitors is, according to Swinton and Lowenberg-DeBoer (s.a.), rapidly in Argentina, but less so in Brazil and France. Despite the growth of yield monitor use in Argentina, the use of VRT is rare. In 1998 the PA adoption rates in the USA varied from 11,3 % in the Midwestern “Heartland” to only 1,1 % of farms in the

Southeastern Seaboard. The adoption of yield monitoring and VRT had surpassed 5 % only in the US and Canada, while for Australia, Brazil, Denmark, the United Kingdom and Germany the adoption rates were 1-5 % (only for favoured subregions). The adoption of PA technologies during 1998 was virtually unknown in Africa and Asia, except for a few yield monitors in South Africa and some VRT fertilisation being conducted locally.

In 2000, a telephone survey was conducted to gather information about PA activity within 95 Tennessee counties. PA technology was defined as any technology that would allow a farmer to gather information about variation in yield potential, make decisions about variable input application and apply inputs at variable rates. 284 producers used some type of PA technology in 38 (40 %) of the counties. 186 (65 %) of these producers were situated in 18 of the 21 counties west of the Tennessee River. The status of the Tennessee producers showed that 34 (36 %) used yield monitors and 21 of these producers (62 %) used GPS yield monitors. 28 (29 %) used grid soil sampling and the overlap between grid soil sampling and yield monitor activity was evident in 25 of the 28 producers. 18 of these producers (19 %) used VRT, and all of these producers also made use of yield monitors and grid soil sampling (English *et al*., 2000).

In 2002, the adoption rates of yield monitoring and variable-rate technologies within the United States and Canada were not higher than 13 %. It was projected to increase several fold during the next three to five years (Doerge, 2002). According to Lowenberg-DeBoer (2003), some aspects of PA are becoming standard practice in American agriculture. Since 1992, PA has attracted enormous media attention in North America. In South America, PA is probably in its early stages of development. Row crop farmers were surveyed in the south-eastern United States. Of the 98 producers surveyed, 85 returned usable surveys. Seventy percent of the respondents said they already use or plan to use PA tools within the next year. Forty nine percent already use at least one PA tool. The selection of farmers was based on who attended the Cooperative Extension sponsored production meetings. Of the farmers who plan to use PA tools, more than half are looking at variable-rate applicators (51,8 %). Of the farmers who already use PA tools, the biggest percentage use site sampling, namely 43,5 % (Adrian *et al.*, 2005). Srinivasan (1998) listed the following constraints of adopting PA in Asia:

- The high cost of obtaining data;
- The lack of willingness to share spatial data;
- The complexity of tools and techniques;
- The culture, attitude and perceptions of farmers;
- The small size of farms;
- Infrastructure and institutional constraints;
- The lack of success stories of PA adoption and of demonstrated impacts on yields;
- A lack of local technical expertise;
- Uncertainty on returns from investments; and
- Knowledge and technological gaps.

The next section will give some insight into some of the motivations behind the adoption of PA.

2.7.2 Why precision agriculture?

Adrian *et al.* (2005) reported that the intension to adopt PA technologies can be influenced positively by perceptions of net benefit, farm size and farmer educational levels. When a potential user finds technology to be useful, then it is more likely that the technology will be adopted.

According to Srinivasan (1998), the deterioration of environmental quality, the decline of input response of major crops and a widening gap between the potential and realised farm yields are of greatest concern in the current Asian agriculture. Asian farmers may optimise yields and profits and reduce pressure on natural resources by making use of modern strategies such as PA and this could contribute to sustainable land management. Efforts have been initiated by Asian countries to promote PA, and the Ministry of

Agriculture has been allocating funds for PA research since April 1998. Some examples of the aforementioned are research projects conducted at the Kyoto, Tokyo and Hokkaido Universities in Japan, where PA technologies for rice at research farm level have been tested. The Malaysian Agricultural Research and Development Institute (MARDI) is currently conducting research on PA for upland rice. Researchers in India employed in the private sector, are undertaking PA studies on high-value crops such as cotton, coffee and tea. Researchers at the Tea Research Institute in Sri Lanka are examining precision management of soil organic carbon. Studies in the USA, Canada, Europe and Australia have shown that the application of PA leads to reductions in input application rates without sacrificing crop yields. This section can be concluded by giving a summary of results of some PA studies as shown in Table 2.3.

TABLE 2.3: PROFITABILITY CONCLUSIONS FROM PRECISION AGRICULTURE STUDIES IN NORTH AMERICA

Crop	*Inputs Managed*	*Treatment of Sampling & VRT ($)*	*Precision Agriculture Profitability*
Wheat, barley	N, P, K	Not included	Mixed
Wheat	N	Not included	Yes, potentially
Wheat	N, P	Variable & fixed w/ 1 year amort.	No (but over-ests. annual fixed costs)

Source: Lowenberg-DeBoer (1996a)

When three inputs are managed (N, P and K), the results are mixed. The results become potentially positive when only one input is managed (N in this case). However, for these two cases the cost of treatment of sampling and VRT were not included. When N and P were managed and the costs of the treatment of sampling and VRT were included, the results were negative.

Rilwani and Ikhuoria (2006) reported that in developing economies such as Nigeria, PA could assist agriculturalists in determining which land is suitable for the growth of various crops, as well as in the building of databases used to quantify yield variables. In this manner they can achieve a better understanding of poor plant growth or yield. In the following section, PA practices in South Africa will be discussed. The section is divided into three different sub-sections, namely background information, the status of adoption, and factors which could influence adoption patterns.

2.8 PRECISION AGRICULTURE IN SOUTH AFRICA

2.8.1 Background

South Africa has an area of 1 223 million km^2, and 82,3 % of this area is used for agricultural purposes. Agriculture accounts for about 5 % of South Africa's gross domestic product.

After starting quite slowly, the application of PA is currently increasing more rapidly in South Africa. Precision agriculture is a process and does not constitute a single action. The process starts with the evaluation of the environment by the farmer, who does a study of the soil characteristics, the yield potential and the climate of the area. This study is followed by soil analysis, the drawing up of maps and corrective actions (for instance with regard to the pH of the soil) (Van Rooyen, 2004). In South Africa, various types of soils are found, and most cultivated soils are low in organic matter and tend to have a below normal pH (Van Rooyen & Jordaan, 2002). The soils in which plants are sown have a definite influence on farming practices, and crop selection and PA can be seen as technologies used to assist the farmer in the management of the variability of soil potential (Helm, 2005).

It is interesting to note that PA has gained momentum in South Africa as a result of the pressure applied to farmers to optimise inputs while cutting production costs (News Announcements, 2003). Nell *et al.* (2006) stated that the adoption of PA affords the farmer the opportunity to increase the profitability of his farming business, to increase yields, to improve the quality of crops, to incur lower manpower costs and, eventually, to conserve the natural resources of South Africa. The Satellite Applications Centre (SAC) at the Council for Scientific and Industrial Research (CSIR) has developed a new product called Agri-I. This product enables individual farmers to benefit from remote sensing by means of satellites. Information such as vegetation indexes are now available directly to subscribers via the Internet at a cost of ZAR4,00 per hectare (News Announcements, 2003).

In South Africa, efforts are made by farmers to catch up with global trends in PA technology. All farmers should be informed regarding this technology and its advantages. Although the aforementioned technology cannot replace basic cultivation practices, it can add value to farming if it is managed properly. The main aim of this technology is to achieve better uniformity with regard to yield in a specific field (Coetsee, 2003). Since 1998, variable-rate applications of phosphorus and lime, based on chemical grid sampling, were done by companies such as Nitrophoska and TechniLand (Helm, 2005). According to Lowenberg-DeBoer and Erickson (2010) many of the PA technologies developed for mechanised agriculture in North America, Australia and Europe are used to a limited extent commercially in South Africa for example yield monitors, VRT, GPS guidance, remote sensing, proximate N sensors and soil electrical conductivity sensors.

2.8.2 Status of adoption patterns in South Africa

In Van Rooyen and Jordaan’s (2002) opinion, PA should be considered to be the future of successful farming in South Africa. Local farmers, who are already using this form of technology, are excited and it is believed that this is the beginning of a new stage in South African agriculture. Nell *et al.* (2006) reported that PA is already prevalent in the three main agricultural regions, namely the Maize Triangle (which includes the Northern Free State and part of North West Province and Mpumalanga), the irrigation schemes of the Northern Cape, as well as the Swartland and Ruens areas in the Western Cape to a lesser extent. Between 1% and 2 % of farmers in South Africa were involved in PA in 2005. According to StatsSA (2002), there were 45 818 commercial units (farms) in South Africa in 2002, with the Free State totalling 8 531 units, the North West Province had 5 349 units, Mpumulanga 5 104 units, the Northern Cape 6 114 units and the Western Cape 7 185 units. PA is growing fast. A survey done by StatsSA in 2001 and 2005 on the status of PA in South Africa showed the following:

- Yield monitors and mapping increased from 40 (2001) to more than 600 (2005) farming units, with 35 % doing just monitoring, not mapping.
- Variable-rate controlled (VRC) application of lime increased from 16 (2001) to 244 (2005). 87,5 % was done by companies contracting VRC services with 12 % of farming units doing their own VRC application, with their own converted applicators and planters.
- Variable-rate application of fertiliser increased from 8 (2001) to 251 (2005). 87,5 % was done by companies contracting VRC services to farming units with 15 % farming units doing their own VRC application, with their own converted applicators and planters.
- Manual Guidance showed that 200 (2005) farming units were involved, and Automatic Guidance showed that 50 (2005) farming units were involved.

During 2005, information was obtained from the role-players concerning the use of PA technologies and the information obtained showed the estimates of hardware used for PA in South Africa, namely 600 units of yield monitors (GPS linked) and 500 units of variable-rate applicators (Nell *et al.*, 2006). Questionnaires were sent to 25 farmers for the research of Matela (2002) and 17 implemented grid soil sampling, 15 used non-geo referenced yield monitor, 12 out of 25 used GPS yield monitoring and VRT. Lime application was popular, and 16 out of the 25 farmers were involved in differential lime application. The use of yield monitors is popular in the Free State, and farmers in the Western Cape are investigating the effectiveness of variation in the application of lime and fertiliser. The new technology can play an important role in providing in the needs of farmers, but the first step should be to identify correct farming methods (Van Rooyen & Jordaan, 2002).

2.8.3 Factors that can influence adoption patterns in South Africa

Matela (2002) reported the following identified factors which could influence adoption patterns in South Africa:

- Different regions can have different trends;
- Land availability;
- The size of the farm and yields;
- Demographics of farmers;
- The question of adoption incentive;
- Required capital – purchasing costs;
- Management requirements – increased management capacity;
- Education level;
- Experience level;
- Path dependency (adoption of simpler technologies);
- Readiness to pay for highly sophisticated information;
- Farmer characteristics;
- Vintage and productivity of existing equipment;
- Time available; and
- Supporting infrastructure (skilled labour, software development, hardware reliability)

Roberts *et al.* (2002) reported that more precise placement of inputs with PA may increase farm profits. However, it is important to note that the key to farmer adoption is the profitability of the technology. It is predicted that more farmers will adopt PA techniques as soon as more scientific research results on the profitability of PA become available (Nell *et al.*, 2006). Different data analysis techniques will accordingly be discussed with the emphasis placed on spatial auto-correlation and spatial heterogeneity.

2.9 DIFFICULTIES IN THE ANALYSIS OF SPATIAL DATA

2.9.1 Introduction

One of the key constraints identified on the widespread adoption of PA technology is the gap between data analysis and site-specific recommendations (Lambert, Lowenberg-DeBoer & Bongiovanni, 2003). Anselin, Bongiovanni and Lowenberg-DeBoer (2004) also confirmed that the difficulties experienced in the analysis of spatial crop data are some of the key constraints. Spatially dense agronomic data such as the data obtained from yield monitors are often auto-correlated. This dependence among neighbouring observations violates the assumptions of classical statistical analysis (Lambert *et al*., 2003). Anselin *et al*. (2004) also stated that any observation obtained from yield monitors can clearly be correlated with the neighbouring observations. Spatial regression analysis is one way of exploiting more fully the information contained in spatially dense data (Lambert *et al*., 2003). Spatial statistics expands upon traditional regression when data are spatially correlated, for instance data obtained from yield monitors and site-specific data. The problems of spatial dependence (spatial autocorrelation and spatial heterogeneity) can be addressed. If correlation is not accounted for in the analysis of these kinds of data, the results will be biased and misleading (Griffin, Brown & Lowenberg-DeBoer, 2005). Spatial analysis can include analysis with GIS and printing yield maps. It may be defined as "explicitly modelling the spatial auto-correlation in a spatial process model capable of making statistical inference" (Griffin & Lowenberg-DeBoer, 2008).

2.9.2 Spatial auto-correlation

Spatial auto-correlation is described by Bongiovanni and Lowenberg-DeBoer (2001) as a situation in which the dependent variable or error term at each location is correlated with observations on the dependent variable or values for the error term at other locations. It can be formally expressed as follows:

$$Cov\,[y_i, y_j] = \varepsilon\,[y_i y_j] = \varepsilon\,[Y_i].\,\varepsilon[Y_j] = 0$$

$$\text{For } i \neq j$$

Where i, j, refer to individual observations (locations) and y_i (y_j) is the value of the random variable of interest at that location.

When values such as yield data are obtained, spatial auto-correlation is caused by coincidence of similarities between location and these values. The reason for this is the fact that there is always a high chance that high or low values for a random variable will be surrounded by neighbouring observations with similar values.

2.9.3 Spatial heterogeneity (Heteroscedasticity)

LeSage (1998) described spatial heterogeneity as a variation in the average relationships between X and Y over space. One can expect every point in space to have different relationships. The results of this study reveal that the relationship between P as an X variable and yield (Y) varies from one point to the next or from one management zone to the next. When sample data are associated with a location, spatial dependence exists between the observations. The fact that underlying relationships may vary systematically over space, creates problems for regression and other econometric methods if these methods do not accommodate spatial variation in the relationships being modelled (LeSage, 1998). Lambert *et al*. (2003) stated that when general heterogeneity is ignored, VRT profit margins may appear less reliable.

2.9.4 Model specification

PA poses several challenges to both models and modellers as it does not just require simulation of the mean, but also a simulation of spatial variation. The model chosen should match the research objectives. For PA to succeed, one would expect the primary goal to be the ability of the model to simulate spatial variation. The accuracy of the model will determine how good the conclusions will be. In the case of the application of PA, regression has been used as primary test in most model tests. When using the regression approach, the model will produce useful results if the simulated output represents 70 % to 80 % or more of the variation in the observed result (Sadler, Jones & Sudduth, 2007). One of the biggest challenges remain to link yields to soil conditions and to clearly establish the profitability of VRT fertiliser application. This complexity of yield response makes model specification difficult (Anselin *et al*., 2004).

2.9.5 Data analysis techniques used for VRT in other studies

2.9.5.1 Spatial and non-spatial models (OLS and ML)

Ordinary least squares (OLS) is a classical regression technique. When yield monitor data are analysed, it is important to take into account the spatial correlation of regression residuals. When auto-correlation is ignored, the OLS estimates yielded will be inefficient and will bias the standard errors and *t*-test statistics (Anselin *et al.*, 2004). Griffin *et al.* (2005) reported that OLS are unreliable in the presence of spatial variability, or in the cases of spatial auto-correlation and spatial Heteroscedasticity. In spatial regression methods, maximum likelihood (ML) estimations are normally used.

2.9.5.2 REML geo-statistic approach

When spatial correlation is present, field heterogeneity may be underestimated. The inferences about crop response to VRT may be misleading. Spatial regression techniques are necessary, because the data obtained from agronomic experiments are almost always spatially correlated. The restricted maximum-likelihood (REML) technique is one of the most common spatial regression techniques used (Bullock & Lowenberg-DeBoer, 2007). The REML-geostatistical approach was introduced by Cressie in 1993. This approach is often used to analyse yield monitor data and the semi-variogram is the backbone of this approach (Lambert, Lowenberg-DeBoer & Bongiovanni, 2004).

In yield monitor data and other spatial data, there is often correlation among neighbouring observations and this violates the assumptions of classical statistical analysis. From the viewpoint of classical agronomic research, this correlation makes the analysis of this type of data rather difficult and invalid. The reason is that the ignorance of spatial structure results in variance estimates that tend to be inflated. This means that significant levels of test statistics therefore tend to decrease which results in unreliable statistical inference. The under-estimation of heterogeneity and inefficient or biased inferences can result in imprecise inferences about the profitability analysis of trials comparing VRT to SR application rates of P (Maine, 2006).

2.10 CONCLUSION

According to Lowenberg-DeBoer (1996a), hardware and software are sure to change dramatically in future. Farmers and agribusinesses must develop management skills and databases. These site-specific databases and the farmers' capacity to use precision management tools will profitably provide a competitive advantage to farmers in the long run.

When farmers consider the application of PA, one constraint often mentioned is the high cost of technology and human development. However, the high cost of obtaining computer support and software can be recovered in one season from the amount of money saved on fertiliser alone. The advances in technology will also improve the economics of PA, but only time will tell whether or not this new agricultural practice will become more efficient and profitable. It will take more than statistics presented on paper to make farmers convert to these practices. The cooperation of farmers around the world is needed to successfully implement PA (Coates *et al.*, 2002).

Chapter 3 will focus on the research methodology used in this study. The study area will be discussed with specific attention to the climatic conditions, as well as soil sampling and soil types. A detailed description of the experimental design, experimental procedures and techniques will then follow. How the data were collected, the analysis of the data and model specifications will then be discussed. In conclusion, the researcher will take a brief look at the limitations incorporated in this system.

CHAPTER THREE

RESEARCH METHODS:

ON-FARM TRIALS

3.1 INTRODUCTION

When conducting agricultural research, the researcher should keep in mind that production occurs in a specific space, which consists of various fields (in the case of a farming enterprise). It is important, however, to remember that all fields are not necessarily spatially homogeneous. Spatial variability will occur in most cases due to various characteristics such as yield, soil characteristics, landscape outline, pest populations and a host of other factors. The role of the spatial effect on farming led to the development of precision agriculture (PA) technology. An increasing need for management practices in order to adapt to the new technology was experienced. Precision agriculture seemed like a good process to follow, because it made it possible for the farmer to collect, store, manipulate, analyse and act upon the spatial characteristics of farming fields. The spatial oriented perspective of PA presents as both a challenge and an opportunity for agricultural economists (Weiss, 1996).

One of the main aims of the researcher was to investigate the effect of precision phosphorus (P) application on the profitability of PA. The researcher realised that only one fertiliser could be varied during the trials and therefore only P was varied which, according to most farmers, can be viewed as the most important of the three elements (N:P:K) involved. According to Gildenhuys (2003) their estimate P in the soils was 40 parts P per million. During the first trial year (2004), varying levels of P were applied to different soil types according to the soil analysis report. In the original planning phase, the researcher endeavoured to obtain a homogeneous pH. The results of the testing revealed, however, that the pH invariably varied between 4.1 (the bottom margin) and 8 (the top margin).

In order to ensure a practical approach, the researcher conducted on-farm trials which represented the actual farming operations. In view of the fact that “small plot” trials differ from the real farming situation, it was important to conduct on-farm trials. The choice of variables (yield and P) in this study was guided by the researcher’s field of interest, the problem to be solved and the physical on-farm situation. The most important variable in this study is yield, and the study also reflects on the relationship between yield (output) and fertiliser (input). A distinction must also be made between independent and dependent variables. An independent variable is a variable that the researcher can manipulate (Leedy & Ormrod, 2005). P was identified as the independent variable in this study. Therefore P was manipulated by using different application rates as required by the soil potential and it was considered to be the cause of variation in yield. The effects of variable-rate (VRT) and single-rate (SR) treatments of P on yield were the focus of the measurement. The yield was measured as the effect or result of the treatment with P.

In the following section, the study field of this research will be discussed, with specific reference to the crop rotation systems that were followed, as well as the current production system used. This is followed by a comprehensive discussion of the soil-sampling technique which is used to determine the various soil types found in the different fields. Climatic conditions such as temperature and rainfall will also be discussed with regard to their contribution towards yield.

3.2 THE STUDY AREA

3.2.1 Background

The Western Cape is home to 36 % of the total wheat hectares (660 000 ha of a total of 1 835 000 ha), 70,6 % of the total barley hectares (164 000 ha of a total of 232 340 ha) and 100 % of the total canola hectares (40 240 ha) planted in South Africa (Murdoch, 2007).

Farming practices were studied on the farms Môrelig and Duinerug in the Western Cape. A three-year production cycle was used to estimate the potential benefit of PA by means of on-farm trials.

Climatic conditions are an uncontrollable variable that needs some attention. A discussion of the climatic conditions experienced during the study will follow with specific emphasis on long-term average minimum and maximum temperatures, as well as effective rainfall figures which are provided in the form of graphs.

3.2.2 Climatic conditions

3.2.2.1 Temperature

The average minimum and maximum temperatures over a 35-year period (starting on 01/01/1973 and ending on 31/12/2008) were studied. These temperatures were recorded at the Karringmelksrivier Automatic Weather Station for the period 1973 to 1995 and at Voorstekop Automatic Weather Station for the period 1996 to 2008. These two automatic weather stations are approximately 15 km from Heidelberg in a south-western direction. A summary of the minimum and maximum temperatures is provided in Table 3.1.

TABLE 3.1: MINIMUM AND MAXIMUM TEMPERATURES FOR A 35-YEAR AVERAGE

	Minimum temperature (°C)				Maximum temperature (°C)			
Weather station	**Karring-melksrivier**	**Voorstekop**	**Voorstekop**	**Voorstekop**	**Karring-melksrivier**	**Voorstekop**	**Voorstekop**	**Voorstekop**
Period	01/01/1973 – 30/11/1995	07/02/1996 – 31/07/2003	24/07/2003 – 31/12/2006	01/2007 – 12/2008	01/01/1973 – 30/11/1995	07/02/1996 – 31/07/2003	24/07/2003 – 31/12/2006	01/2007 – 12/2008
Month								
January	15,84	16,00	16,73	16,10	28,20	27,97	27,86	28,30
February	16,18	16,87	17,20	16,35	28,18	28,17	28,35	27,80
March	14,99	15,69	14,28	14,40	26,52	26,32	26,57	26,65
April	12,92	13,48	12,94	12,80	23,97	24,33	23,60	24,35
May	10,64	11,58	11,22	11,80	20,83	21,81	21,08	22,65
June	8,74	9,75	9,26	9,60	18,40	19,51	18,72	18,70
July	7,57	8,62	8,74	7,85	17,77	17,93	18,65	17,85
August	7,47	8,87	7,90	8,10	18,20	19,50	17,98	18,75
September	8,82	9,62	9,63	8,50	20,18	20,81	20,87	20,65
October	10,46	11,62	11,23	11,05	22,61	23,82	23,20	22,30
November	12,61	12,90	13,58	12,55	25,19	24,33	25,58	23,45
December	14,67	15,07	14,44	15,20	27,27	27,15	26,95	26,10

Source: Wentzel (2009)

Temperature is very important for wheat production, and rapidly rising temperatures, with daily maximums of 30˚C or more, can terminate grain filling. Wheat seed germination occurs between 4º C and 37˚C, with the optimal level at 20-25˚C. Seed set is promoted by high light intensities and is very susceptible to high temperatures, such as those above 32˚C (AGR 343, 2004).

The optimum planting date of barley for the Eastern Ruens part of the Western Cape is from the 4th week of April until the 3rd week of May. Early plantings generally have a higher yield potential and this is the results of increases with disease and pest control programmes in early plantings (SAB Maltings (Pty) Ltd, 2008). Table 3.1 shows that the average minimum and maximum temperatures at the Voorstekop weather station, for this optimum planting date, ranges during the month of April from 12,8°C to 13,5°C and during May it ranges from 11,2°C to 11,8°C. The average maximum temperature during the month of April ranges from 23,6°C to 24,4°C and during May from 21,1°C to 22,7°C.

High temperatures can shorten the different growth stages of canola. The optimum temperature for photosynthesis and dry material accumulation is 20-25°C. Temperatures of 15-20°C is optimum for germination and temperatures that are too low (<5°C) slow down germination. The pollination of flowers can be negatively affected at temperatures above 30°C as the developing stage of seed will be shortened and this affect yield and quality (Proteiennavorsingstigting (PNS), 2008).

3.2.2.2 Rainfall

Barley can tolerate drought conditions during the early growth stages. However, barley is sensitive to drought during the pipe stage and thereafter. A dry ripening period is a prerequisite as rain and moist conditions can easily cause barley to discolour (AGR 343, 2004). Waterlogging (too much rain) or drought (too little rain) can determine grain yields in the same production season. The amount of rain is a given production factor and the producer can only manage the utilisation of the rain to provide better moist conditions for the grain (Agenbag & Tolmay, 2008). The seed of canola is very small and therefore higher groundwater levels in comparison to wheat are required for successful germination. The canola plant can, after establishment, withstand drier periods better than the wheat plant, due to the fact that the main root can penetrate the soil to a depth of 100 cm in order to obtain water and nutrients. Rain of 300 mm and more (April to October) is ideal for seed yields of 2 ton/ha. If the rainfall is only 200 mm, the yield potential decreases to 1 ton/ha. The distribution of rain is very important and a long rainfall season with enough rain in the pod and seed development stages is very important. The long-term average rainfall for the Eastern Ruens part of the Western Cape is 275-300 mm.

From April until September the rainfall on the farm is approximately 181 mm. Data gathered for the 2004, 2005 and 2006 planting seasons were collected and in Figure 3.1 a summary of the monthly rainfall is shown.

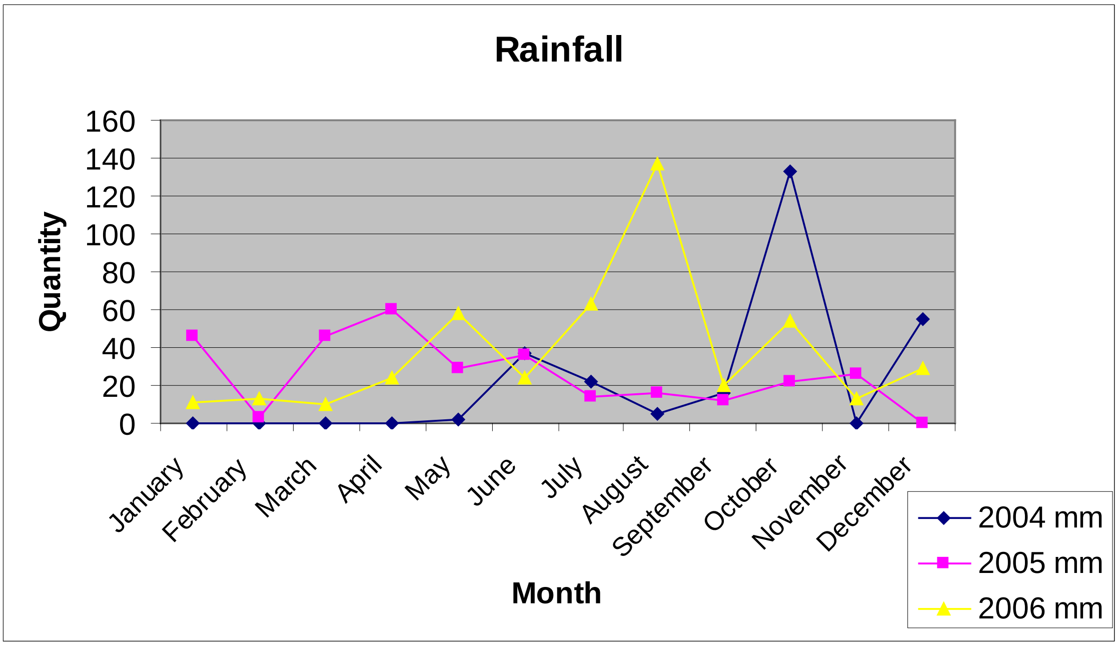


Figure 3.1: Rainfall (2004 – 2006)

Figure 3.1 shows that for the 2004 season the first seasonal rain fell during May. The highest rainfall was recorded during October. The highest rainfall in 2005 was recorded in April, and for the 2006 season it was during August. The different soil types have different water requirements. The Cartref soil has poor drainage and is not very permeable and the Gamoep soil is very hard. These two soils will need rain early in the season to promote the chances of a successful season. The Glenrosa, Etosha, Coega, Oakleaf and Swartland soil types have better soil structures and are higher potential soils.

3.3 THE FARM

Mr Gildenhuys is the owner of two farms, namely Môrelig and Duinerug, in the Western Cape Province of South Africa. The farms are situated 8 to 10 km from the sea on the Witsand road. Môrelig is approximately 13 km south and Duinerug is approximately 22 km south from the nearest town, Heidelberg.

3.3.1 Current production system

The farms consist of 1 300 ha, a part is cultivated and the rest is used for grazing. Four fields, totalling 109,63 ha in size, were selected for the study and were identified for this purpose as L2 (24,33 ha), K3A (25,80 ha), K5 (38,98 ha) and K7A (20,52 ha). The farmer used a 10-year no-till crop rotation production system (five years of cash crop and five years dryland lucerne). The only cultivation is during planting. It is general farming practice on this farm that in the last year of the crop rotation system (2006) before lucerne is planted, the P-levels of the soils are corrected to make provision for the five years of planting dryland lucerne. This practice resulted in high fertiliser recommendations during 2006. (A comprehensive description of the aforementioned will be included under Section 3.5.2.).

In the following section, soil sampling technology will be discussed, followed by an in-depth explanation of the different soil types identified. The rotation systems used on the farm, the fertilisation of crops, as well as planting actions, weed control and harvesting, will also be scrutinised.

3.3.1.1 Soils

Canola thrives on a well-drained soil which is also good for high-quality wheat production. Light, sandy soils should rather not be used for canola production. Cool and dry soils on southern slopes also provide good yields. The pH of the soil can vary between 5 and 7 (KCI). P fertiliser must be applied according to the soil analysis conducted, and the norm is approximately 36 dpm P (citric acid) or 24 dpm P (Bray 1) (PNS, 2008). Loam soil is best for wheat production. Clay and sandy loam soils can also be used, but there must be a proper drainage system. Care must be taken that the soils are not acidic or sodic (Jaiswal, 2009). Barley, on the other hand, can be grown on many soil types, including soils that are well drained, fertile loams and lighter clay soils. It will, however, not fare well in waterlogged soils, but will tolerate loamy to heavy soils. Barley is the most salt-tolerant among the various cereal crops and it grows well in soil with a pH of between 5,0 and 8,3 (Valenzuela & Smith, 2002).

The main problem identified was that there were up to 5 soil types per field and the management of the differences between these soils made it difficult to maximise yields. Fertiliser was applied in accordance with the different soil types. In general, most soils found in the area are shallow and there are very few natural water pans. Due to the aforementioned, moisture retention is limited.

3.3.1.2 Soil sampling

At the beginning of 2004, grid soil sampling was conducted by using 80 x 80 m grids on the four fields. The reason for carrying out the sampling by using the 80 x 80 m grid was that very accurate data were required for the study. In the researcher's opinion, the use of a 100 x 100 m grid would not provide information that was accurate enough. On the other hand, the use of a 50 x 50 m grid would be too costly. In the application of the preferred grid, the physical and chemical components of the soil were determined for every 80 m. The costs of hiring the necessary equipment to do the soil profiles and to determine the coordinates are summarised in Annexure A, Table A1. Table A1 indicates that the cost of hiring equipment for the soil profiles was the highest, namely

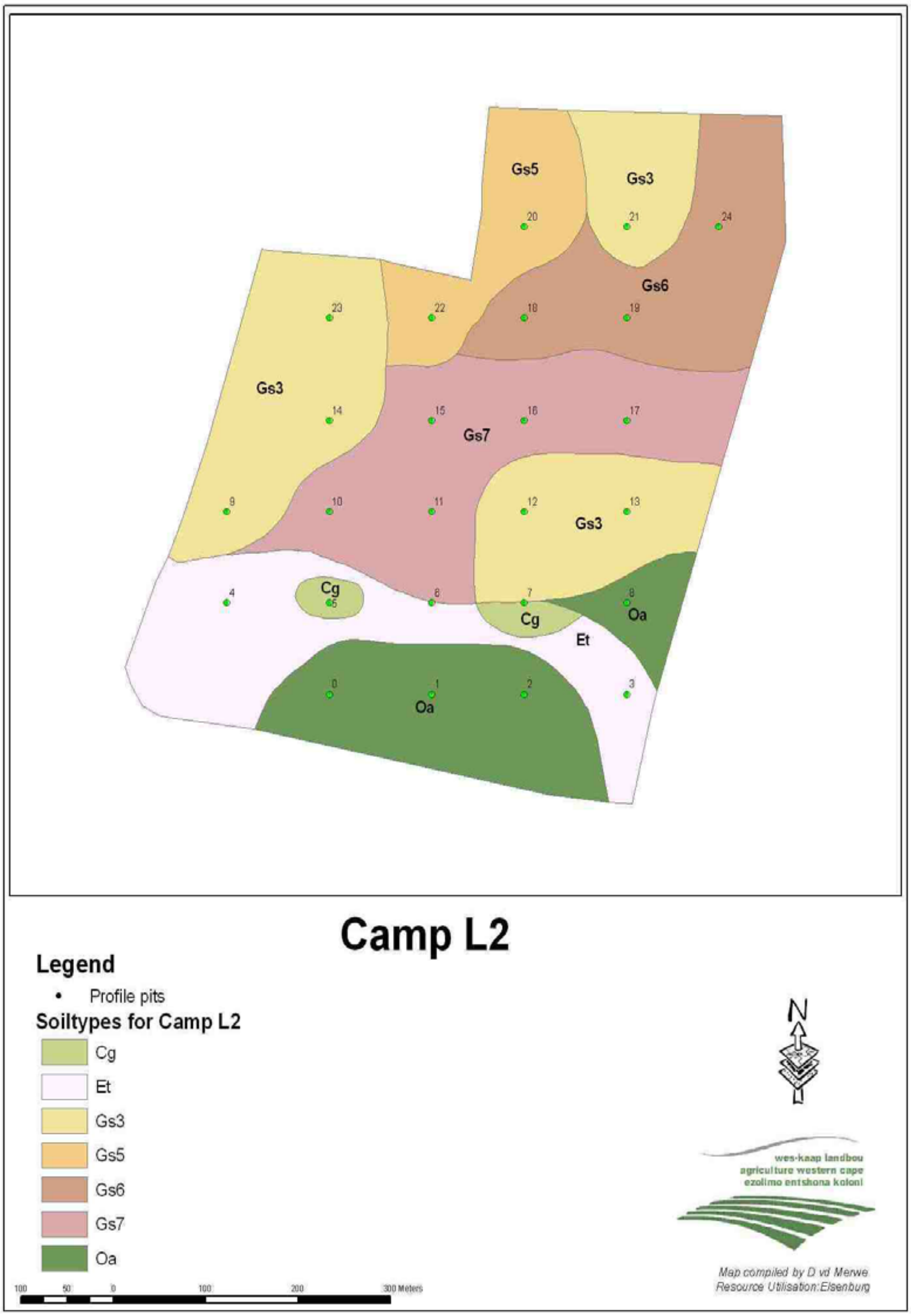
ZAR3 517,47, or 59,39 % of the total cost. Annexure A (Tables A2 to A4) outlines the relevant physical and chemical analysis costs.

Although Table A2 illustrates that the total cost for the physical and chemical analysis of the soil samples was ZAR24 007,50, it must be kept in mind that a complete analysis is only undertaken every 5 years. This amounts to a cost of ZAR4 801,50 per year (ZAR24 007,50 ÷ 5). For the remaining 2 years of the study, representative samples were taken. Each soil sample taken was given a specific coordinate and numerical number starting at one. The representative samples were identified using the previous year's yield maps. Tables A3 and A4 provide a summary of the cost of the physical and chemical analysis of the soil samples for the 2005 and 2006 production seasons respectively.

Tables A3 and A4 show that the total cost for the 35 representative soil samples taken during 2005 and 2006 amounts to ZAR4 392,50 for the four fields. The total soil sampling cost for the duration of the trial is ZAR32 792,50 (ZAR24 007,50 for 2004, ZAR4 392,50 for 2005 and ZAR4 392,50 for 2006). With the technique used and the cost of the soil sampling being covered, a comprehensive discussion of the various soil types follows in the next section.

3.3.1.3 Soil types

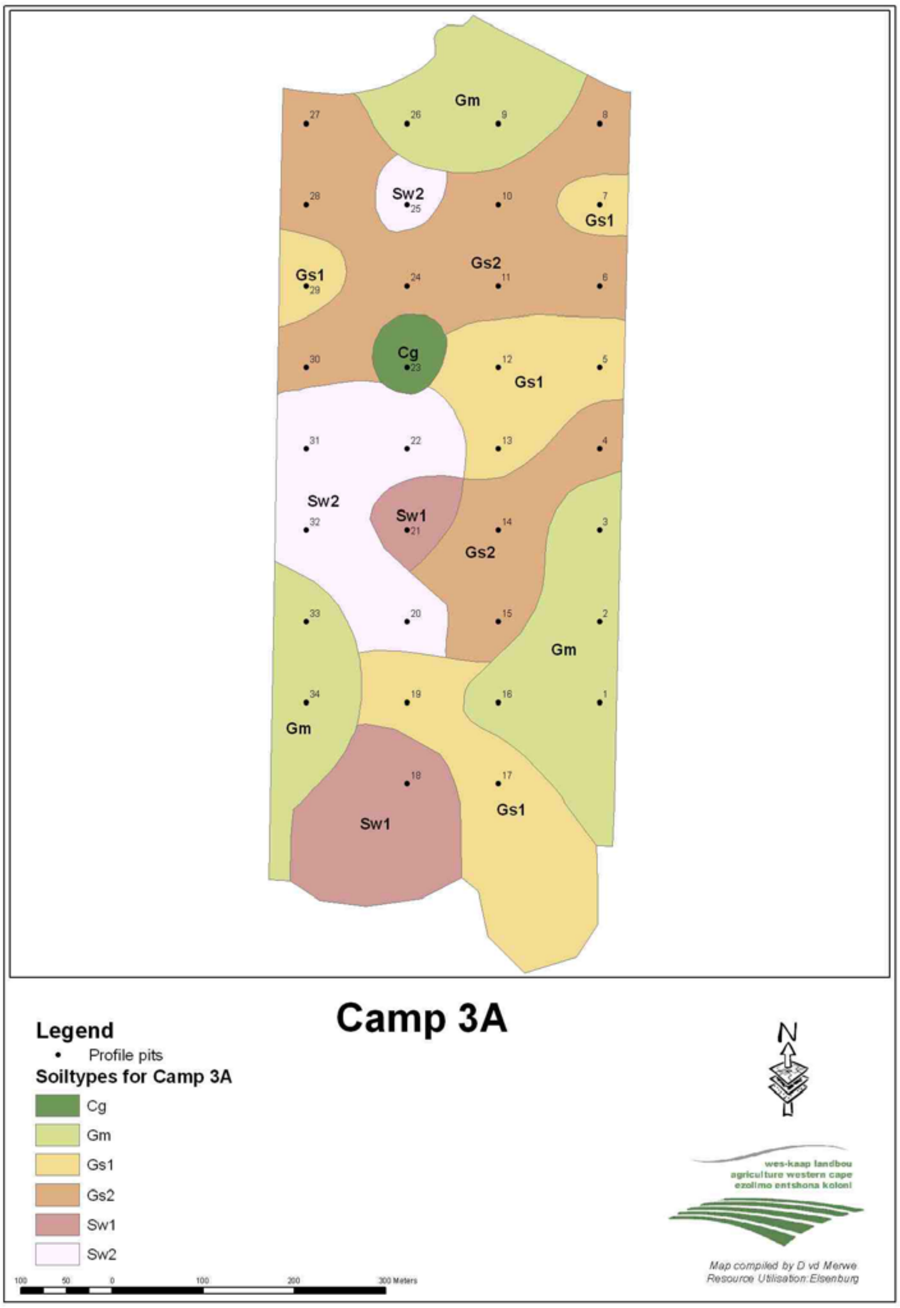
The litho logical material on Môrelig is homogeneous over great areas and consists of shale from the Bokkeveld Group. The parent material on Duinerug is Limestone (Calcite) originating from the Quaternary Period. Although many differing soil areas have been found in this region, many of them are physically similar and vary mainly with regard to their morphological nature. The dominant soil type has been classified as Glenrosa (Gs1 to Gs7) with other secondary soil types classified as Cartref (Cf), Etosha (Et), Gamoep (Gm), Coega (Cg), Oakleaf (Oa) and Swartland (Sw1 to Sw2) (Oberholzer, 2004). In Figures 3.2 to 3.5, the different soil maps of the four experimental fields are shown and Figure 3.2 shows the soil map of L2.



Source: Van der Merwe (2009)

Figure 3.2: Soil map of L2

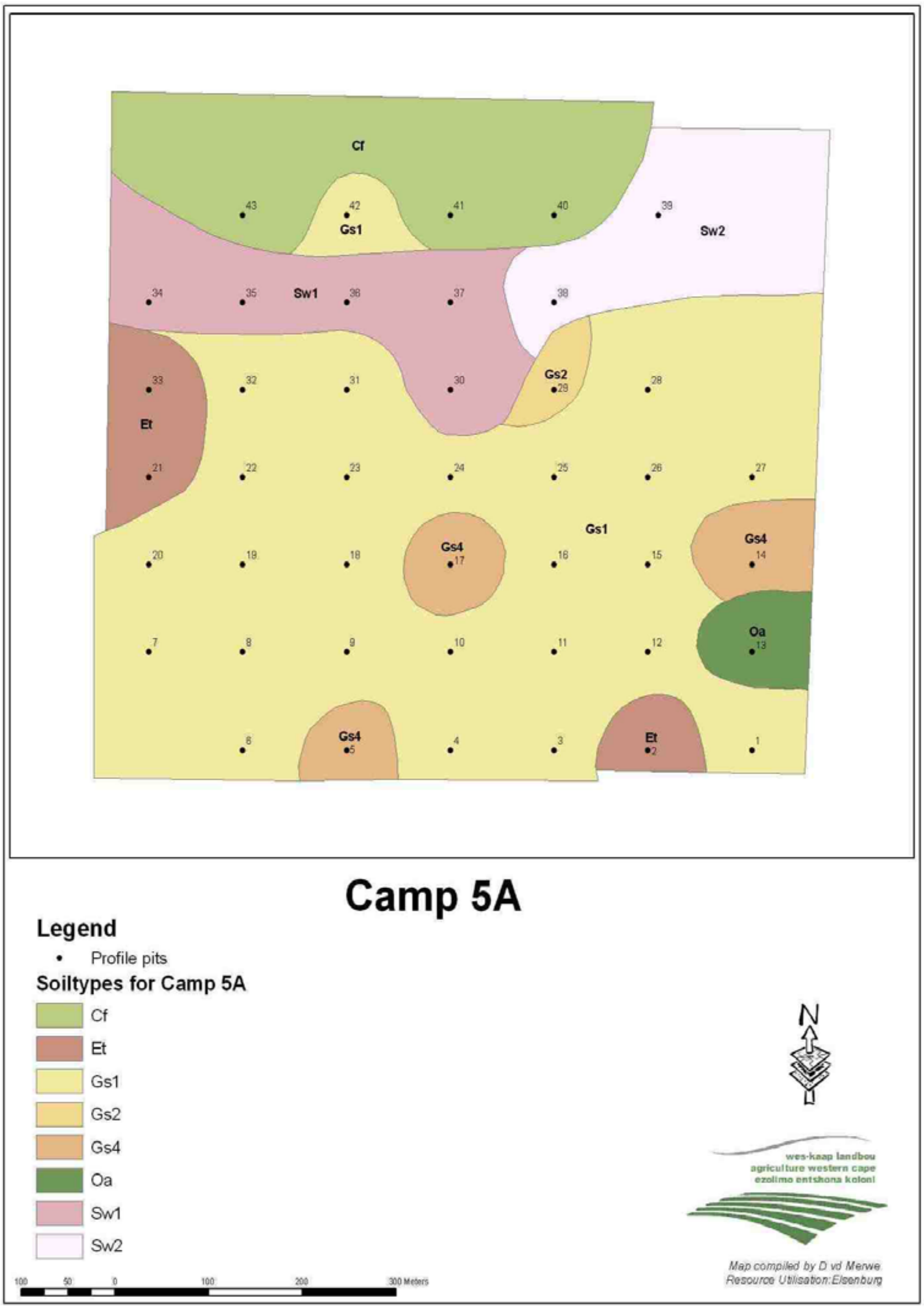
The Glenrosa soil type is dominant for L2 with the following soil forms, Gs3, Gs5, Gs6 and Gs7. The different soil types are described fully under Section 3.3.1.3.1 to 3.3.1.3.7. Figure 3.3 shows the soil map of K3A.



Source: Van der Merwe (2009)

Figure 3.3: Soil map of K3A

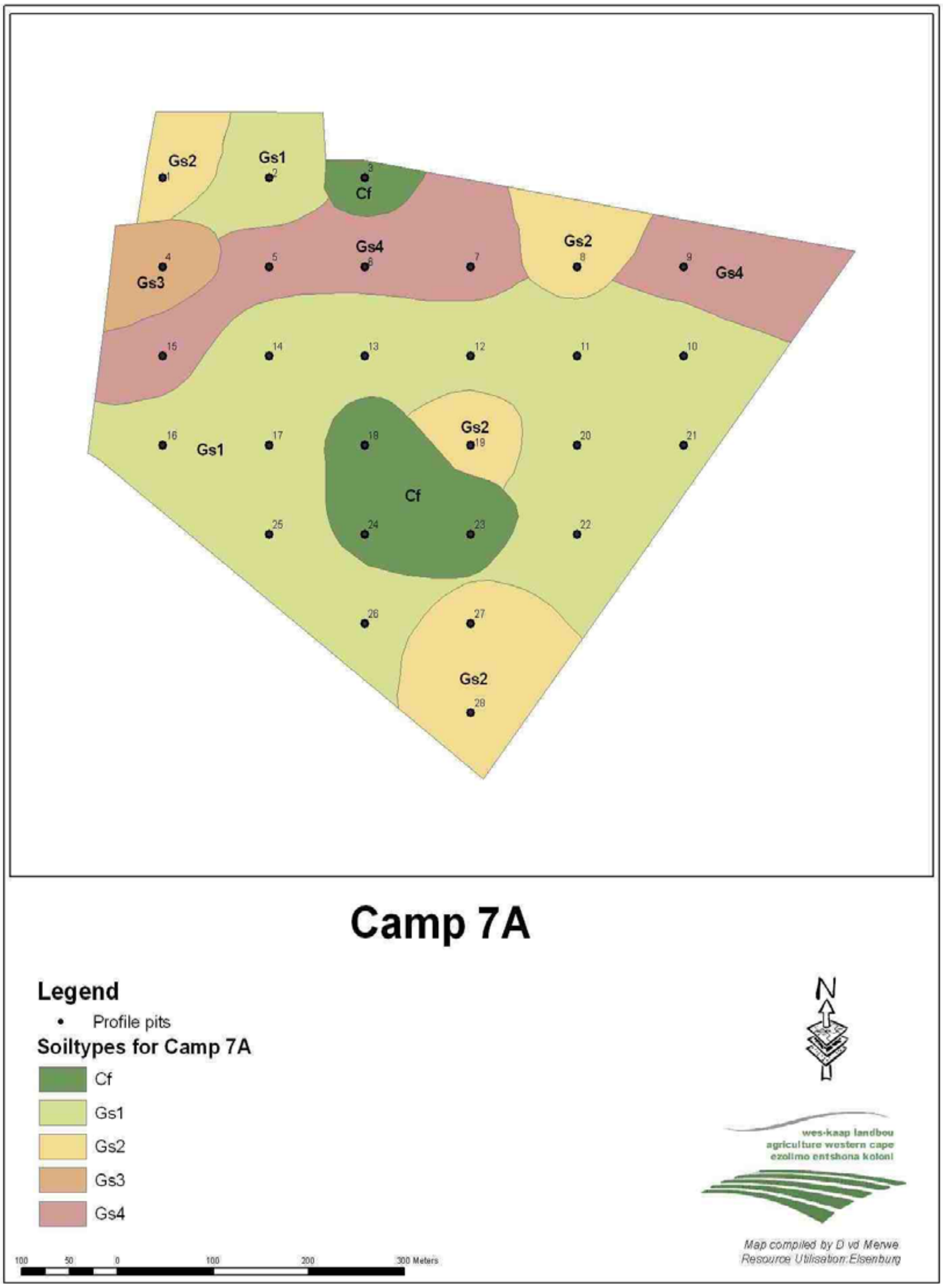
The Glenrosa soil type is dominant for K3A with Gs1 and Gs2 as the associated soil forms. The soil map of K5 is shown in Figure 3.4.



Source: Van der Merwe (2009)

Figure 3.4: Soil map of K5

The Glenrosa soil type is dominant for K5, Gs1, Gs2 and Gs4. Figure 3.5 shows the soil map of K7A.



Source: Van der Merwe (2009)

Figure 3.5: Soil map of K7A

Figure 3.5 shows that the Glenrosa soil type (Gs1, Gs2, Gs3 and Gs4) is also dominant for K7A.

3.3.1.3.1 Glenrosa (Gs)

The typical Glenrosa found in this valley region consists of deep layers of tilted, fractured shale sediments with saprolite or weathering rock in various stages of breakdown. Between fracture planes, soil material is evident and varies from 5 % to more than 40 %. Figure 3.6 is a representative picture of what a typical Glenrosa soil type will look like.

Source: Soil classification working group (1991)

Figure 3.6: Glenrosa soil form

This soil form covers large areas and is a high potential soil for annual dryland crop production. The A-horizon is not bleached. The subsoil mainly consists of weathered shale parent material with sandy clay to clay texture. The clay percentage can be as much as 89 % in this soil type. Another characteristic of Glenrosa is good internal drainage and moderate to good water-holding capacity, as well as good porosity. These characteristics are mainly due to the tilted lying shale (Oberholzer, 2004).

The different Glenrosa soil families are distinguished by scrutinising the following aspects:

a) Whether the A-horizon is bleached;
b) Whether the B1 horizon is hard or not;
c) Whether there are signs of wetness in the B1 horizon;
d) Whether the B1 horizon is calcareous or not.

Table 3.2 illustrates the different Glenrosa soil families and the fields where they are classified.

TABLE 3.2: DIFFERENT GLENROSA SOIL FORMS AND SOIL FAMILIES AND THE FIELDS WHERE THEY ARE CLASSIFIED

Soil form	Soil family	Fields
Gs1	1111	K7A, K3A, K5
Gs2	1112	K7A, K3A
Gs3	1221	K7A, K3A
Gs4	1121	K7A, K5
Gs5	1212	L2
Gs6	1222	L2
Gs7	1211	L2

Source: Oberholzer (2004)

From Table 3.2 it is clear that Gs1 is mostly found in fields K7A, K3A and K5. This soil form consists of small to medium soft fragments of weathered shale. The B1-

horizon is not hard and no signs of wetness are found, and this horizon is also non-calcareous. Gs2 is mostly found on fields K7A and K3A. The B1-horizon is not hard, but is calcareous. Gs3 is mostly found on fields K7A and K3A. This soil form consists of medium to large, not very loose fragments of weathered shale. The B1-horizon is hard and no signs of wetness are found. This horizon is also calcareous. Gs4 is mostly found on fields K7A and K5. Signs of wetness are found and the B-horizon is not hard and also non–calcareous. Soil forms Gs5, Gs6 and Gs7 are found on field L2. Soil family Gs5 has a hard B-horizon that is calcareous and contains no signs of wetness. The B-horizon for soil family Gs6 is hard and calcareous with signs of wetness in the B1-horizon. For soil family Gs7, the B-horizon is hard but is non-calcareous with no signs of wetness.

3.3.1.3.2 Cartref (Cf)

This soil form, which is found on field K7A, is not an ideal example of a Cartref soil form. The soil is not very permeable and this results in a raised (perched) water table. The washed-out E-horizon is the result of poor internal drainage. Figure 3.7 indicates the washed-out E-horizon which is represented by the double white lines.

Source: Oberholzer (2004)

Figure 3.7: Cartref soil form

3.3.1.3.3 Gamoep (Gm)

Figure 3.8 shows the Gamoep soil form as found on field K3A.

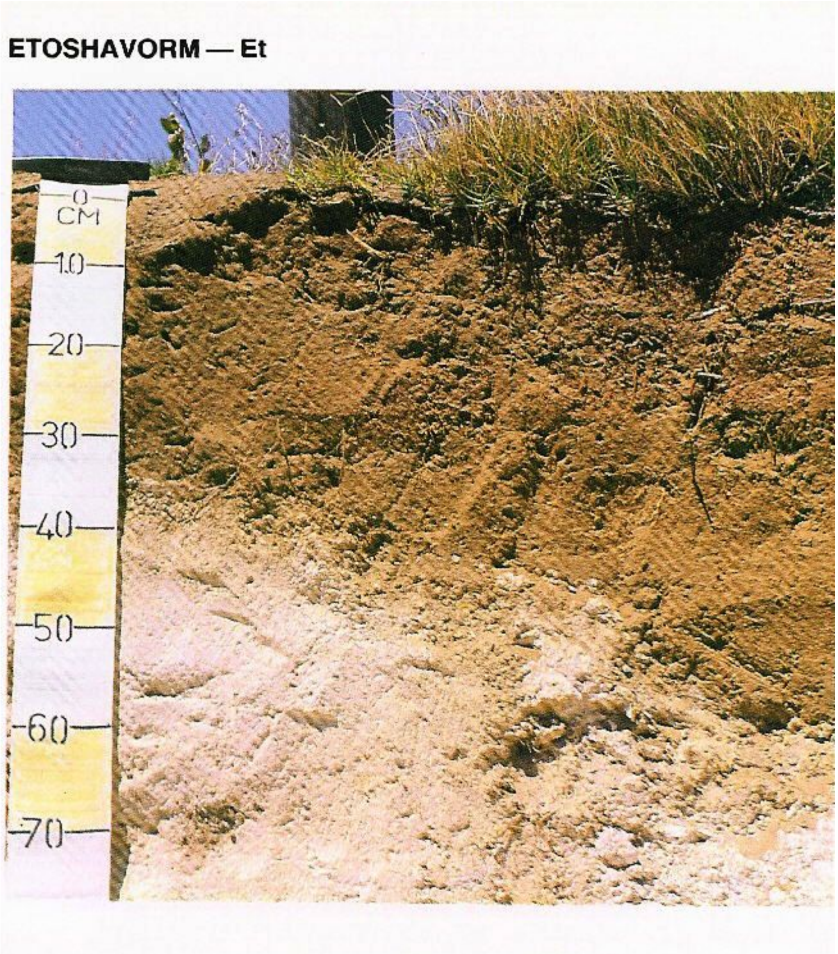
Source: Oberholzer (2004)

Figure 3.8: Gamoep soil form

The neo-cutanic B-horizon has a deep red colour. At approximately 75 cm, the hardpan carbonate is found on field K3A. This horizon is so hard that it is called calcrete or dorbank.

3.3.1.3.4 Etosha (Et)

This soil form has a soft, carbonated B-horizon. Figure 3.9 shows a typical Etosha soil type (representative picture).



Source: Soil classification working group (1991)

Figure 3.9: Etosha soil form

The substratum consists of hard parent rock of calcite (CaO). The A-horizon is not bleached and the B-horizon has no signs of wetness. This soil form is found on fields K5 and L2.

3.3.1.3.5 Coega (Cg)

On field K3A, a red-brown A-horizon of 25 cm is underlaid by a hardpan carbonate horizon, as illustrated in Figure 3.10.

Source: Oberholzer (2004)

Figure 3.10: Coega soil form

3.3.1.3.6 Oakleaf (Oa)

This soil form is dominated by dark red colours. Figure 3.11 contains a representative picture of this soil form.

Source: Oberholzer (2007)

Figure 3.11: Oakleaf soil form

These soils have sandy clay and loam subsoils. The characteristics are the following: very good porosity, internal drainage and water-holding capacity, which result in the potential for root growth and root development. The subsoil has a strongly developed, fine, crumbly structure.

3.3.1.3.7 Swartland (Sw)

This soil form consists of pedo-cutanic B-horizon with tongues of saprolite in the B1-horizon. The A-horizon is not bleached and the B-horizon is red in colour. The soil has a sub-angular to angular structure. In Table 3.3 a summary of the two soil families of the Swartland soil type is given.

TABLE 3.3: DIFFERENT SWARTLAND SOIL FORMS AND SOIL FAMILIES AND THE FIELD WHERE THEY ARE CLASSIFIED

Soil form	Soil family	Field
Sw1	1211	K3A, K5
Sw2	1212	K3A, K5

From Table 3.3 it is clear that the two soil forms, Sw1 and Sw2, are found on fields K3A and K5. The two types are distinguished by calcareous B- to upper C-horizon in the case of Sw2, while no signs are found in the case of the Sw1 soil type. In Figure 3.12, the clear transition from the A- to the B-horizon is indicated by means of a white arrow.

Source: Oberholzer (2004)

Figure 3.12: Swartland soil form

The following section will focus on the experimental design used in the study. The research method of using on-farm trials will be discussed in detail, as well as the plot layout of this research, followed by a short discussion on replication and randomisation.

3.3.1.4 Rotation

The increasing incidence of root diseases is an emerging factor that can threaten wheat yields and thus the farmers' income. A well-planned and -managed crop rotation system is the only practical control strategy used. The aim of using a suitable crop rotation system is to ensure the build-up of soil organic material, and this can be linked to the recovery of soil structure and increased soil water accumulation capability (ARC-guidelines, 2008). The rotation system used for the four fields by Mr Gildenhuys is presented in Table 3.4.

TABLE 3.4: CROP ROTATION FOR ON-FARM TRIALS

	L2	***K3A***	***K5***	***K7A***
2004	Wheat	Wheat	Canola	Canola
2005	Canola	Canola	Wheat	Wheat
2006	Wheat	Wheat	Barley	Barley

As illustrated in Table 3.4, a rotation system including wheat, canola, followed by wheat again, was used in field L2. The same was true for field K3A. In fields K5 and K7A, the same rotation system, including canola, wheat and barley, was used for the research period.

By introducing canola into a crop rotation system with wheat and barley, the risk of failure decreases because it is spread more widely. It also ensures the optimal utilisation of land, machinery and labour, because canola has the same soil, machinery and labour requirements as wheat and is sown earlier in the season. Canola also improves the soil structure due to its tap root system (PNS, 2008).

3.3.1.5 Fertilisation

Treatments applied included a fertiliser rate and formulation for each soil unit in the various fields, as well as a rate and formulation for the entire area tilled. A strategy was developed to generate greater returns by using the method of varying fertiliser according to soil differences rather than applying a uniform rate and formulation throughout a field.

3.3.1.6 Machinery

The width of the machinery used was selected according to the requirements for the planting and harvesting processes. The width of the planter was 12,3 m and that of the herbicide sprayer was 24 m, the cutter width was 9 m, and the width of the combine was 8,98 m. The machinery had been purchased during 1996.

3.3.1.7 Weed control

The first and most important process to be followed was the control of grass (rye- and bristle-grass are the two most important weeds, causing most problems). Due to no-till, grass had become a major problem as the control was only chemical in nature (Gildenhuys, 2009) and the weed could become resistant to chemical control over time. Rye-grass can very easily develop a resistance against Roundup and one way to overcome this problem is to rotate the chemicals used. The rotation system can play an important role in the controlling of weeds in certain types of grain, because it is easily achievable. The entire rotation system was planned in accordance with this method. The control of broadleaf weeds (devil's thorn) also caused a problem and became a challenge it was important to overcome. The main constraint of chemical weed control is the costs involved, as well as the selective usage of the product.

3.3.1.8 Harvest

The harvesting of the grains normally stretches from the beginning of October until the end of October. At this stage, the rows are spaced at 183 mm. During the harvesting process, the grain is first cut and windrowed, and then combined. The purpose of windrowing for canola is to ensure that it falls in even rows and this helps with more uniform ripening, faster and more uniform drying of the crop, easier and earlier harvesting and less seed loss during ripening and harvesting. Rain or moist conditions during the harvesting of canola could increase the moisture content of the seeds. As soon as the moisture content of the seeds fall to below 8 %, the windrows can be collected (AGR 343, 2004).

Emphasis is now placed on the methods used in gathering and analysing data with specific focus on the experimental design and the general philosophy underlying the split-plot design and on-farm trials. The reasons for selecting the design used are also explained. This is followed by a plot layout, as well as some discussion of the concepts of replication and randomisation.

3.4 EXPERIMENTAL DESIGN

The experimental design refers to the decision of how the treatments will be physically arranged in the field. The split-plot design (Alleman, 2007; Anderson, 2007) was used for this on-farm research experiment. According to Davis, Harris, Roberts and MacDonald (1999), a decision must be made regarding the question to be answered when designing an experiment. The variables that will be tested in the experiment are called the "treatments", and the physical areas to which the treatments are applied are called the "plots". Information such as yield is called the "data", and this information is needed to evaluate how well each treatment will work in order to compare treatments. One familiar treatment that is in accordance with existing practices should be included and this is often called the "standard" treatment, "check" or "control". As mentioned under Section 3.2.1, four fields had been identified as experimental plots and each field had been split into two treatments (VRT application of P and SR application strategy of the same input). On the side of the main plot subjected to VRT application, varying P rates were applicable. The following section will focus on the experimental design of on-farm trials.

3.4.1 Split-plot design and on-farm trials

Kowalski and Potcher (2003) reported that split-plot experiments began in the agricultural industry. Split-plot experiments consist of the application of one variable factor such as fertiliser to large sections of land called “whole plots”. At the same time, there are variations of fertiliser rate applied to smaller sections of land, called “subplots”. Another feature of this type of experimental design is the varying sizes of experimental units. Holmes (2005) also confirmed that this type of experimental design can be used to compare different treatments by dividing the plots in half. Whitcomb and Kraber (2002) describes this type of design as an experiment in which an extra factor is introduced into a study by dividing large experimental units (whole plots) into smaller experimental units (subplots) on which different levels of the factor will be applied.

The participation of farmers in research trials has rapidly gained popularity over the past few years. The conditions for on-farm trials are typically less controlled than those at research institutes, and with these kinds of experiments the farmer is also involved to a greater extent. There are different types of on-farm experiments. One type is designed and controlled by the research team; the other type is researcher-designed and farmer-managed; and the last type is farmer-designed as well as farmer-managed. The advantage of on-farm trials is that a broader range of soils are involved in the experiment. Interaction with farmers is also encouraged. Some data are collected at the plot level (as in an experiment) and other data at the farmer level (as in a survey). Where the researcher and farmer work together, the objectives of the study must be clearly specified and the objectives must also be re-assessed during the planning of the trial (Statistical Services Centre, 2007).

The treatments will depend on the objective of the trials, but usually there will be one or more control or baseline treatments which are in accordance with the farmer’s normal practice. It is recommended that normally at least two treatments should be compared. Replication of treatments is important for precise treatment comparison. It is often assumed that the plots should be larger for on-farm than on-station trials, but on statistical grounds there is no general justification for preferring large plots in on-farm trials. The size of the plots can rather be determined by the preferences of the farmer and the researcher. The layout of the plots will primarily be guided by perceived or known variation in the farming area. For instance, a split-plot design may be chosen because it is convenient to plant one large area at one time, whilst the application of different levels of fertiliser can be on smaller areas. There can be different types of variables that are measured, for example the type that is taken in on-station trials such as yield, and the type that is on farm level, such as rainfall and soil type. When the data are analysed, the yield data can be of particular importance. The analysis of data is not the end process in a study, but it does conclude those aspects that have merit for discussion. The results should be reported and the collaborating farmer must play an important role in the report (Statistical Services Centre, 2007).

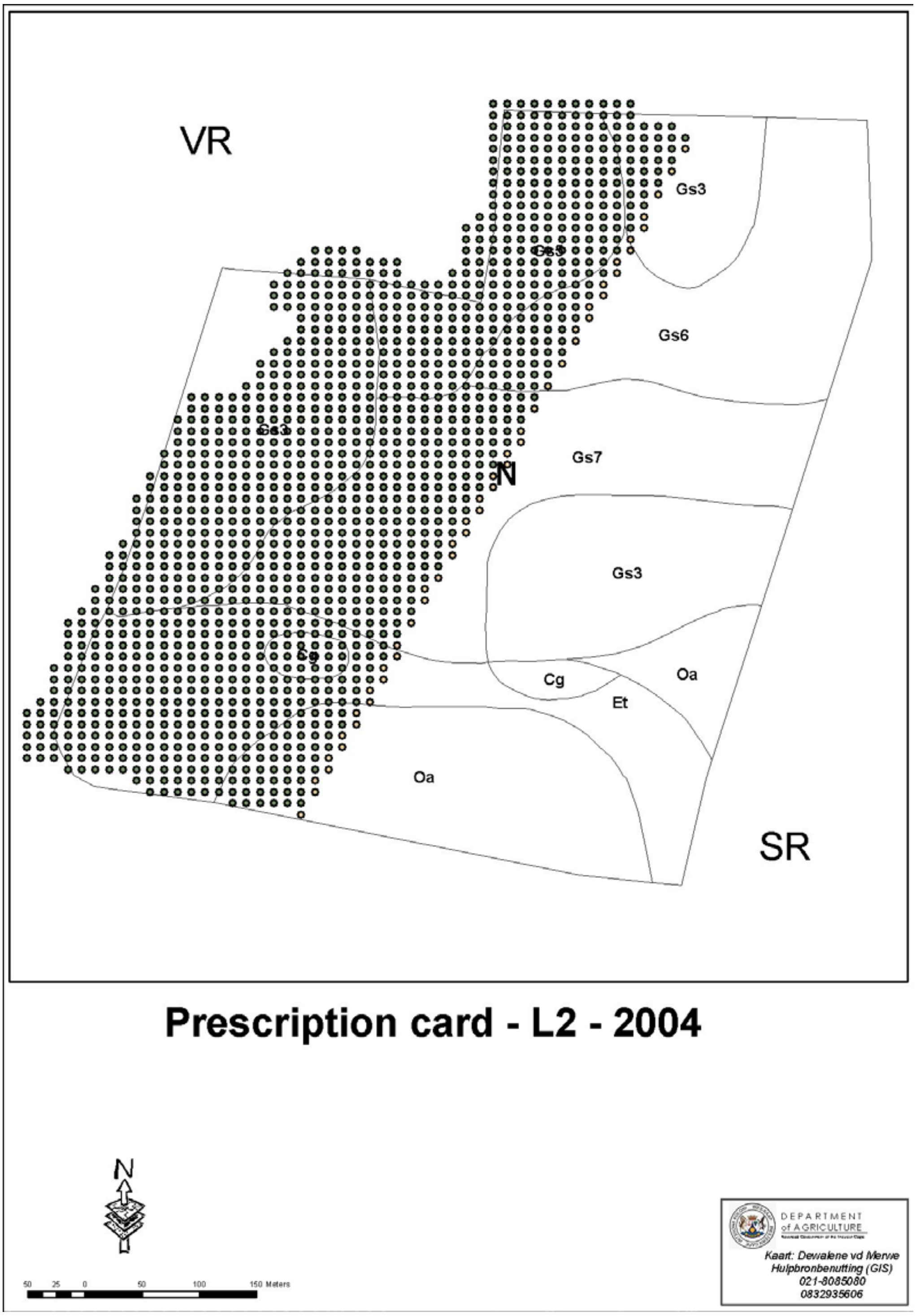
An important aspect to take into account when conducting research by means of on-farm trials is communication between those involved to ensure that an entire season's work is not lost because the right people are not present when the combine is in the field. It is also important to always make a plot map showing the type and placement of treatments (OMAFRA Staff, 2002).

3.4.2 Plot layout

A study conducted by Maine in 2006 in South Africa showed that a plot layout can be used by farmers in order to identify an optimal fertiliser application strategy in any particular field. To achieve this goal, it is necessary to use standard farming machinery and equipment for the experiment and move away from the traditional small-plot randomised block experimental design. The small-plot design, as used in traditional agronomic trials, has some advantages such as reducing heterogeneity, but requires intensive planning, management and labour input during planting and harvesting. This type of design is also cost-intensive and could interfere with regular farming activities.

When using larger experimental units (> 5 ha), the interference with farming activities is limited and thus the design can be easily implemented by farmers. Treatment edge effects can be managed effectively in a large experimental unit, since data points that are known to have been inaccurately measured can be deleted without compromising data availability.

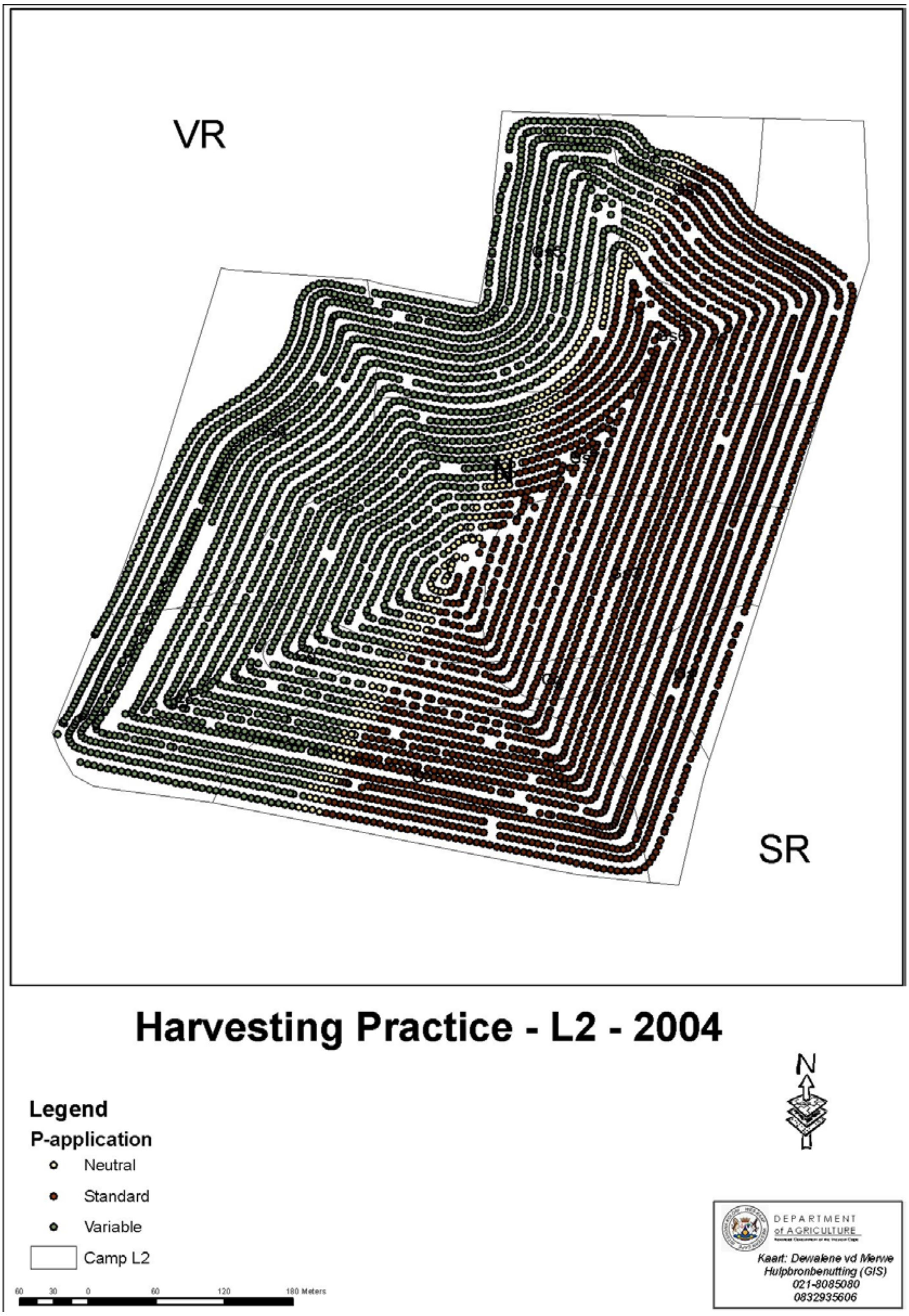
As mentioned previously, the 106 ha concerned consist of four fields, namely L2, K3A, K5 and K7A. L2 is on Duinerug and K3A, K5 and K7A are on Môrelig. Each field was divided into two. The one half was treated as the control field with SR application of P as it was done in the past, and the other half was treated with VRT application of P (Figure 3.13). Each of the other fields’ application maps can be seen in Annexure B.



Source: Van der Merwe (2009)

Figure 3.13: Prescription card for L2 2004

This design was used to compare fertiliser (P) application programmes under VRT and SR applications. This design also agrees with current farming practices because a rotation system is involved and the farmer plants and harvests by starting from the outside of the field going in circles to the inside of the field (Figure 3.14 illustrates this practice). As also mentioned, during 2003/2004, physical and chemical soil analyses were conducted with regard to every 80 x 80 m grid in each field. This practice is illustrated in Figures 3.2 to 3.5. Each number represents a soil sample. During 2005 and 2006, soil samples were taken only by using representative points as can be seen in Annexure C (Tables C1 to C4). These points were identified by using the previous years' yield maps and were treated as management zones. The decision was also taken to link the wide range of soil types in each field to the management zones, as the prescription cards were compiled using only the chemical analysis of each year's soil sampling. For this research, a 10 m strip was identified where the field was divided in half and treated as neutral ground. The aforementioned strip is shown in Figure 3.14.



Source: Van der Merwe (2009)

Figure 3.14: Harvesting practice for L2 2004

The principles of replication and randomisation as used in an experimental design will be discussed in the next two sections.

3.4.3 Replication

According to Davis *et al.* (1999), replication is necessary because all test plots are not identical. This leads to variation in the data that can be collected and results from two plots that receive the same treatment while not being exactly the same. Steps can be taken to minimise the effect of variation if it has an identifiable cause, but there will always be some variation that cannot be controlled. In statistical terms this is called "experimental error". The purpose of replication is to ensure more accurate estimates of how each treatment will perform even though there may be uncontrolled variation in an experiment. The biology of what a person is testing, how close the treatments are to each other and the number of variations within a treatment will determine the number of replications. It may range from a minimum of four replications, but usually five to six replications will be much better. The replication treatments used in this study were identical to the initial treatments and were carried out on the same location in each season of the three-year grain production period.

3.4.4 Randomisation

The purpose of randomisation in an experiment is to assign treatments to plots where no discernable pattern can be identified. It is important to randomise as the positioning of treatments within a block may affect the performance (Davis *et al.,* 1999). For this research, the experimental fields are relatively flat and the topographic effects are minimal, however, soil characteristics, and more specifically soil type, as well as applied inputs, had an effect on variation in yield. Blocks or strips consisting of six rows could not be formed as in the study conducted by Maine in 2006, because the farming practices for this research were different therein that the planter and combine worked together in a circular movement starting from the edge of the field and moving towards the centre. This practice resulted in the crops not being planted in easily identifiable rows as shown in Figure 3.14. The experimental procedures and techniques involved will be discussed in the next section, with special emphasis on field management which includes the different activities that took place during the three experimental years. The variable application of P will also be discussed and tables will be used to present the different P-levels (mg/kg) for each of the four fields for the three experimental years, as well as the standard and variable P levels (kg/ha) applied.

3.5 EXPERIMENTAL PROCEDURES AND TECHNIQUES

The Ag Leader Advanced Farming Software System enabled the researcher to identify soil sampling points within management zones, by using a system of coordinates. The amount of each nutrient that had to be applied was based on the chemical analysis of the soil samples and the inputs of the farmer's fertiliser company representative. A Flexicoil planter was used and with the aid of the Ag Leader System, the input applications were varied continuously throughout the field on the VRT area as determined by the prescription cards for each field, set up beforehand by the farmer.

3.5.1 Field management

As stated in the research by Maine in 2006, field management encompasses all field activities, beginning with soil preparation and ending with harvesting. For this research, no soil preparation was done before planting as the farmer follows a no-tillage practice. In Tables 3.5 to 3.7 there is a summary of all the activities involved in the trials over the three production years, namely from 2004 to 2006. Firstly, the planting time is shown, followed by the product being applied, as well as the quantity of input used and the application date. Finally there is a summary indicating when the grain was cut and combined. The treatment for this experiment, namely VRT and SR application of P, will be discussed under Section 3.5.2.

TABLE 3.5: ACTIVITIES FOR 2004 PLANTING SEASON

Planting dates	***Field and crop***	***Planting density***	
11 May 2004	L2 (wheat)	65 kg/ha	
11 May 2004	K3A (wheat)	65 kg/ha	
10 May 2004	K5 (canola)	4 kg/ha	
10 May 2004	K7A (canola)	4 kg/ha	
Field No	***Date***	***Product***	***Application/ha***
L2			
Spraying	18/6/2004	Bumper[1]	400 mℓ
		Dimethoate (Lice)[2]	500 mℓ
Top dressing	28/6/2004	N[5]	20 kg
Spraying	3/8/2004	Folicur[1]	750 mℓ
		Coptrel[4]	125 mℓ
K3A			
Spraying	24/6/2004	MCPA / Aurora[3]	25 g
		Dimethoate (Lice)[2]	500 mℓ
		Coptrel[4]	125 mℓ
Top dressing	29/6/2004	N[5]	21 kg
Spraying	30/6/2004	Bumper[1]	400 mℓ
		Dimethoate (Lice)[2]	500 mℓ
	3/8/2004	Folicur[1]	750 mℓ
K5			
Spraying	23/6/2004	Photrel [4]	1 kg
		Coptrel[4]	125 mℓ
		Metamidifos[7]	750 mℓ
Top dressing	26/7/2004	N[5]	21 kg
Spraying	27/7/2004	Bortrac[4]	1 litre
		Metamidifos[7]	750 mℓ
		Coptrel[4]	150 mℓ
K7A			
Spraying	17/6/2004	Gallant [3]	400 mℓ
Spraying	24/6/2004	Photrel[4]	1 kg
		Metamidifos[7]	750 mℓ
		Coptrel[4]	125 mℓ
Top dressing	26/7/2004	N[5]	21 kg
Spraying	27/7/2004	Metamidifos[7]	750 mℓ
		Bortrac[4]	1 litre
		Coptrel[4]	150 mℓ
Date		***Action***	
11 October 2004		Cut K7A	
12 October 2004		Cut K5	
3 November 2004		Combined L2	
2 November 2004		Combined K3A	
30 October 2004 until 1 November 2004		Combined K5	
30 October 2004		Combined K7A	

[1]Fungicide
[2]Pesticide
[3]Herbicide
[4]Plant nutrient
[5]Fertiliser
[6]Micro elements
[7]Insecticide

TABLE 3.6: ACTIVITIES FOR 2005 PLANTING SEASON

Planting dates	***Field and crop***	***Planting density***	
16 April 2005	L2 (canola)	3.51 kg/ha	
16 April 2005	K3A (canola)	3.51 kg/ha	
18 April 2005	K5 (wheat)	59 kg/ha	
18 April 2005	K7A (wheat)	59 kg/ha	
Field No	***Date***	***Product***	***Application/ha***
L2			
Spraying	26/5/2005	Gallant[3]	500 mℓ
		Dimethoate (Lice)[2]	500 mℓ
Spraying	10/6/2005	Bortrac[4]	1 litre
		Photrel[4]	1 litre
Top dressing	16/6/2005	N[5]	20 kg
Spraying	20/6/2005	Dimethoate (Lice)[2]	500 mℓ
		Supermetrien[2]	150 mℓ
Spraying	5/8/2005	Supermetrien[2]	150 mℓ
		Metamidifos[7]	500 mℓ
K3A			
Spraying	27/5/2005	Dimethoate (Lice)[2]	500 mℓ
		Co-pilot[1]	500 mℓ
Top dressing	6/6/2005	N[5]	20 kg
Spraying	20/6/2005	Bortrac[4]	1 litre
		Photrel[4]	1 litre
		Dimethoate (Lice)[2]	500 mℓ
		Supermetrien[2]	150 mℓ
Spraying	5/8/2005	Metamidifos[7]	500 mℓ
		Supermetrien[2]	150 mℓ
K5			
Spraying	30/5/2005	Dimethoate [2]	500 mℓ
		Coptrel[4]	1 litre
Top dressing	17/6/2005	N[5]	18 kg
Spraying	22/6/2005	Bumper[1]	500 mℓ
		Dimethoate[2]	500 mℓ
		Coptrel[4]	200 mℓ
Spraying	13/7/2005	Orius[1]	400 mℓ
		Dimethoate[2]	500 mℓ
		Boor[6]	1 litre
		Fulfaat[4]	1 litre
Spraying	19/8/2005	Bumper[1]	500 mℓ
		Fulfaat[4]	1 litre
K7A			
Spraying	30/5/2005	Dimethoate[2]	500 mℓ
Spraying	22/6/2005	Bumper[1]	500 mℓ
		Dimethoate[2]	500 mℓ
		Coptrel[4]	200 mℓ
Top dressing	17/6/2005	N[5]	17 kg
Spraying	14/7/2005	Orius[1]	400 mℓ
		Boor[6]	1 litre
		Fulfaat[4]	1 litre
Spraying	19/8/2005	Bumper[1]	500 mℓ
		Fulfaat[4]	1 litre

Date	Action
2 October 2005	Cut K7A
2 October 2005	Cut K5
4 October 2005	Cut L2 en K3A
17 October 2005	Combined K7A
14 October 2005	Combined K5
18 October 2005	Combined L2
15 October 2005	Combined K3A

[1]Fungicide
[2]Pesticide
[3]Herbicide
[4]Plant nutrient
[5]Fertiliser
[6]Micro elements
[7]Insecticide

TABLE 3.7: ACTIVITIES FOR THE 2006 PLANTING SEASON

Planting dates	***Field and crop***	***Planting density***	
10 May 2006	L2 (wheat)	62 kg/ha	
9 May 2006	K3A (wheat)	62 kg/ha	
8 May 2006	K5 (barley)	35 kg/ha	
8 May 2006	K7A (barley)	35 kg/ha	
Field No	***Date***	***Product***	***Application/ha***
L2			
Spraying	24/06/2006	MCPA / Aurora[3]	500 mℓ / 25 g
		Dimethoatehoate[7]	500 mℓ
Spraying	7/9/2006	Metamidifos[7]	750 mℓ
		Bumper[1]	400 mℓ
		Mn.Zn.Boor[6]	
Top dressing	7/09/2006	1:0:0 (40)[5]	6 kg N/ha
K3A			
Spraying	23/6/2006	MCPA / Aurora[3]	500 mℓ / 25 gm
		Dimethoatehoate[7]	500 mℓ
Spraying	8/9/2006	Metamidifos[7]	750 mℓ
		Bumper[1]	400 mℓ
		Zn.Mn.Boor[6]	
Top dressing	8/9/2006	1:0:0 (40)[5]	6 kg N/ha
K5			
Spraying	8/6/2006	Trigras[3]	1.1 litre
Spraying	29/6/2006	MCPA / Aurora[3]	500 mℓ / 25 gm
		Dimethoatehoate[7]	500 mℓ
Spraying	12/7/2006	Bumper[1]	300 mℓ
Spraying	17/8/2006	Capitan/Dimethoate[7]	300 mℓ / 500 mℓ
Spraying	13/9/2006	Bumper[1]	500 mℓ
K7A			
Spraying	20/6/2006	Trigras[3]	1.1 litre
Spraying	30/6/2006	MCPA / Aurora[3]	500 m ℓ/ 25 g
		Bumper[1]	300 mℓ
Spraying	17/8/2006	Capitan / Dimethoate[7]	300 mℓ / 500 mℓ
Spraying	13/9/2006	Bumper[1]	500 mℓ

Date	Action
20 October 2006	Cut K7A
21 October 2006	Cut K5
28 October 2006	Combined K7A
28 October 2006	Combined half of K5
11 October 2006	Combined other half of K5
28 November 2006	Combined K3A
21 November 2006	Combined L2

[1]Fungicide
[2]Pesticide
[3]Herbicide
[4]Plant nutrient
[5]Fertiliser
[6]Micro elements
[7]Insecticide

The planting dates identified for canola in 2004 and 2005 are in line with the information supplied in the Canola Manual of 2008. The Manual states that if there is sufficient soil moisture, canola may be sown as early as the middle of April up until the first week of June. It is also advantageous to sow barley before 15 May in the Ruens area, because this area is sometimes plagued by drought in the first half of September and this time usually corresponds with the barley's initial kernel filling phase. The strong south-easterly winds constitute another risk factor during September and October (AGR 343, 2004). The variable application of phosphorus will accordingly be discussed in the next section.

3.5.2 Variable phosphorus application

As this study focuses on the variable application of P, a comparison is given in Annexure C, Tables C1 to C4, regarding the various P levels for the different fields over the three experimental years. In year two (2005) and three (2006), representative soil samples were taken from the different management zones (Section 3.4.2) by using the coordinates of the first year (2004) as guideline. The soil samples were taken on a depth of 15 cm and analysed in a soil laboratory using the Psit method (citric acid). Some soil samples showed high levels of P (>100mg/kg) and the reason for this is that only 10-15 % of the applied P is accessible to the plant in the season when it is applied due to the immobile nature of P (Grego, 2001). Representative samples can be used to identify the accumulation of P.

As early as the 1800s, researchers learned that P promotes growth in plants and animals. Soils also need P and other nutrients. Deficiencies in the available P in soils are a major cause of limited crop production. P is one of the primary nutrients essential for plant growth and crop production (Florida Institute of Phosphate Research, 2004). According to AGR 343 (2004), P plays a crucial role in energy storage and transfer in cells in grains. Wheat plants that are deficient in P keep their green colouring, mature late and have less resistance to a number of diseases. It is, however, difficult to correct P deficiencies quickly and the strategy should be one of building up or maintaining reserves over several years. Barley has higher P requirements than wheat. PNS (2008) confirms that it is important to do soil analyses in order to determine P fertiliser levels for canola. The aim is to achieve levels of approximately 36 dpm P (citric acid) or 24 dpm P (Bray1).

The information summarised in Tables C1 to C4 (Annexure C) was used to compile the prescription maps for the variation of P. In Tables 3.8 to 3.15, the different prescription rates are summarised, as well as the applied rates of fertiliser and quantities of P that each field requires during all three experimental years. Some of these application maps can be seen in Annexure B (Figure B1 to B12) and the yield maps are included in Annexure F (Figure F1 to F11). The prescription rates are dependent on the results of the chemical analysis of the soil sampling. The prescription rates of L2 are summarised in Table 3.8 (VRT and SR).

TABLE 3.8: VARIABLE AND STANDARD PRESCRIPTION RATES (L2)

	*2004**	*2005**	*2006***
Variable rate	6 kg P per ha	8 kg P per ha	10 kg P per ha
	8 kg P per ha	8-10 kg P per ha	10-20 kg P per ha
	10 kg P per ha	10-12 kg P per ha	
	12 kg P per ha		
Standard rate	15 kg P per ha	8-10 kg P per ha	10 kg P per ha

*Prescription rates are only based on the chemical analysis of the soil samples and not on yield potential

**The large intervals were only used to place the legends into categories

Table 3.12 shows the application rates

Maxifos (20) was used in 2004, and in 2005 and 2006, Profos20 was used on all the fields. Table 3.8 shows that during 2004, 15 kg P per ha was prescribed for the SR treatment, and during 2005 and 2006 it ranged between 8-10 kg P per ha. The VRT treatment ranged from 6 kg P per ha in 2004 to a maximum of 20 kg P per ha in 2006. The next table (Table 3.9) shows the prescription rates of K3A (VRT and SR treatments).

TABLE 3.9: VARIABLE AND STANDARD PRESCRIPTION RATES (K3A)

	2004	*2005*	*2006**
Variable rate	8 kg P per ha	8 kg P per ha	10 kg P per ha
	12 kg P per ha	8-10 kg P per ha	10-20 kg P per ha
	16 kg P per ha	10-12 kg P per ha	20-30 kg P per ha
			30-40 kg P per ha
			40-60 kg P per ha
Standard rate	15 kg P per ha	8-10 kg P per ha	10 kg P per ha

*Prescription rates are only based on the chemical analysis of the soil samples and not on yield potential

**The large intervals were only used to place the legends into categories

In Table 3.13, the application rates are given.

Table 3.9 shows that the prescription rates for the SR treatment ranged from 8 to 15 kg P per ha, and for the VRT treatment the minimum was 8 kg P per ha and the maximum was 40-60 kg P per ha in 2006. The variable and standard prescription rates of K5 are summarised in Table 3.10.

TABLE 3.10: VARIABLE AND STANDARD PRESCRIPTION RATES (K5)

	2004	***2005***	***2006****
Variable rate	15 kg P per ha	8 kg P per ha	10 kg P per ha
	20 kg P per ha	8-10 kg P per ha	10-20 kg P per ha
	25 kg P per ha	10-12 kg P per ha	20-30 kg P per ha
	30 kg P per ha		30-40 kg P per ha
	35 kg P per ha		40-60 kg P per ha
Standard rate	20 kg P per ha	8-10 kg P per ha	10 kg P per ha

*Prescription rates are only based on the chemical analysis of the soil samples and not on yield potential

**The large intervals were only used to place the legends into categories

In Table 3.14, the application rates are given.

Table 3.10 shows that the prescription rates for 2005 and 2006 for K3A (Table 3.9) and K5 were the same, but there were differences in comparison with the 2004 prescription rates, namely the SR treatment of 15 kg P per ha (K3A) and 20 kg P per ha (K5), the VRT treatment for K3A had a maximum prescription of 16 kg P per ha and K5 had a maximum of 35 kg P per ha. The next table (Table 3.11) shows the VRT and SR prescription of K7A.

TABLE 3.11: VARIABLE AND STANDARD PRESCRIPTION RATES (K7A)

	2004	***2005***	***2006****
Variable rate	15 kg P per ha	8 kg P per ha	10 kg P per ha
	20 kg P per ha	8-10 kg P per ha	10-20 kg P per ha
	25 kg P per ha	10-12 kg P per ha	20-30 kg P per ha
	30 kg P per ha		30-40 kg P per ha
	35 kg P per ha		
Standard rate	20 kg P per ha	8-10 kg P per ha	10 kg P per ha

*Prescription rates are only based on the chemical analysis of the soil samples and not on yield potential

**The large intervals were only used to place the legends into categories

In Table 3.15, the application rates are given.

Table 3.11 shows that the prescription rates for 2004 are the same for K5 and K7A as both fields were planted with canola during that season. The SR treatments for 2005 and 2006 ranged from 8 to 10 kg P per ha and for the VRT treatments, a minimum of 8 kg P per ha was prescribed during 2005 and a maximum of 40 kg P per ha in 2006. The actual rates of fertiliser and P that were applied will now be summarised in Tables 3.12 to 3.15. The actual applied fertiliser and P rates of L2 can be seen in Table 3.12.

TABLE 3.12: VARIABLE AND STANDARD APPLICATION RATES (L2)

	2004	***2005***	***2006***
Variable rate	7 kg P per ha	8 kg P per ha	0 kg P per ha
	8 kg P per ha	10 kg P per ha	8,8 kg P per ha
	10 kg P per ha	12 kg P per ha	10,8 kg P per ha
	12 kg P per ha		15,4 kg P per ha
			20,8 kg P per ha
Standard rate	10 kg P per ha	10 kg P per ha	8,8 kg P per ha

The application rates for VRT varied from 7 to 12 kg P per ha during 2004 and from 8 kg P per ha to a maximum of 12 kg P per ha during 2005. The application rate for SR was 10 kg P per ha in 2004 and 2005. During 2006 it went down to 8,8 kg P per ha. The 2006 data show that 0 to 20,8 kg P per ha was applied (VRT). The 0 kg ranges represent the zones where the P levels were sufficient and no additional P was required. Table 3.13 shows the variable and standard application rates of fertiliser and P for K3A.

TABLE 3.13: VARIABLE AND STANDARD APPLICATION RATES (K3A)

	2004	*2005*	*2006*
Variable rate	0 kg P per ha	4,2 kg P per ha	3,8 kg P per ha
	9,4 kg P per ha	7 kg P per ha	9 kg P per ha
	13,6 kg P per ha	8,4 kg P per ha	14 kg P per ha
		9 kg P per ha	26,2 kg P per ha
		9,6 kg P per ha	
Standard rate	13,6 kg P per ha	9,6 kg P per ha	9 kg P per ha

The lowest application rate was 3,8 kg P per ha and the highest rate was 26,2 kg P per ha (VRT). These values were noted during the 2006 production season. The application rates during 2004 and 2005 fell within these ranges. The SR application rate was 13,6 kg P per ha (2004) versus 9,6 and 9 kg P per ha (2005 and 2006). See Table 3.14 for the actual applied fertiliser and P rates of K5.

TABLE 3.14: VARIABLE AND STANDARD APPLICATION RATES (K5)

	2004	*2005*	*2006*
Variable rate	20 kg P per ha	3 kg P per ha	1,8 kg P per ha
	25 kg P per ha	6,8 kg P per ha	8,2 kg P per ha
	30 kg P per ha	8,2 kg P per ha	18 kg P per ha
	35 kg P per ha	9 kg P per ha	33,2 kg P per ha
		9,6 kg P per ha	49 kg P per ha
Standard rate	30 kg P per ha	9,6 kg P per ha	8,2 kg P per ha

Table 3.14 shows that the VRT application rates during 2004 were in line with the prescription rates (Table 3.10). The maximum rates during 2005 and 2006 were 9,6 kg and 49 kg P per ha respectively. The 2004 SR rate was 30 kg P per ha with a decline in 2005 and 2006 to 9,6 and 8,2 kg P per ha respectively. Table 3.15 shows the application rates of K7A (VRT and SR).

TABLE 3.15: VARIABLE AND STANDARD APPLICATION RATES (K7A)

	2004	***2005***	***2006***
Variable rate	8,2 kg P per ha	5,2 kg P per ha	0 kg P per ha
	13,2 kg P per ha	6,4 kg P per ha	8,2 kg P per ha
	17,8 kg P per ha	8,4 kg P per ha	23,4 kg P per ha
	23,2 kg P per ha	9 kg P per ha	54,2 kg P per ha
	28,4 kg P per ha	9,6 kg P per ha	211,6 kg P per ha
Standard rate	17,8 kg P per ha	9,6 kg P per ha	8,2 kg P per ha

Table 3.15 shows that the VRT application rate during 2004 ranged from 8,2 to 28,4 kg P per ha. The VRT application rates during 2005 were lower than during 2004 with a maximum of 9,6 kg P per ha. The VRT application rates for 2006, however, showed a wide range of application from as little as 0 kg to a maximum of 211,6 kg P per ha. The SR application rates ranged from 8,2 kg to 17,8 kg P per ha over the three-year period.

It is important to note that the application rates shown in Tables 3.12 to 3.15 were the corrections made for the current crop, as well as the five-year lucerne grazing. The application rates applicable only to the crop in the production season constituted half of the total rates applied.

The various pH-levels for the different fields over the three years are listed in Annexure D under Tables D1 to D4. The values listed were obtained from the soil laboratory report. From Tables D1 to D4 one can derive that the aim to achieve homogeneous pH- levels for the four fields over the three-year trial period was not achieved. The main reason for this was that the farmer did not apply lime for the correction of the pH-levels.

The collecting of data, how the data were analysed, as well as model specification, will be covered in the next section.

3.6 DATA

3.6.1 Data collection and cleaning

The yield data were collected with a combine harvester fitted with a yield monitor that was referenced with regard to location. The yield was measured as points in space. The yield monitor was equipped with a GPS and the yield was indicated at a specific place (height, latitude and longitude). The yield was then recorded on a yield monitor card.

Some of the yield monitor's data are erroneous and this can be the result of rapid speed changes, extraneous vibration from crossing bumps in the field, not cutting a full header width, erroneous position information and a yield sensor that is not calibrated properly. When a combine crosses an area in a field that has already been combined, the yield monitor continues to record yield and this can result in a zero yield reading. Problem values are removed when the data are cleaned and this can improve the ability to explain yield variability. The removal of erroneous data can impact in two ways. The first impact is from a visual perspective where it has little impact upon the appearance of yield maps. The second impact is from an analytical perspective, where the removal of such data has a significant impact upon the ability to compare data (Kleinjan, Chang, Wilson, Humburg, Carlson, Clay & Long, 2004).

Kleinjan *et al.* (2004) reported that the actual cleaning of the data is a multi-level process of which all the phases are listed below. The first phase is easy to identify, because it occurs when the combine header is up and data are still entering the machine. The aforementioned data are of little value. The second phase occurs when the speed starts to change rapidly. This depends on a decision to be taken that when the velocity change is GREATER THAN 15 %, the data will be excluded. The yield flow is taken into account during the third phase. When the yield monitor is calibrated, both high and low flow rates are taken into account, but it should be kept in mind that these do not necessarily correspond with high and low yield.

For this study the protocol of Griffin, Brown and Lowenberg-DeBoer (2005) was followed in general, although with some differences. The information on the calibration of equipment was unavailable, so the criteria for removing observations from the data set were mainly based on the distributional assumption of normality. The data needed to comply with the assumption of normality for parametric statistical tests to be valid.

In some years, the nature of yield distribution for specific fields was such that only positive high values needed to be removed, because departure from normality in these cases concerned only the very long upper tails (positive skew), and symmetry in the distributions could be achieved (resolving concerns regarding the distribution) without the need to remove any of the observations in the lower tails of the distribution. This fact explains why some criteria only have an upper limit and no lower limit, while in other cases criteria include both an upper and a lower limit (Table 3.16). The fourth and last phase involves the calculating of average and standard deviations of the yield data. Yields exceeding ± 3 standard deviations were removed (the interval from $\mu - 3\sigma$ to $\mu + 3\sigma$ includes more than 99 % of observations).

SAS software was used to edit, filter and clean the data, which were then tested by using Yield Editor Software. According to Griffin, Brown and Lowenberg-DeBoer (2007) better farm management decisions can be made if data is clean with Yield Editor as this is used to remove erroneous data thus filter the raw yield monitor data. Erroneous observations were identified and removed by looking at yield flow and the standard deviation (SD) (Annexure E, Tables E1 to E12 show the normality distribution of yield and SD). The measures used for these variables are presented in Table 3.16. Only yield flow and yield are presented as data-filtering factors.

TABLE 3.16: DATA-FILTERING FACTORS AND CRITERIA

Field	Factor	2004	2005	2006
		Wheat	Canola	Wheat
K3A	Yield Flow (ton/hour)	>10	>40	>60
	Yield (ton/ha)	>3,50	<1,00 & >5,00	>10,00
L2	Yield Flow (ton/hour)	<2 & >8	<2 &>20	
	Yield (ton/ha)	>2,50	>5,00	
		Canola	Wheat	Barley
K5	Yield Flow (ton/hour)	>8	>50	>40
	Yield (ton/ha)	<0,25 & >2,50	<2,50 & >9,00	>10,00
K7A	Yield Flow (ton/hour)	<3 & >40	<3 & >40	<2 & >40
	Yield (ton/ha)	>2,50	<2,00 & >9,00	<1,00 & >5,00

SSToolbox software was used to process the collected spatial yield data into maps to reflect the variations that exist in the harvested yield (Annexure F).

3.6.2 Data analysis

SSToolbox software was used to assemble all the data together (yield monitor data, soil and application data). Dummy variables which represent the two treatments were allocated to the yield and P application data in Excel before assimilating the data in SSToolbox. As the field was divided into two parts, a 10 m strip of data in the middle of the field where the windrows passed from the VRT to the SR application of the treatments was set aside. The purpose for this action was to neutralise the data where the grain of the two sides could mix. The collected data were analysed in three phases by means of exploratory, statistical and profitability analysis methods. Exploratory data analysis draws on graphical techniques to maximise insight into a data set. The underlying structure is uncovered, important variables are extracted, outliers are detected and underlying assumptions regarding anomalies are tested. These graphical visualisations make it possible to gain insight into the characteristics of the data before conducting any complex and detailed analysis (Maine, 2006). In Chapter 4, a detailed discussion of this method and the results obtained are presented. In this study, spatial econometrics is concerned with estimating the relationship between variables that have spatial structure, such as soil nutrient P and soil type. The data collected are then used to calculate outcomes of economic interest such as yields, profits and costs. Maine (2006) stated that these outcomes are an important tool in management decision-making particularly with regard to the implementation of VRT application to manage variability. The statistical and profitability analyses are presented in Chapter 5.

When analysing PA data, spatial auto-correlation and spatial heterogeneity must be taken into consideration. A short description of these two spatial effects is given in Chapter 2. The next section in this chapter will focus on model specification.

3.6.3 Model specification

The experimental design entails four fields divided into half, with one half subjected to the VRT application of P and the other half subjected to the SR application of P. Equation 1 below is used for analysis to determine the profitability of the VRT application of P as a total package, and the SR and VRT (TRT) of each soil type is taken into account. The same model was used for each field for each production year. Soil type Gs1 was used as Q base for each field (K3A, K5 and K7A) except for L2 where Gs2 was used as Q base. The "Constant" represents the base soil and base treatment (SR) in kilograms (kg) for yield and rand per ha (ZAR/ha) for profit. Soil maps of the four fields are shown in Figures 3.2 to 3.5. The data for each experimental year were analysed separately and the years were not combined into one regression. The following Baseline Model was used in the estimation:

Baseline Model – The regression model to test the technology as a package:

$$Y = \alpha_0 + \alpha_1 TRT + \alpha_2 S_1 + \alpha_3 S_2 + \alpha_4 S_3 + \alpha_5 S_4 + \alpha_6 S_5 + \alpha_7 S_6 + \alpha_8 S_7 + \alpha_9 S_8 + \alpha_{10} S_9 + \alpha_{11} S_{10} + \alpha_{12} S_{11} + \alpha_{13} S_{12} + \alpha_{14} S_{13} + \alpha_{15} S_{14} + \alpha_{16} TRT(S_1) + \alpha_{17} TRT(S_2) + \alpha_{18} TRT(S_3) + \alpha_{19} TRT(S_4) + \alpha_{20} TRT(S_5) + \alpha_{21} TRT(S_6) + \alpha_{22} TRT(S_7) + \alpha_{23} TRT(S_8) + \alpha_{24} TRT(S_9) + \alpha_{25} TRT(S_{10}) + \alpha_{26} TRT(S_{11}) + \alpha_{27} TRT(S_{12}) + \alpha_{28} TRT(S_{13}) + \alpha_{29} TRT(S_{14}) + \lambda \quad (1)$$

Constraint: $\Sigma\alpha S_i = 0$

$\alpha_1 TRT$ =	1 if variable-rate, or 0 otherwise
$\alpha_2 S_1$ =	Soil type 1 (Gs1)
$\alpha_3 S_2$ =	Soil type 2 (Gs2)
$\alpha_4 S_3$ =	Soil type 3 (Gs3)
$\alpha_5 S_4$ =	Soil type 4 (Gs4)
$\alpha_6 S_5$ =	Soil type 5 (Gs5)
$\alpha_7 S_6$ =	Soil type 6 (Gs6)
$\alpha_8 S_7$ =	Soil type 7 (Gs7)
$\alpha_9 S_8$ =	Soil type 8 (Gm)
$\alpha_{10} S_9$ =	Soil type 9 (Sw1)
$\alpha_{11} S_{10}$ =	Soil type 10 (Sw2)
$\alpha_{12} S_{11}$ =	Soil type 11 (Cf)
$\alpha_{13} S_{12}$ =	Soil type 12 (Cg)
$\alpha_{14} S_{13}$ =	Soil type 13 (Et)
$\alpha_{15} S_{14}$ =	Soil type 14 (Oa)
ג =	Coefficient for spatial adjustment

In the model, yield was estimated as a function of the soil type, the applied P (TRT) and the spatial error. The limitations of using on-farm trials as experimental technique will be discussed in the following section.

3.7 LIMITATIONS

On-farm trials are a very important tool for research and are used to evaluate and validate farming technology under local farming conditions. However, the researchers' intentions can sometimes be in conflict with the farmers' objectives as the farmers' interest normally lies in improving management decisions which can possibly increase profits and reduce risks. Management can be adjusted along the way to ensure that the farmer achieves his objectives.

According to Maine (2006), the results obtained from on-farm trials are not statistically valid from the perspective of classical agronomic research. The variability in field soils and essential farming activities results in the best on-station technology, but it rarely performs at the same level under actual farming conditions. The results obtained from on-farm trials can, however, be useful when the spatial auto-correlation present in the data is modelled correctly.

For any experimental design, internal validity is essential. Variables have to be controlled to maximise the internal validity of the experimental study. In field trials that represent traditional crop production, full control of variables such as weather conditions and market situations is impossible. The uncontrollable variables can affect machinery and equipment availability, which in turn, can affect crop cultivation practices and yield. To maximise internal validity, measures can be taken to make sure that only variables of interest are allowed to vary (Maine, 2006).

3.8 CONCLUSIONS

In this study, grain (wheat, canola and barley) crop production was replicated, as it is done on a real farm in order to provide an analysis obtained under the conditions under which farmers operate. The design and the experimental procedures and techniques followed, allowed investigation into the effects that VRT and SR application strategy of P have on yield, without causing major disruption to normal farming activities. It is possible for individual farmers to conduct such trials on their farms, but concerns regarding the issue of validity must be kept in mind. The agricultural industry is subject to uncontrollable factors such as erratic weather conditions and other external factors which could make it impossible to draw valid conclusions from the data collected.

The responses of yield to VRT and SR application strategies of inputs will vary from farm to farm and even from field to field. The conclusion can only be made for the field or farm being studied, as no generalisations are possible. The results of this research are discussed in Chapters 4 (exploratory and descriptive statistics) and 5 (statistical and profitability analysis). These results only reflect the situation of the specified fields. No generalisations can be made with regard to the entire farm. However, this does not imply that the experimental design used is unreliable.

In order to profit most from the data generated, the best analysis techniques must be selected. Due to the spatial structure present in the data, spatial econometrics had to be used to account for both spatial auto-correlation and spatial heterogeneity.

CHAPTER FOUR

EXPLORATORY AND DESCRIPTIVE STATISTICS

4.1 INTRODUCTION

This chapter is divided into two sections. First the exploratory data analysis (EDA) for the three experimental years (2004 – 2006) is presented and this is followed by a descriptive statistical analysis (DSA) of the data. The EDA employs pie charts and histograms to evaluate the distribution of variables across the field. The DSA includes the mean, minimum, maximum and standard deviation of yield and soil characteristics such as the soil type. This chapter concludes with a short summary of the findings of the aforementioned data analyses.

4.2 EXPLORATORY DATA ANALYSIS (EDA)

EDA is an approach to data analysis in which a variety of techniques can be used (mostly graphical) to maximise insight into a data set, to uncover patterns in the data, to uncover the underlying structure of the data, to extract important variables, to detect outliers and, finally, to test the underlying assumptions regarding anomalies (Engineering Statistics Handbook, 2004). Geo-referenced soil and crop parameters (yield) are the basic data for mapping the variability of yield and soil fertility and for optimising fertiliser application. EDA proved to be essential for the aforementioned operations. The basic data analysis carried out in this chapter entails graphical visualisation of the soil type, yield and phosphorus (P) variables. This provides insight into the characteristics of the data before any complex and detailed analysis is conducted. The Microsoft Excel statistical package was also used for creating the pie charts and the histograms.

4.2.1 Distribution graphs

Data were analysed and summarised in pie charts and histograms in order to indicate the distributions across the fields. Pie charts were used to display the distribution of soil types for each field, while yield and P variables were summarised in histograms.

In the yield histograms, the observations on the x-axis represented the treatment and were grouped in variable (VRT) and standard (SR) treatments, while the mean yield was indicated on the y-axis. These operations were performed for each of the four fields for the three production years, as well as for combinations of fields planted with the same crop in each year. Histograms provide an easy-to-read picture of the location and variation in a data set. Maine (2006) reported that there are also limitations associated with histograms that should be borne in mind. Histograms can be manipulated to show different pictures by changing the number of categories to suit the objective. The histogram can be misleading when too few or too many intervals are used. For this study, the intervals were determined after experimentation and the end result represents the true picture.

4.2.1.1 Soil type

Figures 4.1 to 4.4 show the percentage distribution of soil types for the four fields, namely L2, K3A, K5 and K7A. The different symbols at the bottom of each of the figures represent the different soil types which are Glenrosa (Gs1 to Gs7), Cartref (Cf), Etosha (Et), Gamoep (Gm), Coega (Cg), Oakleaf (Oa) and Swartland (Sw1 to Sw2). A full description of the different soil types as well as soil maps can be found in Chapter 3, Section 3.3.1.3. The Glenrosa soil type was dominant for fields L2, Gs3 and Gs7. Gs3 and Gs7 had the highest percentage cover, namely 25% and 24 % respectively (Figure 4.1). The Gamoep and Glenrosa (Gs1 and Gs2) soil types were the dominant soil types for field K3A (Figure 4.2). In fields K5 and K7A, the Glenrosa soil type (Gs1) represented more than 50 % of the soil types, namely 56% as shown in Figure 4.3 and 50 % as shown in Figure 4.4. Figure 4.1 shows the percentage distribution of the different soil types in field L2.

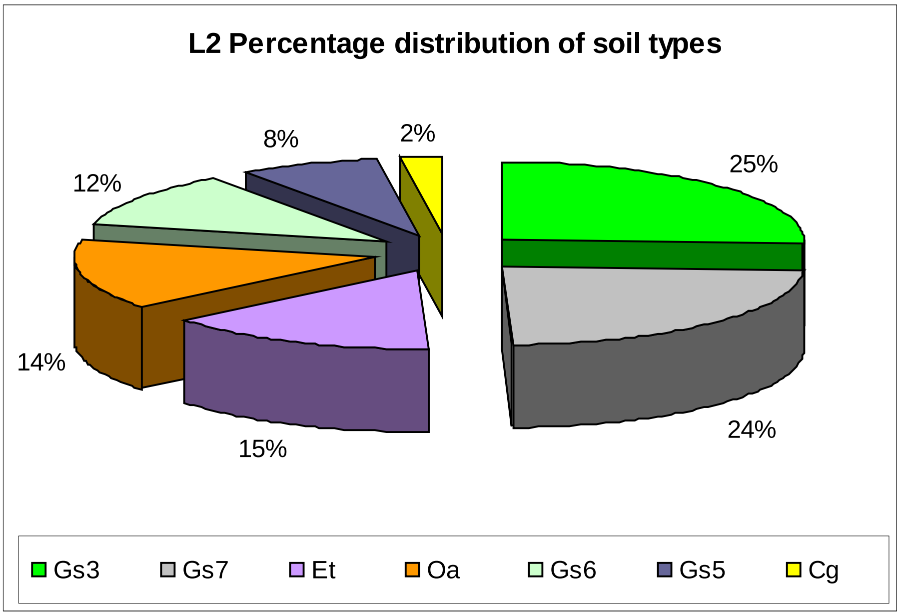


Figure 4.1: Percentage distribution of the soil types L2

Figure 4.1 shows that the two main soil types in L2 were Gs3 (25 %) and Gs7 (24 %). The Cg soil type (yellow) had the smallest distribution (only 2 %). The percentage distribution of the soil types in field K3A is displayed in Figure 4.2.

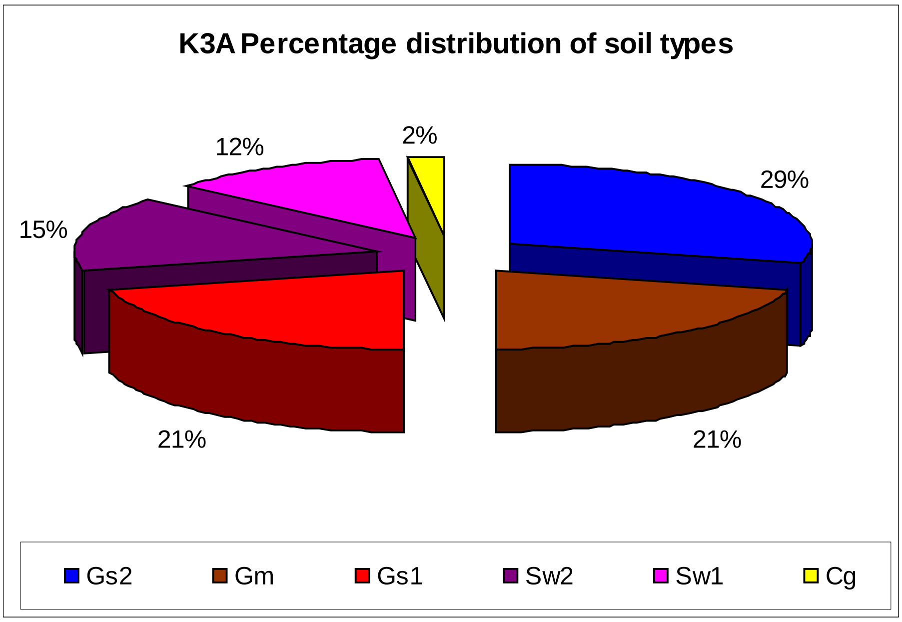


Figure 4.2: Percentage distribution of the soil types K3A

Soil type Gs2 represented 29 % of field K3A (Figure 4.2), with equal distribution of 21 % for soil types Gm and Gs1, followed by Sw2 (15 %), Sw1 (12 %) and Cg with 2 %. Figure 4.3 shows the percentage distribution of the different soil types in field K5.

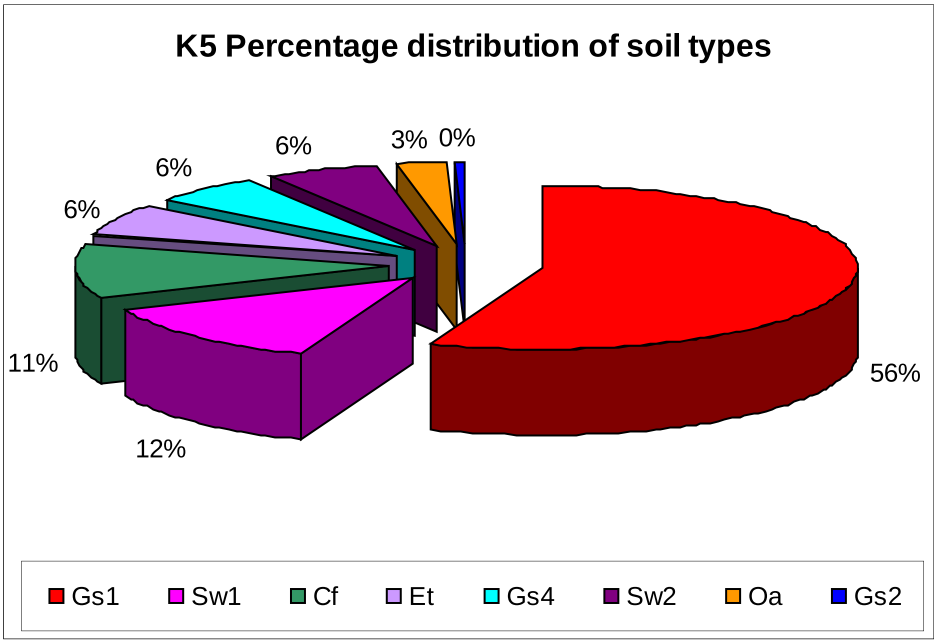


Figure 4.3: Percentage distribution of soil types K5

In field K5, more than half of the area was represented by soil type Gs1 (56 %). The other soil types found in K5 were Sw1 (12 %) and Cf (11 %), as well as Et, Gs4 and Sw2 (each 6 %) and with Oa representing 3 %. Nearly the same pattern as found in field K5 can be seen in Figure 4.4 which shows the percentage distribution of the different soil types in field K7A.

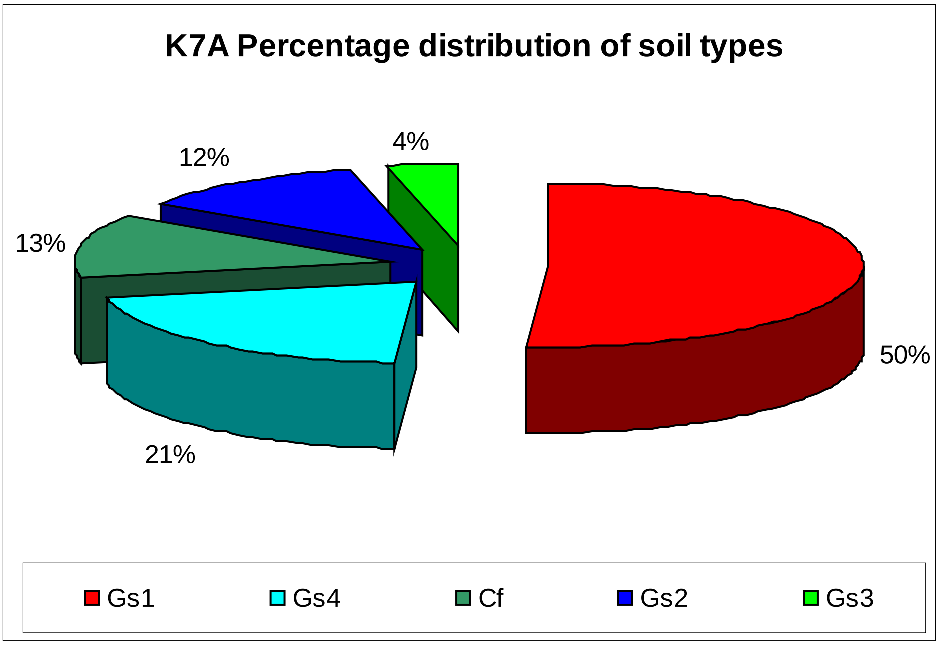


Figure 4.4: Percentage distribution of the soil types K7A

Figure 4.4 shows that soil type Gs1 was found in 50 % of the area of field K7A, which was nearly the same situation applicable in field K5, where Gs1 was found in 56 % of the area. The rest of the distribution for field K7A was as follows: Gs4 (21 %), Cf (13 %), Gs2 (12 %) and Gs3 (4 %). In the next section, the distribution of the statistical mean yield will be discussed.

4.2.1.2 Yield distribution

The statistical mean yield was calculated for each of the four fields during each of the three production years. It is presented in Figures 4.5 to 4.10. The mean yield realised with the two treatments (VRT and SR) is summarised in Table G1 (Annexure G). The data are presented for each year, each field and different soil types. The bold values indicate where the mean yield realised with the VRT treatment was higher than the mean yield realised with the SR treatment. Figure 4.5 shows the yield realised in 2004. The data collected from each field are shown, as well as the difference between the values realised when VRT and SR were used.

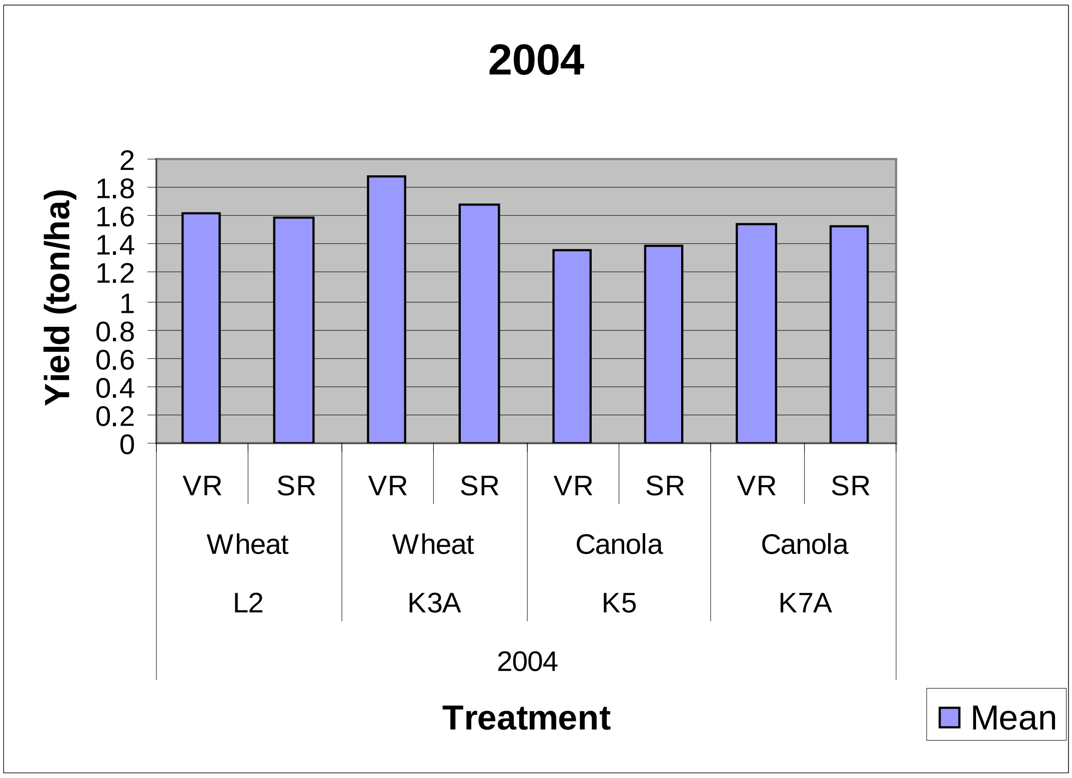


Figure 4.5: Yield for 2004 production year

The yields realised by applying VRT and SR treatments were very similar for L2, K5 and K7A, although where the VRT treatment was used in field K7A, the yield was slightly higher. K3A was the exception, because in this field the VRT treatment led to a higher yield than was realised with the SR treatment. Figure 4.6 shows the yields realised with a combination of L2 and K3A (wheat) and of K5 and K7A (canola) respectively.

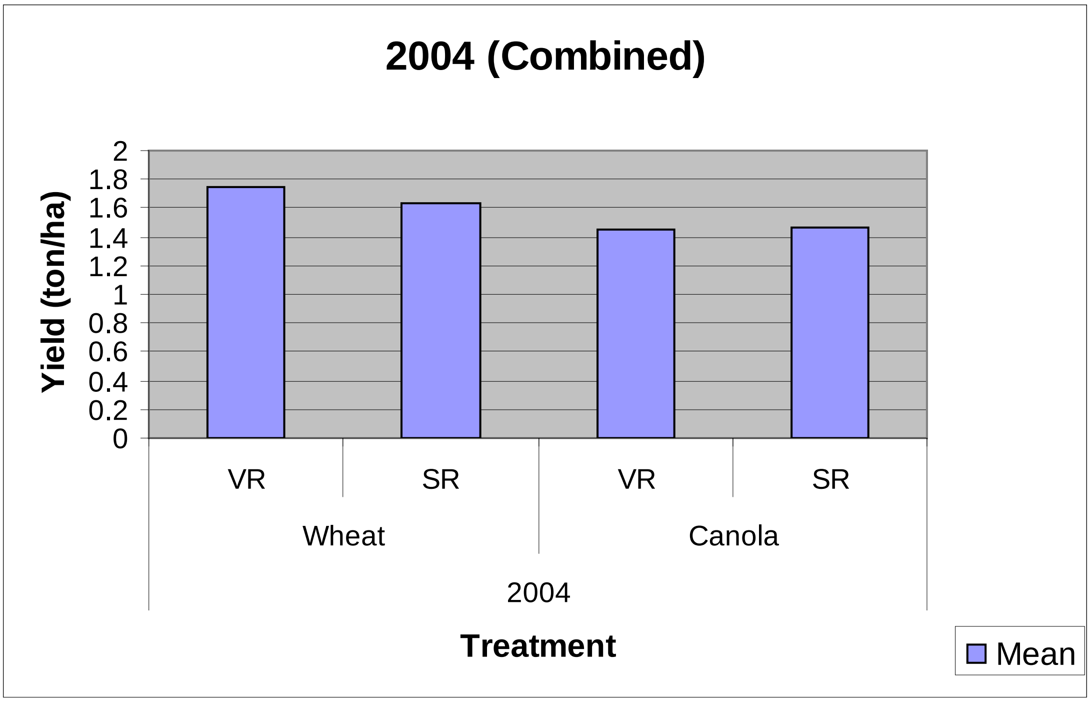


Figure 4.6: Yield for 2004 production year (combined in the case of fields planted with the same crops)

When the two fields L2 and K3A were combined for the wheat planting, a slightly higher yield was realised by means of the VRT treatment in comparison with the SR treatment. In the case of the combined canola planting in fields K5 and K7A, the yields realised with the VRT and SR treatments were very similar, although the SR treatment realised a slightly higher yield. The VRT treatment applied to wheat realised a yield of 1.7 ton/ha in comparison with the SR treatment which realised a yield of just over 1.6 ton/ha. In the case of canola, a yield of 1.4 ton/ha was realised with both the VRT and SR treatments. In 2004, the rainfall season started in May, with the highest rainfall measured during October (91 mm) and with a total annual rainfall of 271,75 mm (Figure 3.1). The yields realised in the four fields in 2005 are displayed in Figure 4.7.

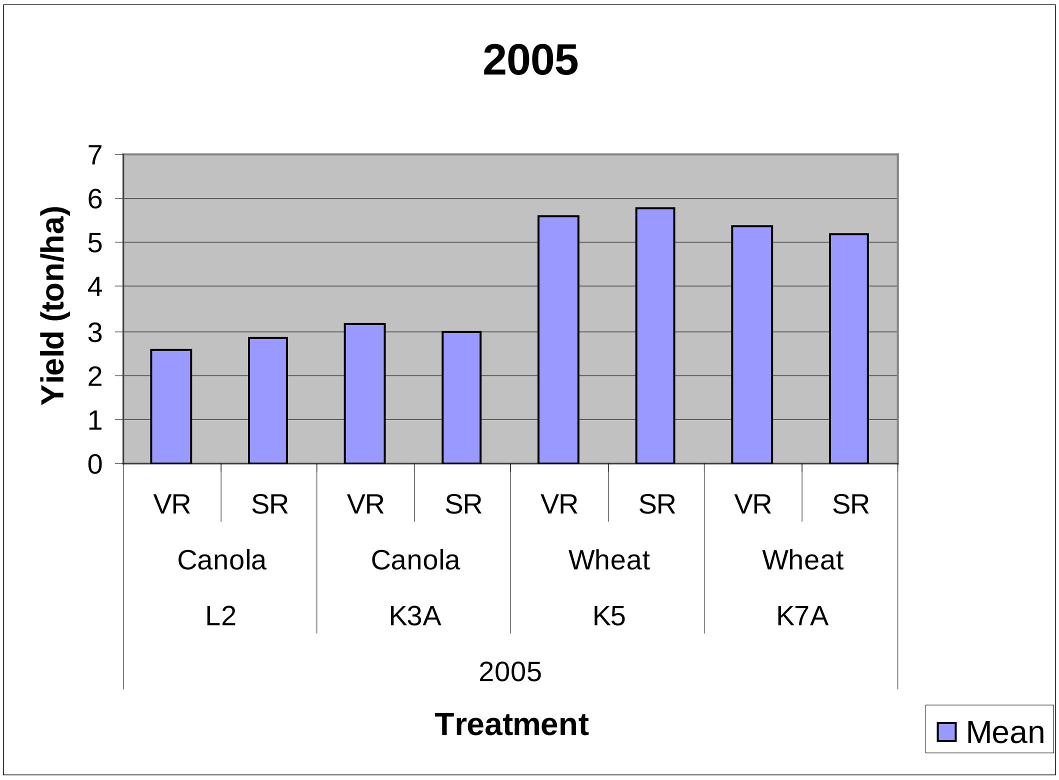


Figure 4.7: Yield for 2005 production year

Figure 4.7 shows that for L2 (canola) and K5 (wheat) the yields realised with the SR treatment were higher than those realised with the VRT treatment. In fields K3A (canola) and K7A (wheat) the opposite was true and the VRT treatment realised higher yields than the SR treatment. Figure 4.8 shows the combined yield results for the fields that carried the same crops.

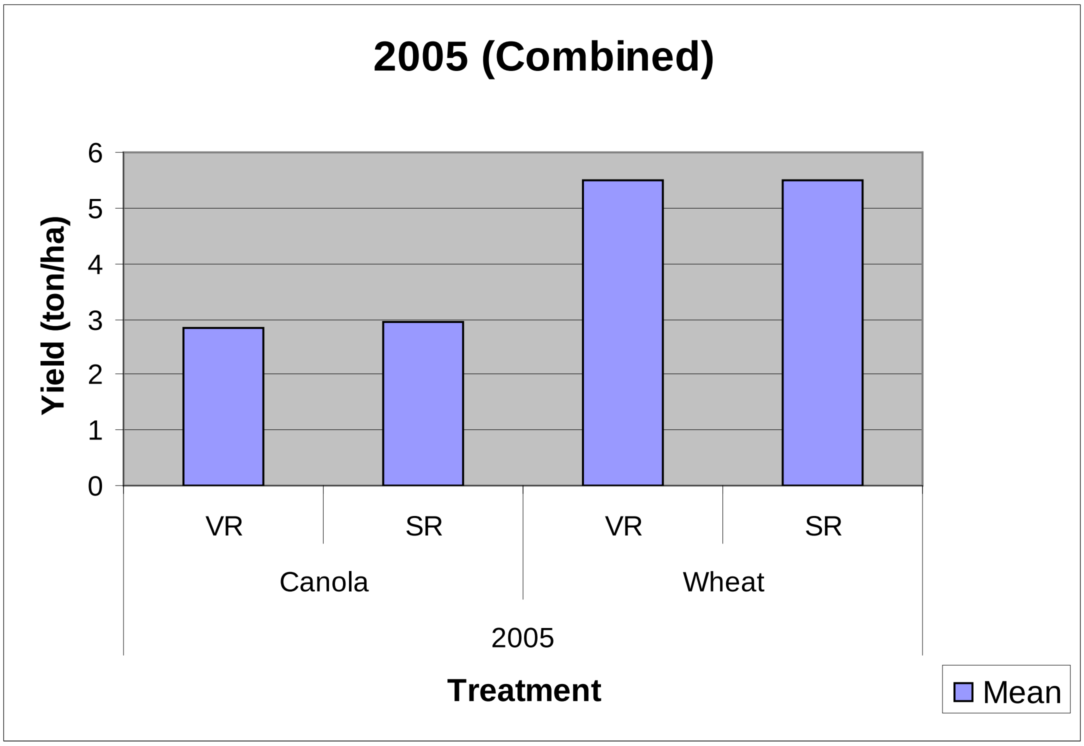


Figure 4.8: Yield for 2005 production year (combined in the case of fields planted with the same crops)

The combined results for 2005 showed that the VRT and SR treatment realised small differences between the yields. In the wheat fields (K5 and K7A), the realised yields with the VRT treatment were slightly higher than with the SR treatment. The opposite was true with regard to the canola fields (L2 and K3A), where the SR treatment realised slightly higher yields than the VRT treatment. Figure 4.8 shows the combined results of 2005. The VRT treatment of wheat realised a yield of 5,49 ton/ha (3,7 ton/ha higher than in 2004), and the SR treatment realised a yield of 5,5 ton/ha (3,9 ton/ha higher than in 2004). The canola yield with the VRT and SR treatments was 1,44 ton/ha higher than those realised in 2004, namely 2,9 ton/ha. The total annual rainfall for 2005 was 313,75 mm, with the highest rainfall recorded in March, namely 40 mm (Figure 3.1). Figure 4.9 summarises the yield results of 2006.

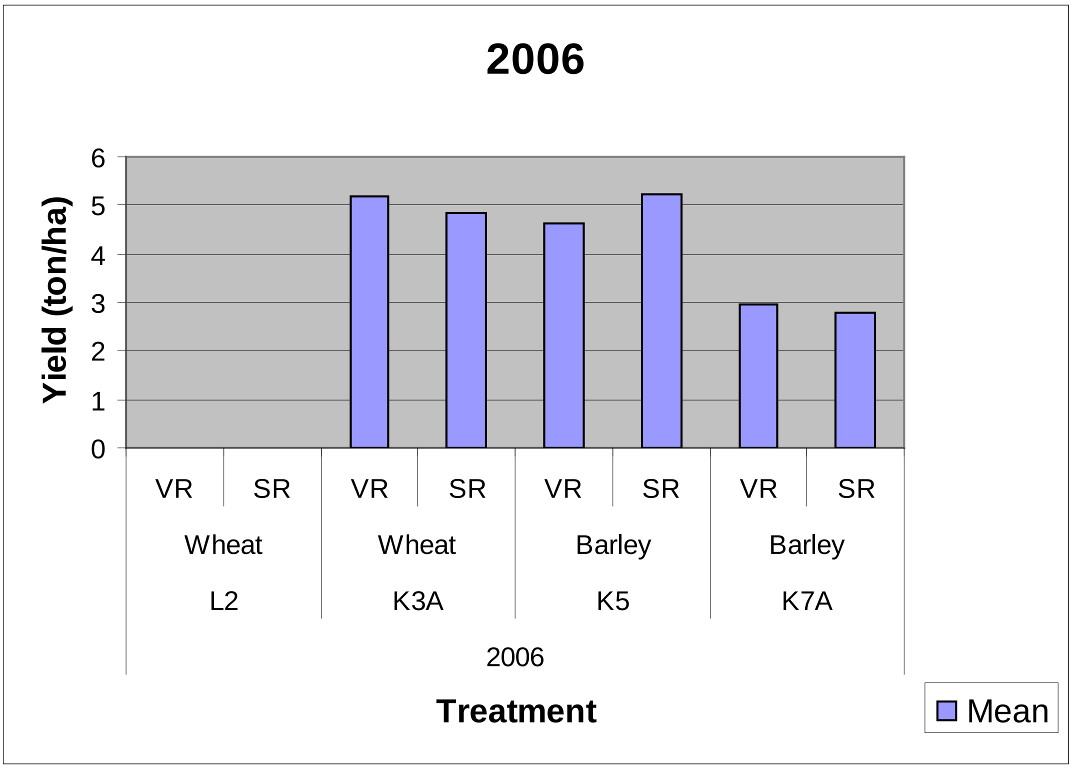


Figure 4.9: Yield for 2006 production year

The data collected in field L2 were corrupted (due to a faulty cable, the data were partially lost) and could not be used, but the yields realised in the other three fields are nevertheless represented. The pattern identified during the 2004 and 2005 production seasons showed that there were only slight differences between the yields realised with the VRT and SR treatments (Figure 4.5 to 4.8). However, in 2006 the pattern changed and a higher yield was realised with the VRT treatment than with the SR treatment on soils in fields K3A and K7A. On K5, a higher yield was realised with the SR treatment than with the VRT treatment. The combined results of the above-mentioned are presented in Figure 4.10.

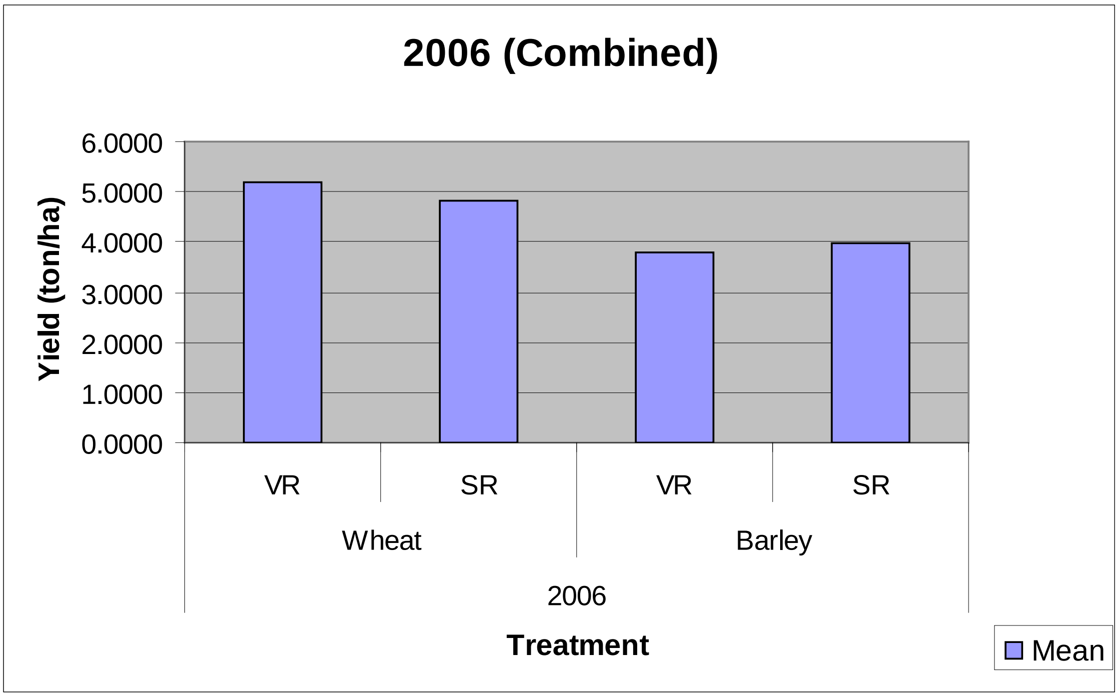


Figure 4.10: Yield for 2006 production year (combined in the case of fields planted with the same crops)

The combination of yields in fields with the same crops, showed very much the same results in the 2004 and 2005 seasons. The VRT (t/ha) treatment of wheat realised a higher yield than the SR (t/ha) treatment. The SR (t/ha) treatment of barley realised a higher yield than the VRT (t/ha) treatment.

During the 2006 production year, barley was introduced in the crop rotation system for the first time. Wheat (only the data of K3A were used because the data of L2 were corrupt) and barley realised the following combined yields: VRT wheat realised 5,2 ton/ha, while the SR treatment realised 4,8 ton/ha. The yield of barley with the VRT treatment was 3,8 ton/ha, while the SR treatment realised a yield of 4,0 ton/ha. The seasonal rainfall started in January, with a total annual rainfall of 459,50 mm and the highest rainfall recorded during August, namely 40 mm. Although a higher rainfall was recorded in 2006, the yields realised with the VRT and SR treatments of wheat were lower than in 2005 (5,5 ton/ha versus just over 5,1 ton/ha, and 5,5 ton/ha versus just under 5,0 ton/ha). The climatic conditions and especially the time when the highest rainfall was recorded (March 2005 versus August 2006) appeared to have had a bigger impact on the yields realised than the different treatments.

In Section 4.2.1.1, the focus was on the distribution of soil types over the four fields. In Section 4.2.1.2, the distribution of yield in the four fields was described. In the next section these concepts will be brought together by focussing on the statistical mean yield versus soil type.

4.2.1.3 Yield versus soil type

In Figures 4.11 to 4.21, a summary of yield versus soil type for each of the four fields (L2, K3A, K5 and K7A) during the three production years (2004 to 2006) is represented. Figure 4.11 illustrates the yield versus the soil type in L2 during 2004 (wheat).

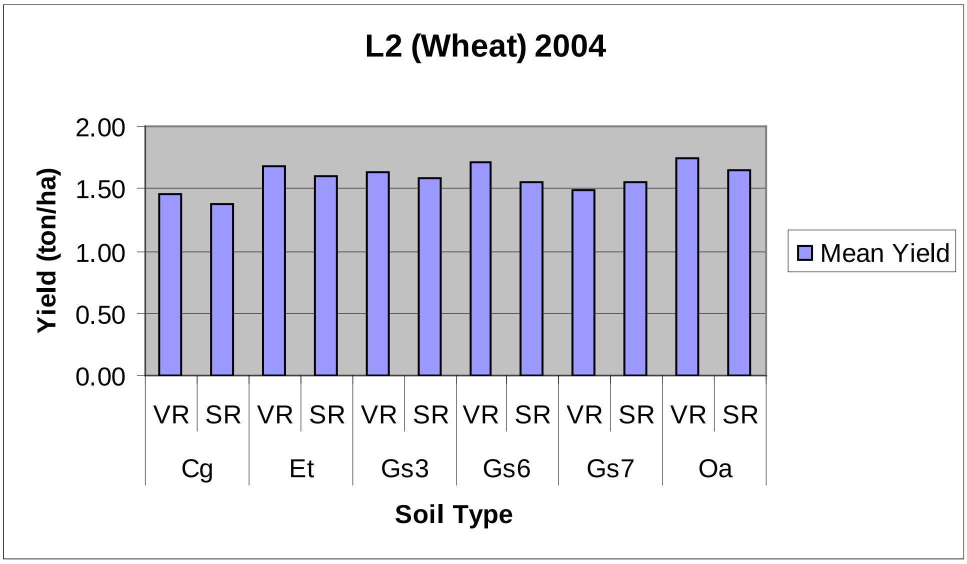


Figure 4.11: Yield *versus* soil type (L2 - 2004)

Five soil types realised yields of well over 1,5 ton/ha, but the highest yield was realised in the Oa soil type, with the VRT treatment performing better than the SR treatment.

During 2005, L2 was planted with canola and Figure 4.12 shows the yield versus the soil type for canola.

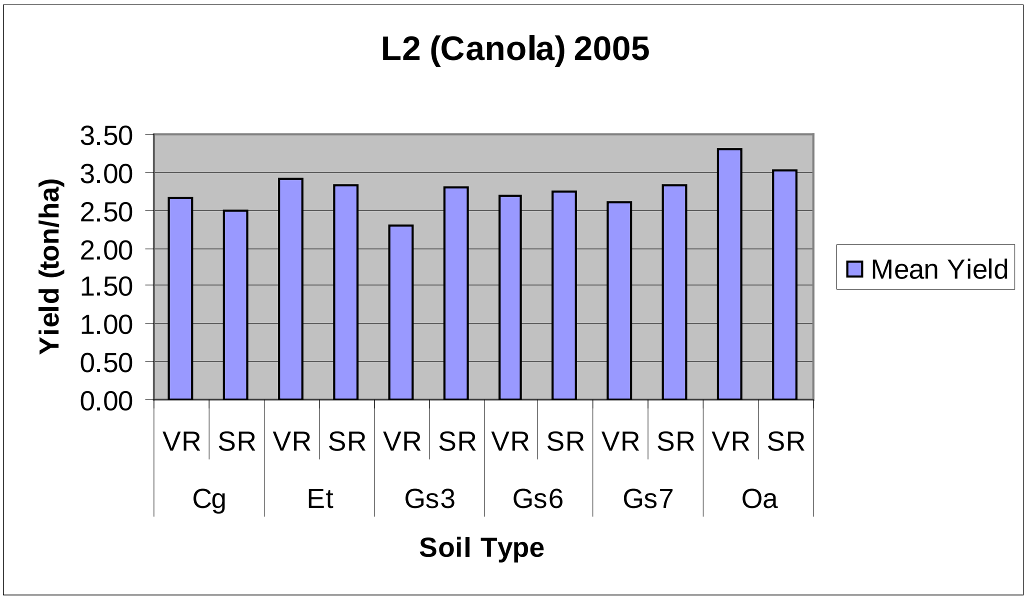


Figure 4.12: Yield *versus* soil type (L2 - 2005)

The yields of canola were higher than those of wheat and for three (Cg, Et and Oa) of the six soil types, the VRT treatment realised higher yields than the SR treatment. In the Glenrosa soil types (Gs3, Gs6 and Gs7) the opposite was true, because the SR treatment realised higher yields than the VRT treatment. The data for 2006 were corrupted and therefore no figure was available for canola planted in 2006. Soil type Oa realised the highest yields with the VRT treatment during 2004 and 2005. The next field that will be discussed is K3A. In Figure 4.13 the wheat yield and soil types during the 2004 production year on K3A are given.

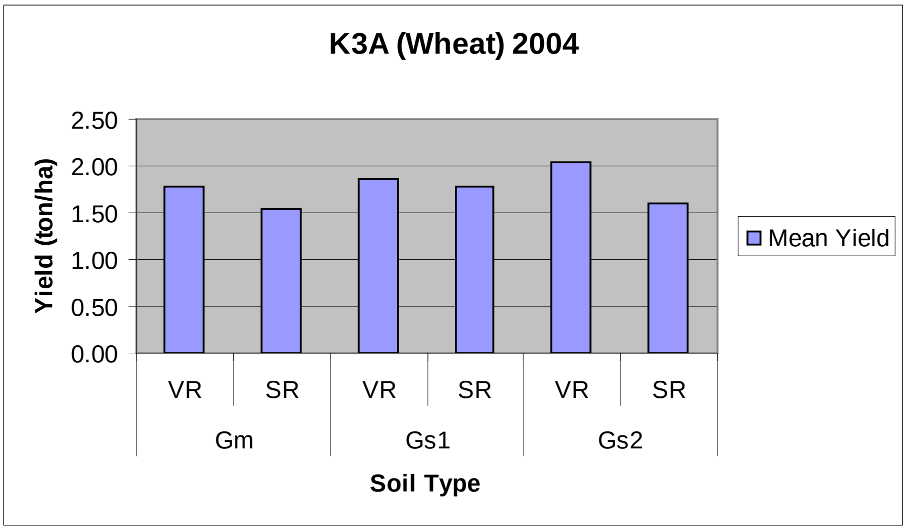


Figure 4.13: Yield *versus* soil type (K3A - 2004)

In all three soil types, the realised yield with the VRT treatment was higher than the realised yield with the SR treatment. The highest yield of just over 2 ton/ha was realised with the VRT treatment of the Gs2 soil type. Figure 4.14 gives a summary of the yields and soil types during the 2005 production year on K3A.

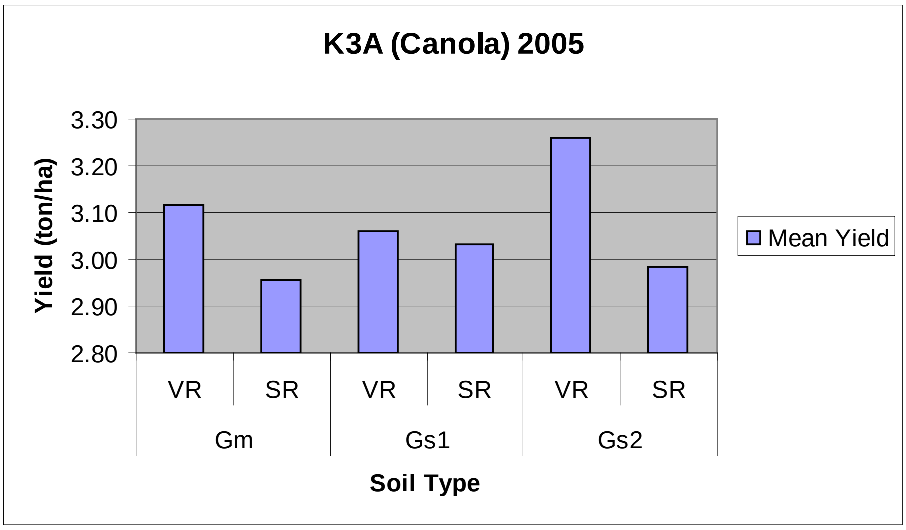


Figure 4.14: Yield *versus* soil type (K3A - 2005)

The results for 2005 showed much higher differences between the yields with the VRT and SR treatments. The VRT treatment realised higher yields than the SR treatment in all three soil types, with the Gs2 soil type performing the best (3,26 ton/ha versus 2,98 ton/ha). The 2006 results (yield and soil type) are presented in Figure 4.15.

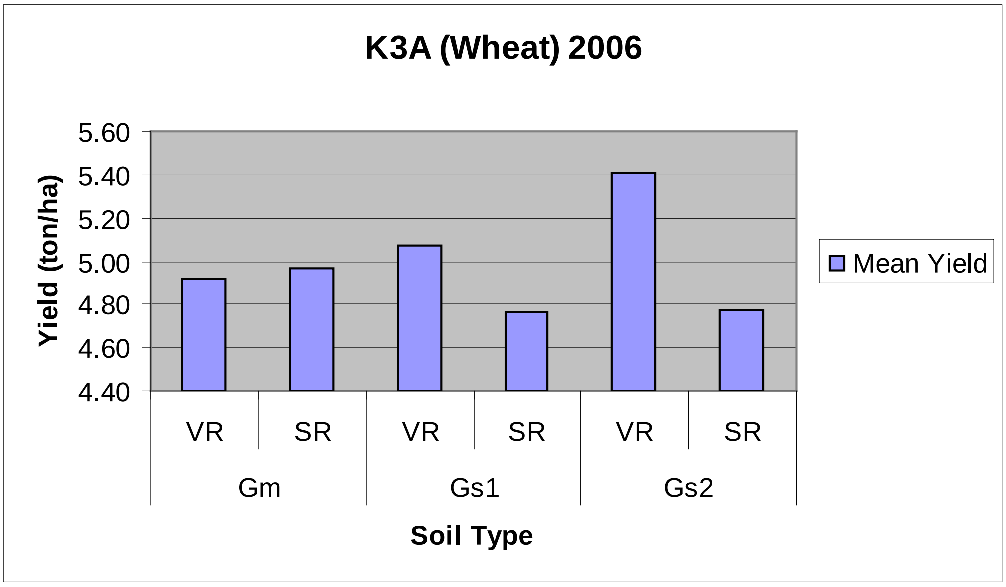


Figure 4.15: Yield *versus* soil type (K3A - 2006)

When comparing the realised yields for 2004 and 2006 (Figure 4.15), it is clear that during 2006 the realised yields were higher than during 2004, although wheat was planted in both years. The 2004 production year realised a maximum yield of 2,5 ton/ha in comparison with 2006 when the maximum yield was 5,6 ton/ha. It is also evident that there were much clearer differences between the VRT and SR treatments. In the Gs2 soil types, the highest differences between VRT and SR were realised, with VRT realising much higher yields than SR (5,4 versus 4,8 ton/ha). The 2004 results realised in K5 (yield and soil type) are presented in Figure 4.16.

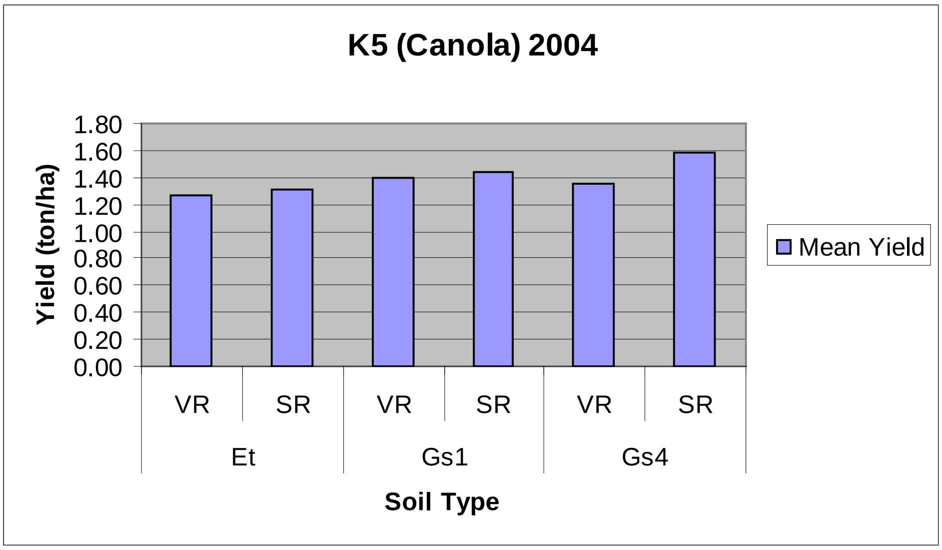


Figure 4.16: Yield *versus* soil type (K5 - 2004)

In the three soil types (Et, Gs1 and Gs4) higher yields were realised with the SR treatment. During 2005, these patterns changed with the VRT treatment realising higher yields in the Et soil type than the SR treatment (Figure 4.17).

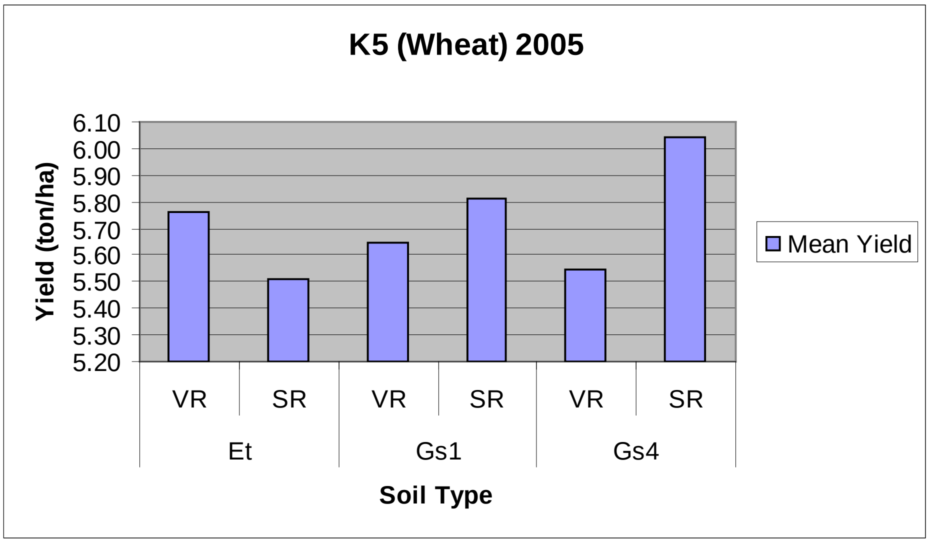


Figure 4.17: Yield *versus* soil type (K5 - 2005)

The Et soil type realised higher yields with the VRT treatment, but the SR treatment realised higher yields in the Gs1 and Gs4 soil types. Barley was introduced into the crop rotation system during 2006, and Figure 4.18 shows the yields realised with the VRT and SR treatment of the different soil types.

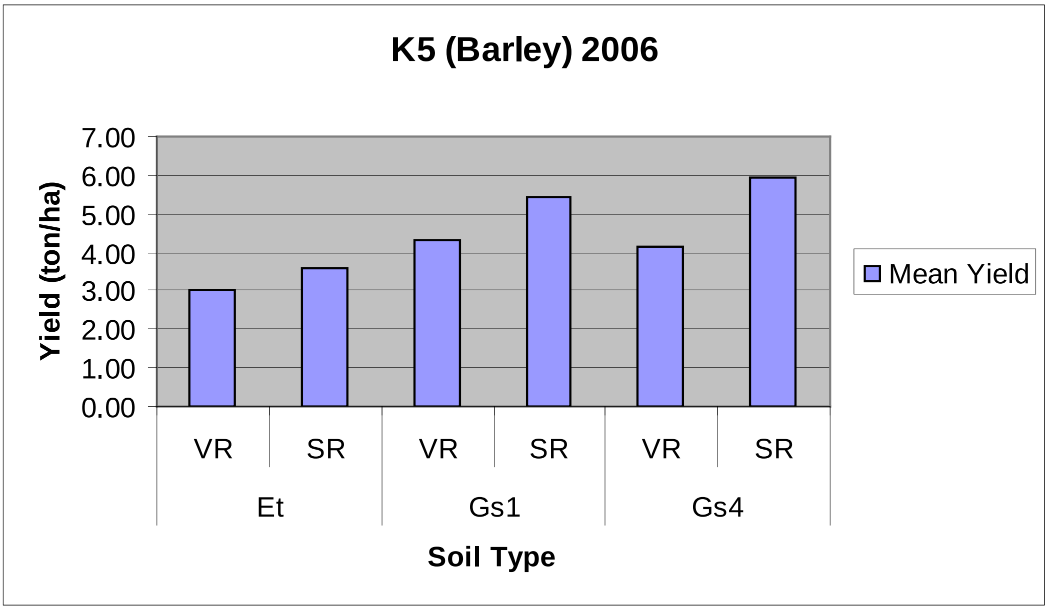


Figure 4.18: Yield *versus* soil type (K5 - 2006)

Although the pattern changed from 2004 to 2005 in the sense that higher yields were realised in the Et soil type by using the VRT treatment instead of the SR treatment, the opposite was true during 2006 and all three soil types realised higher yields by using the SR treatment instead of the VRT treatment. The highest difference between the yields realised by using the SR and VRT treatments was realised by Gs4, with the SR treatment performing better. It would be interesting to scrutinise the yield pattern in K7A in which the same rotation system was followed as in K5, although the soil types found differed considerably from those in K7A. Figure 4.19 gives a summary of the 2004 results for K7A.

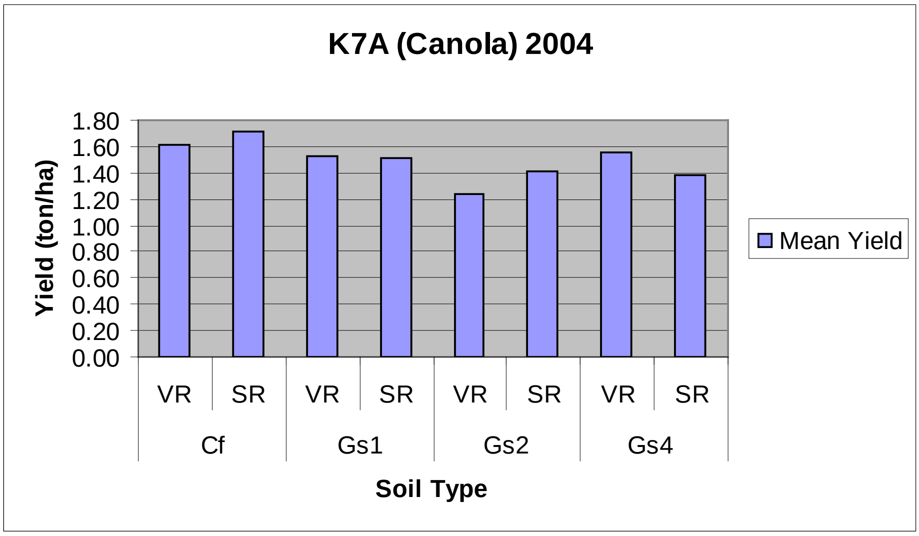


Figure 4.19: Yield *versus* soil type (K7A - 2004)

The realised yields for K7A were different from those of K5, although the same crop was planted and two of the soil types (Gs1 and Gs4) were the same. In Figure 4.18 it is shown that the SR treatment realised higher yields in all three soil types present. According to the results realised in K7A, two of the four soil types (Gs1 and Gs4) realised higher yields with the VRT treatment than with the SR treatment. During 2005, when canola was planted, the pattern became different as can be seen in Figure 4.20.

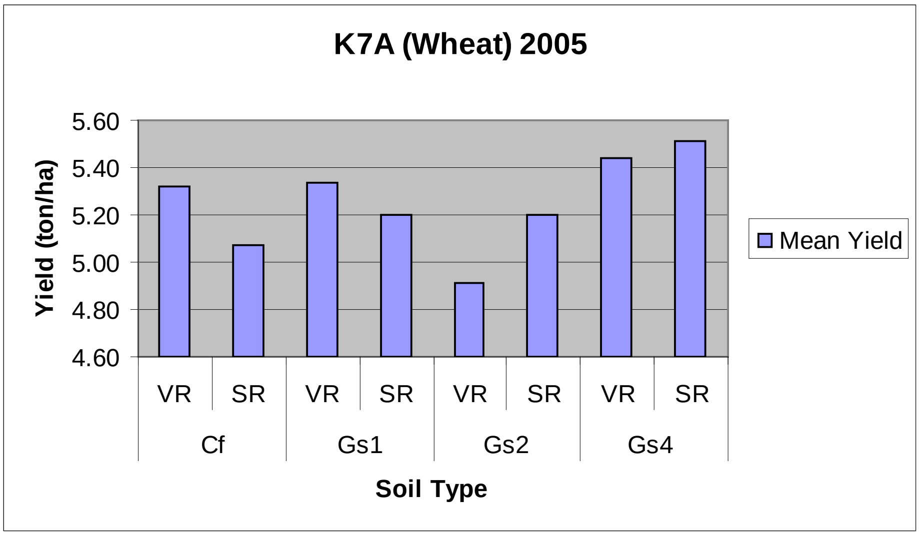


Figure 4.20: Yield *versus* soil type (K7A - 2005)

In Figure 4.20 it is shown that two soil types (Cf and Gs1) realised higher yields with the VRT treatment than with the SR treatment. The biggest difference between the two treatments (with VRT realising higher yields than SR) was evident in the Cf soil type (5,3 versus 5,1 ton/ha). In Figure 4.21, the results achieved with the introduction of barley in K7A during 2006 are shown.

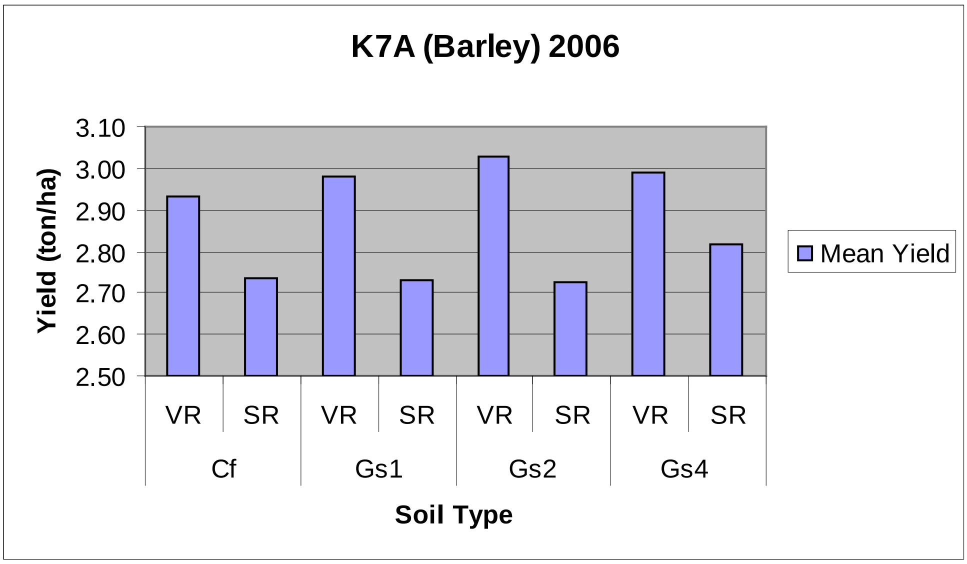


Figure 4.21: Yield *versus* soil type (K7A - 2006)

The VRT treatment realised higher yields in all four soil types than the SR treatment as summarised in Figure 4.21. In contrast with the other three fields, no particular soil type realised higher yields over all three years with the VRT or the SR treatment. It is clear from this graph that the VRT treatment realised higher yields in all four soil types during 2006. Three of the four fields realised higher yields with the VRT treatment than with the SR treatment. The aforementioned proves that larger yields can be realised with the VRT application than with the SR application of fertiliser. In Tables 3.8 to 3.15 (Chapter 3), a summary is given of the prescription of kilograms of fertiliser and kilograms of P to be applied in each field for each year. The applied P distributions (kg/ha) for each year will now be discussed in the next section by means of bar graphs.

4.2.1.4 Applied phosphorus distributions

The distributions of P applications over the three production years (Figures 4.22 to 4.24) show that different application categories are significant. Six categories were used for 2004 (Figure 4.22), three for 2005 (Figure 4.23), and twelve categories for 2006 (Figure 4.24). The application rates indicated in the histograms are only for the VRT treatment, as the rates for the SR treatment remained constant and are not included. Figure 4.22 shows the applied P distributions during 2004.

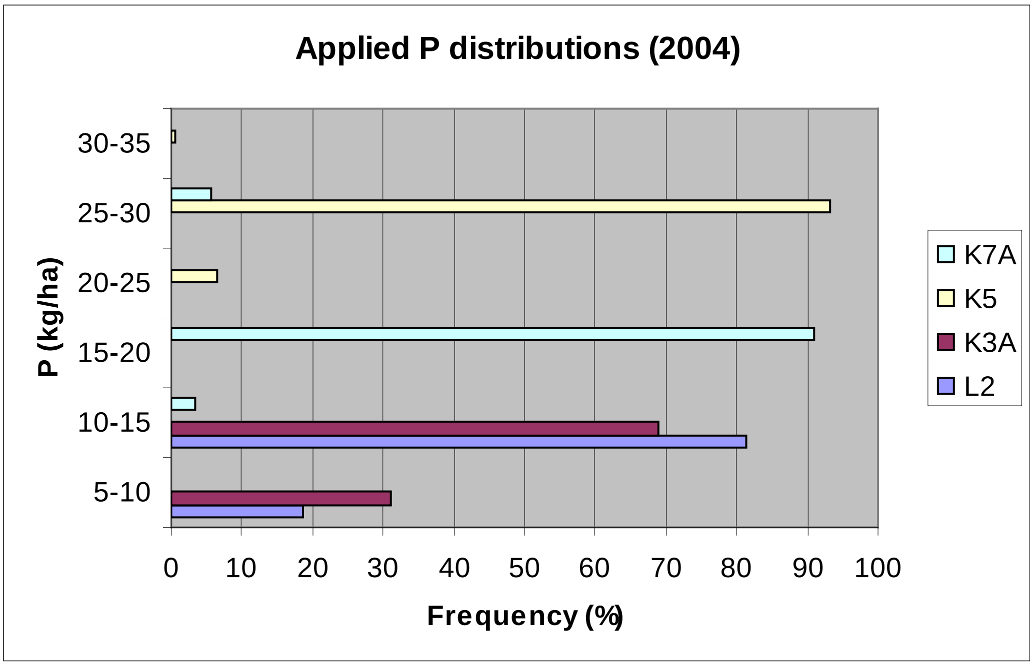


Figure 4.22: Frequency distribution of phosphorus application in 2004

The application rates, ranging from 10 to 15 kg/ha, were predominantly for L2 and K3A. More than 80 % of the total P applied is presented within this range (L2), and for K3A it is nearly 70 %. For K5 the predominant range was 25 to 30 kg/ha (more than 90 % = Figure 4.22), and for K7A it was 15 to 20 kg/ha (also more than 90 %). In Figure 4.23, the applied P distributions during 2005 are summarised.

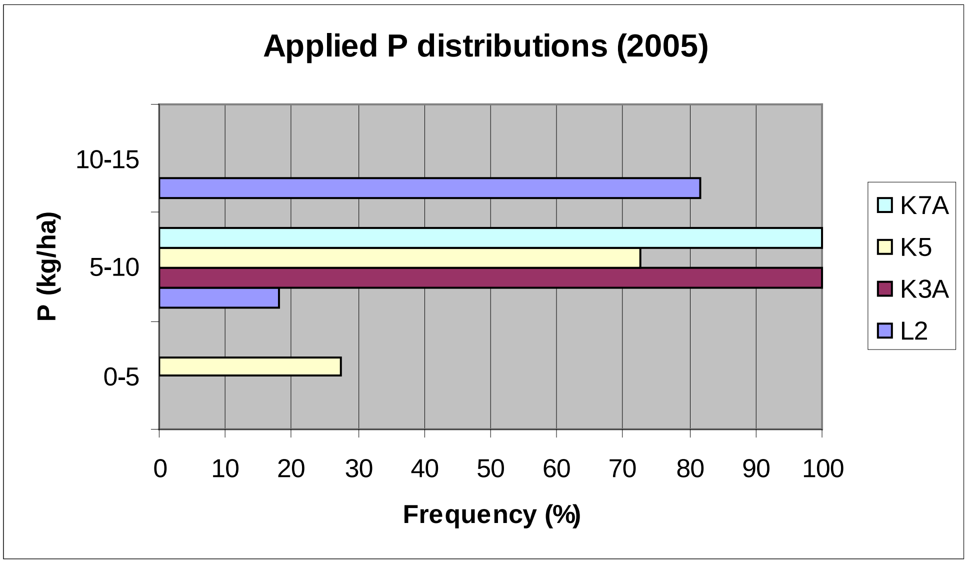


Figure 4.23: Frequency distribution of phosphorus application in 2005

There are three categories representing the applied P distributions for 2005, namely 0-5, 5-10 and 10-15 kg/ha. The 5 to 10 kg/ha range was predominant for K3A, K5 and K7A. In field L2, the predominant range was 10 to 15 kg/ha.

The next graph (Figure 4.24) shows the frequency distribution of P application in 2006. The number of categories was significantly more in 2006 than during the previous two years (2004 and 2005). Twelve categories, beginning with the 0-5 kg/ha category and ending with a final category of 55-110 kg/ha (with 5 kg/ha intervals) were selected. No data were available for L2 (a faulty cable having caused the data to be partially lost) and only the data for experimental fields K3A, K5 and K7A are presented in the graph.

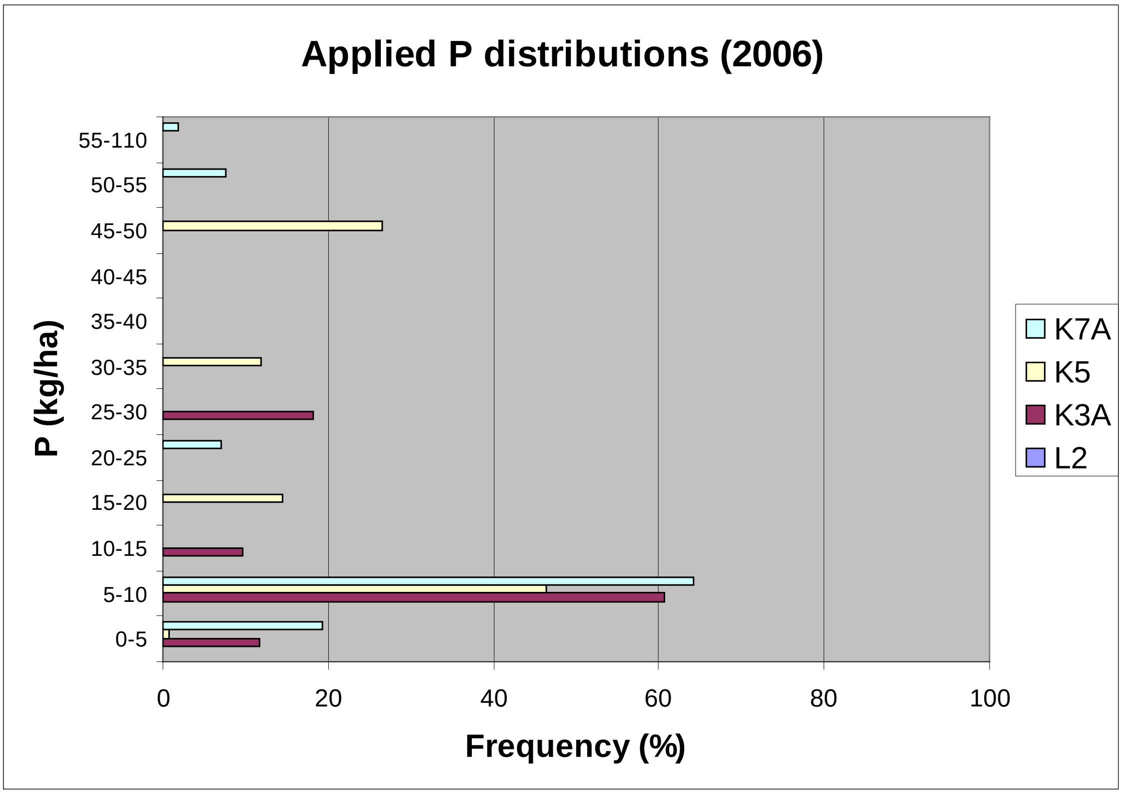


Figure 4.24: Frequency distribution of phoshorus application in 2006

Figure 4.24 shows that one application range was predominant during 2006, namely 5-10 kg/ha. This range represents more than 60 % of the total P application rates for K3A and K7A and more than 40 % for K5. The highest application range of 55-110 kg/ha represents just over 0% of the total P application rates for K7A.

4.2.1.5 Profit distribution

According to the General Linear Model (GLM) procedure, the method of least squares means (LS-Means) is used. The description for means is “computes and optionally compares arithmetic means”, and LS-Means “computes least-squares (marginal) means” (SAS OnlineDoc^{TM}: Version 8, s.a.). Soil and type (VRT and SR treatments) were used as values for the GLM procedure and the dependent variable was profit per hectare. Figure 4.25 to 4.28 show the estimated profit per hectare on the four fields during the three experimental years using the REML-model.

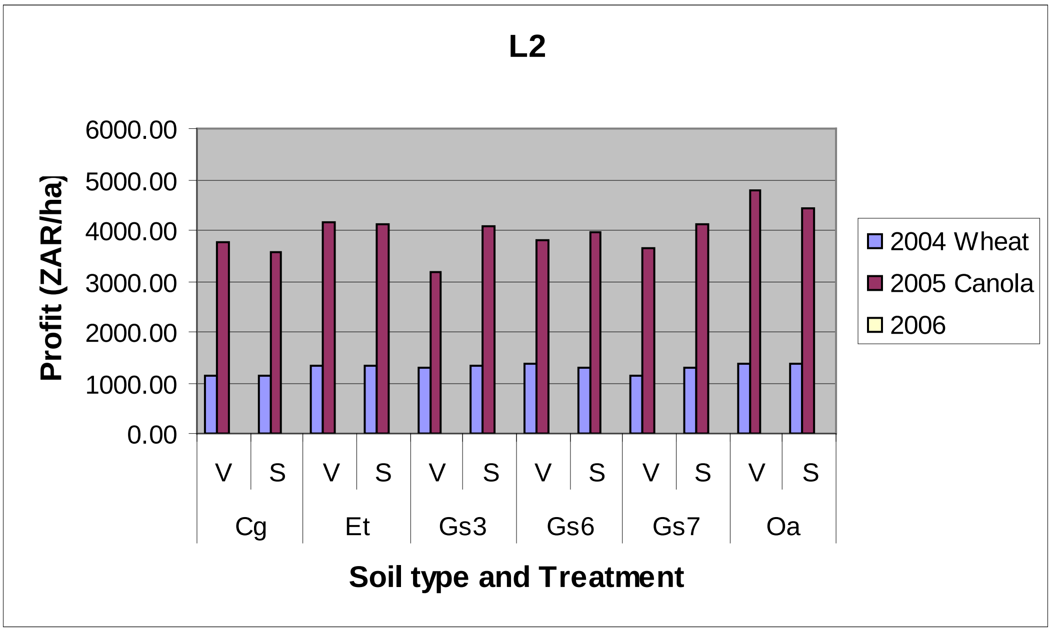


Figure 4.25: Estimated profit for L2: REML model

The figure shows that there was not much difference in 2004 between the estimated profits with VRT and SR, but during 2005 the picture looked totally different. The estimated profits with the VRT and SR treatments show clear differences, The Oakleaf (Oa) soil type performed the best and the estimated profit with the VRT treatment was also the highest (ZAR4 784,13/ha). No data were available for 2006 as the data were corrupted and could not be used. The next figure (Figure 4.26) will show the estimated profit on K3A using the REML model during the three production years.

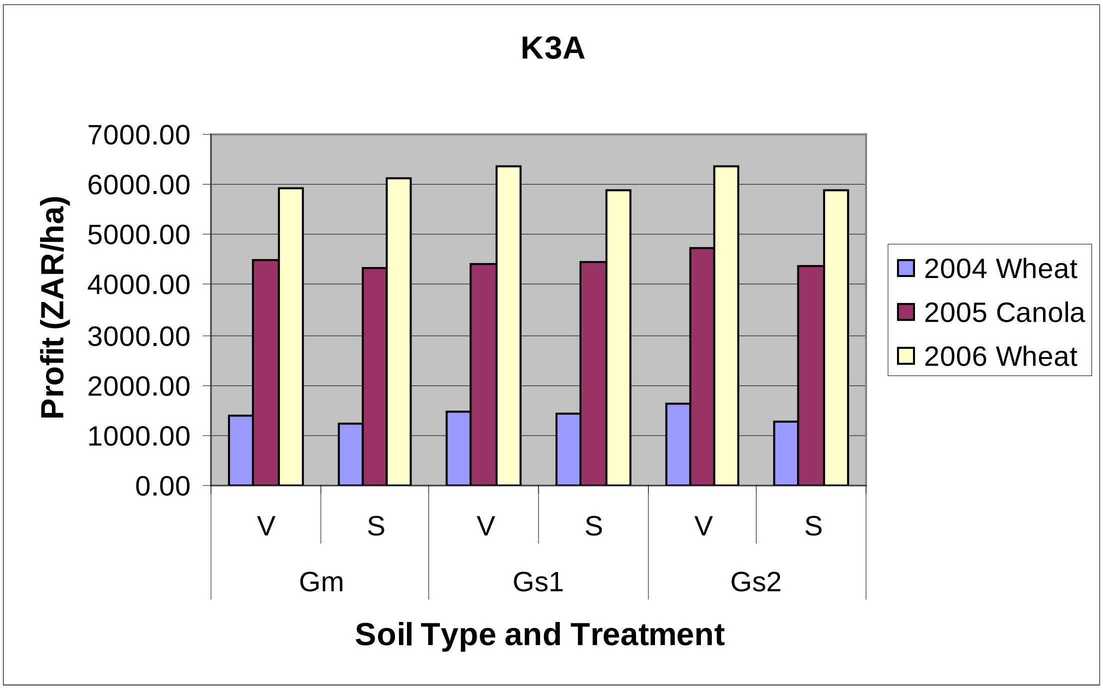


Figure 4.26: Estimated profit for K3A: REML model

Figure 4.26 show that the estimated profit was in 2004 on all three soil types higher with the VRT treatment. The 2005, the estimated profit was higher than in 2004. The estimated profits with VRT treatment of the Gm and Gs2 soil types were higher than those with the SR treatment. During 2006, the estimated profit on every soil type was close to or over ZAR6 000,00/ha, and in the Gs1 and Gs2 soil types, the VRT treatment performed better. In Figure 4.27, the estimated profit results with the REML model on field K5 are summarised, and the Et, Gs1 and Gs4 soil types are present.

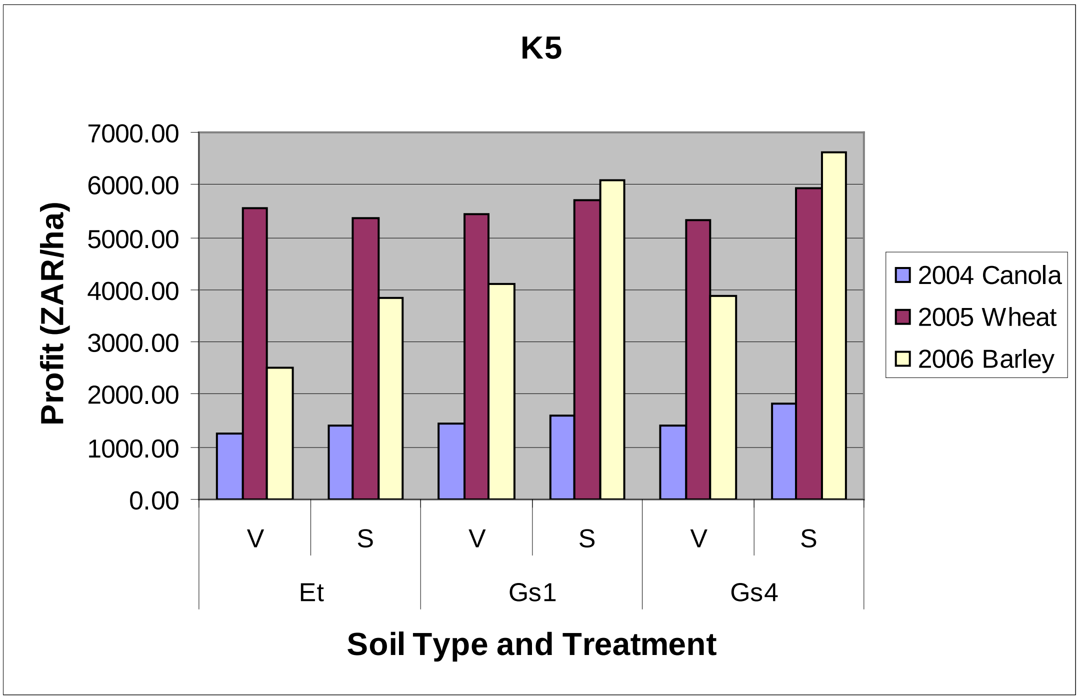


Figure 4.27: Estimated profit for K5: REML model

The graph for K5 (Figure 4.27) shows that the SR treatment realised higher profits in 2004 than the VRT treatment in all three soil types. During 2005, the VRT treatment of the Et soil type realised higher profits than the SR treatment. The SR treatment realised overall higher profits than the VRT treatment during 2006. The next graph (Figure 4.28) summarises the results realised on K7A.

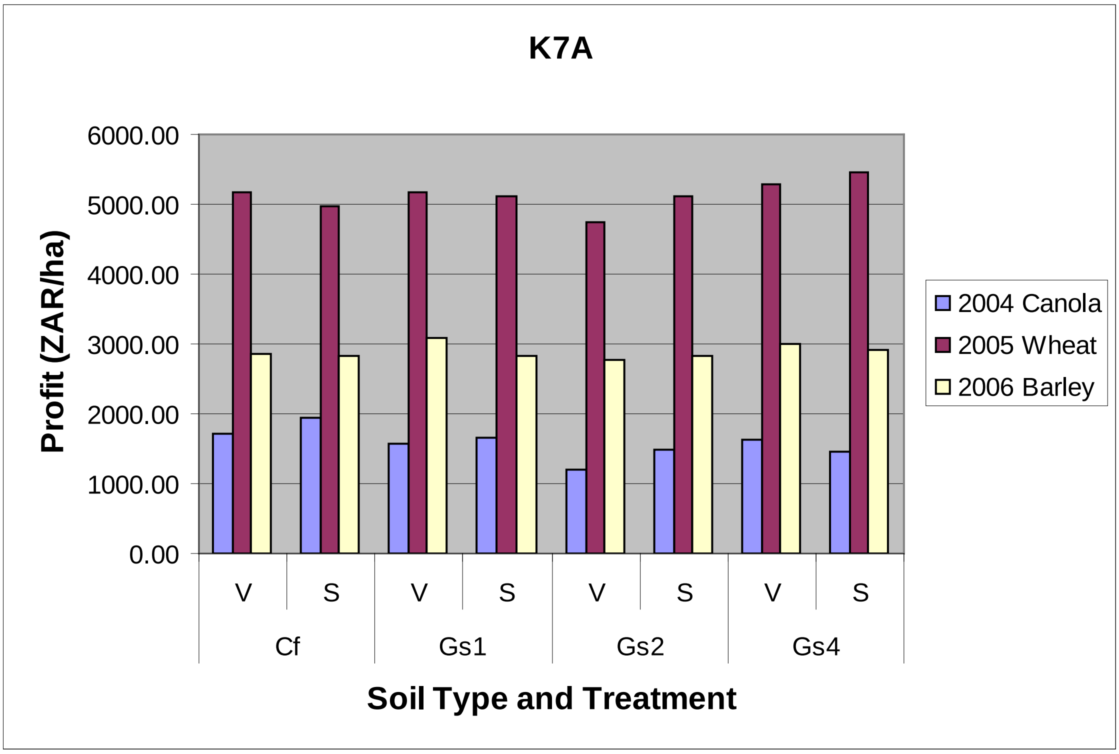


Figure 4.28: Estimated profit for K7A: REML model

The graph shows that the highest estimated profits were realised during 2005 with the VRT treatment, and that the Cf and Gs1 soil types realised higher profits with the SR treatment. During 2006 only the Gs1 soil type realised higher profits with the VRT treatment.

It is evident from the four graphs that during all three years, the VRT treatment realised higher profits than the SR treatment on some soil types (Gs1, Gs2, Gs4 and Cf), but there is not an overall soil type where the VRT treatment realised higher profits. The estimated profit shows quite some differences from year to year. Although these graphs do not reflect an overall greater performance with VRT treatment on a specific soil type, all the statistical analysis show significant differences (Chapter 5) and the probability in most cases falls between 1 and 5 %.

The next section will focus more specifically on descriptive statistics. While the graphs provided an easy-to-read picture, descriptive statistics summarised the data in a clear and understandable way.

4.3 DESCRIPTIVE STATISTICS

The aim of this section is to summarise the data collected in a clear and understandable way. This can be achieved by employing descriptive numerical summaries. Descriptive statistics are used to describe the basic characteristics of data and the aim is to provide simple summaries and a foundation for inferential analysis. The variables include yields in tons per hectare as the dependent variable, soil type and P applied in kilograms per hectare, as the explanatory variables. Another explanatory variable is treatment (VRT and SR application of P), represented by dummy variables (1=VRT, 0=SR). Descriptive statistics include the mean, minimum, maximum and standard deviation of yield. A comparison is made between the two treatments, namely the VRT and SR applications.

4.3.1 Descriptive statistics of yield

Descriptive statistics of yield obtained in this study are presented in Table. 4.1. The mean, minimum and maximum and standard deviation of yield (ton/ha) for the VRT and SR approaches in the four fields during each of the study years are presented in Table 4.1.

TABLE 4.1: SUMMARY OF STATISTICS OF YIELD (ton/ha)

Year	2004							
Field	L2		K3A		K5		K7A	
Crop	Wheat		Wheat		Canola		Canola	
Treatment	VRT	SR	VRT	SR	VRT	SR	VRT	SR
N	3703	4004	1735	3222	2982	4129	1792	1883
Mean	1.6197	1.5895	1.8811	1.6845	1.3659	1.3958	1.5415	1.5307
Std Dev	0.2948	0.2965	0.4610	0.5270	0.3319	0.3526	0.3378	0.3541
Minimum	0.8515	0.7785	0.3976	0.1214	0.2720	0.2537	0.8740	0.8720
Maximum	2.4887	2.4985	3.4863	3.4929	2.4758	2.4804	2.4940	2.4960
Year	2005							
Field	L2		K3A		K5		K7A	
Crop	Canola		Canola		Wheat		Wheat	
Treatment	VRT	SR	VRT	SR	VRT	SR	VRT	SR
N	3708	3838	2814	4434	3962	6714	2484	2818
Mean	2.5668	2.8573	3.1430	3.0005	5.6200	5.7981	5.3589	5.2055
Std Dev	0.6211	0.4970	0.5711	0.6252	0.9724	1.0600	0.8074	0.7976
Minimum	0.9240	0.8910	1.0080	1.0060	2.5430	2.5010	2.0480	2.3340
Maximum	4.7700	4.6570	5.0000	4.9990	8.9990	8.9870	8.9810	8.8700
Year	2006							
Field	L2		K3A		K5		K7A	
Crop	Wheat		Wheat		Barley		Barley	
Treatment	VRT	SR	VRT	SR	VRT	SR	VRT	SR
N	.	.	1955	3476	2489	3825	1697	2017
Mean	.	.	5.1084	4.8296	4.6190	5.2096	2.9696	2.7690
Std Dev	.	.	1.1262	1.1500	1.7539	1.8236	0.5100	0.5494
Minimum	.	.	0.4620	0.4430	0.4420	0.4430	1.0300	1.0100
Maximum	.	.	9.9930	9.9670	9.3940	9.7170	4.9070	4.9890

The first year (2004) showed that the yield realised with the VRT treatment in fields L2, K3A and K7A was higher than that realised with the SR treatment. The yield in L2 was 1,62 ton/ha (VRT) versus 1,59 ton/ha (SR), a difference of 0,03 ton/ha. The difference in K3A between the VRT and SR treatment was 0,20 ton/ha. K7A's yield with both treatments (VRT & SR) were very similar (1,53/1,54 ton/ha). The yields realised with the VRT and SR treatments of K5 were respectively 1,37 and 1,40 ton/ha.

The 2005 production year's results were slightly different from 2004, namely in L2 the SR treatment (2,86 ton/ha) realised a higher yield than the VRT treatment (2,57 ton/ha). The opposite was the case on K3A and the VRT treatment realised a higher yield than the SR treatment, 3,14 and 3,0 ton/ha, respectively. The yield in K5 followed the same trend as in L2 and the SR treatment realised a higher yield than the VRT treatment. The opposite is true in K7A and this field's yield with the VRT treatment was higher than with the SR treatment. The same trend also occurred in the case of K3A. It is also interesting to note that the 2005 yields were overall much higher than those in 2004. Factors that could have had a possible influence are climatic conditions, specifically the distribution of rainfall (see Chapter 3, Section 3.3.2.2 where the rainfall is described, as well as Figure 3.12 which shows the rainfall figures during the three experimental years) and also the fact that the crops started to react to the precise application of P.

The 2006 data for L2 2006 were corrupt. The yields in the remaining three fields indicated that in K3A and K7A the VRT treatment realised higher yields than the SR treatment. The opposite was true with regard to K5. The yield of K3A was higher in 2006 than in 2005. The yields of K5 and K7A were lower than 2005, with great differences being seen for K7A. The minimum yield in K5 was in the region of 2,5 ton/ha in 2005, and in 2006 it was less than 0,5 ton/ha. The maximum yield in this field did not show such significant differences. In 2006, the minimum and maximum yields in K7A were nearly the half of what they were in 2005. The minimum yield with the VRT treatment was 2,05 ton/ha in 2005 versus 1,03 ton/ha in 2006. The maximum yield was 8,98 ton/ha versus 4,91 ton/ha.

4.3.2 Descriptive statistics of soil type

The farmer has to plan his management in such a way as to accommodate the different soil types that can be present in the different planting fields. It is clear from the discussions in Section 4.2.1.1 that the Glenrosa soil type was dominant in the four fields that were used for this on-farm trial.

4.3.3 Descriptive statistics of input (P)

The relationship between the observed yields and the applied input had to be investigated. Each of the three years' relationship had to be investigated for each of the four fields. Table 4.2 shows the kg fertiliser and kg P applied, as well as the frequency applied and percentage distribution (L2). Frequency refers to the ratio of the number of observations in a statistical category to the total number of observations.

TABLE 4.2: APPLIED FERTILISER AND PHOSPHORUS (KG/HA): FIELD L2

2004			2005			2006		
Kg/ha	**Frequency**	**%**	**Kg/ha**	**Frequency**	**%**	**Kg/ha**	**Frequency**	**%**
35 kg Maxifos (7 kg P)	400	18,67	40 kg Profos20 (8 kg P)	396	18,22			
50 kg Maxifos (10 kg P)	1476	68,88	50 kg Profos20 (10 kg P)	1481	68,15			
60 kg Maxifos (12 kg P)	267	12,46	60 kg Profos20 (12 kg P)	296	13,62			

The data (L2, 2004) showed 50 kg Maxifos (10 kg P) per ha had the highest frequency (1 476 or 68,88 %). This rate was also true for the SR treatment. It means that out of a total of 2 143 (400 + 1 476 + 267) observations, 1 467 or 68,88 % was observed with 50 kg Maxifos (10 kg P). The highest frequency of 1 481 (68,15 %), 50 kg Profos20 (10 kg P) per ha was analysed for 2005, also realised with the SR rate. The 2006 data were corrupted and could not be used due to a cable that was faulty. Table 4.3 shows the applied fertiliser and applied P (kg/ha) in field K3A over the three production years.

TABLE 4.3: APPLIED FERTILISER AND PHOSPHORUS (KG/HA): FIELD K3A

2004			2005			2006		
Kg/ha	**Frequency**	**%**	**Kg/ha**	**Frequency**	**%**	**Kg/ha**	**Frequency**	**%**
0 kg Maxifos (kg P)	71	4,26	35 kg Profos20 (7 kg P)	258	16,25	19 kg Profos 20 (3,8 kg P)	170	11,69
47 kg Maxifos (9,4 kg P)	334	20,16	43,5 kg Profos20 (8,7 kg P)	346	21,79	45 kg Profos 20 (9 kg P)	882	60,66
68 kg Maxifos (13,6 kg P)	1 251	75,58	48 kg Profos20 (9,6 kg P)	984	61,96	70 kg Profos 20 (14 kg P)	139	9,56
						131 kg Profos 20 (26,2 kg P)	263	16,23

In field K3A, 68 kg Maxifos (15 kg P) per ha showed the highest frequency for 2004, namely 828 (50 %). The 2005 data showed that 48 kg Profos20 (9,6 kg P) per ha, realised the highest frequency (984 or 61,96 %), and during 2006 the highest frequency was realised with 45 kg Profos20 (9 kg P) per ha. These three years' rates which had the highest frequency were also the rates with the SR treatment. It is also interesting to note that during 2004, data were analysed for 0 kg fertiliser and 0 kg P per ha and the frequency was 71 or 4,26 %. The frequency results achieved in field K5 are summarised in Table 4.4.

TABLE 4.4: APPLIED FERTILISER AND PHOSPHORUS (KG/HA): FIELD K5

2004			2005			2006		
Kg/ha	**Frequency**	**%**	**Kg/ha**	**Frequency**	**%**	**Kg/ha**	**Frequency**	**%**
125 kg Maxifos (25 kg P)	159	6,40	24,5 kg Profos20 (4,90 kg P)	682	27,43	9 kg Profos 20 (1,8 kg P)	16	0,81
150 kg Maxifos (30 kg P)	2315	93,12	43,5 kg Profos20 (8,7 kg P)	325	13,07	41 kg Profos 20 (8,2 kg P)	919	46,30
175 kg Maxifos (35 kg P)	12	0,48	48 kg Profos20 (9,6 kg P)	1 479	59,49	90 kg Profos 20 (18 kg P)	288	14,51
						166 kg Profos 20 (33,2 kg P)	234	11,79
						245 kg Profos 20 (49 kg P)	528	26,60

Table 4.4 shows that more than 90 % of the frequency (2315) during 2005 was analysed with 150 kg Maxifos (30 kg P) per ha. In 2005 and 2006, the highest frequency was more in the region of 50%, and the amount of fertiliser that had the highest frequency, was also lower than in 2004 (48 and 41 kg Profos20 per ha respectively in 2005 and 2006). These were also the rates with the SR treatments in all three years. The applied fertiliser and applied P (kg/ha) in field K7A during the three production years can be seen in Table 4.5.

TABLE 4.5: APPLIED FERTILISER AND PHOSPHORUS (KG/HA): FIELD K7A

2004			2005			2006		
Kg/ha	**Frequency**	**%**	**Kg/ha**	**Frequency**	**%**	**Kg/ha**	**Frequency**	**%**
53.5 kg Maxifos (10,7 kg P)	63	3,40	29 kg Profos20 (5,8 kg P)	399	20,40	0 kg Profos 20 (0 kg P)	378	19,21
89 kg Maxifos (17,8 kg P)	1686	90,89	43,5 kg Profos20 (8,7 kg P)	150	7,67	41 kg Profos 20 (8,2 kg P)	1265	64,28
129 kg Maxifos (25,8 kg P)	106	5,71	48 kg Profos20 (9,6 kg P)	1407	71,93	117 kg Profos 20 (23,4 kg P)	138	7,01
						271 kg Profos 20 (54,2 kg P)	150	7,62
						529 kg Profos 20 (105,8 kg P)	37	1,88

The 2004 data for field K7A showed that 89 kg Maxifos (17,8 kg P) per ha had the highest frequency and the percentage was more than 90 %. During 2005 48 kg Maxifos was realised and during 2006 41 kg Maxifos had the highest frequency. Nearly 20 % of the frequency was analysed with 0 kg fertiliser applied. These rates were also the rates for the SR treatment.

4.4 CONCLUSION

Frequency distributions and descriptive statistics of the soil types together with P, as an applied input, were determined in preparation for further analysis of their relationship with yield.

Soil types Gs3 and Gs7 are the dominant soils for L2 with a 20 % distribution. Field K3A shows the same 20 % distribution for soil types Gs2, Gm and Gs1. Soil type Gs1 represents more than 50 % of the soil types for K5 and 50 % for K7A.

The VRT treatment realised higher yields in 2004 and 2006. The 2005 production year showed even distributions of the yield with the VRT and SR treatments. When bringing the soil types also into account, the most soil types showed higher yields with the VRT treatment in fields L2 and K3A. The results for K5 were not following this trend and the SR treatment in most of the soil types resulted in higher yields. Field K7A showed an improvement in the quantity of soil types which had reflected higher yields with the VRT treatment over the three production years and during 2006 all the soil types showed higher yields with the VRT treatment.

The wheat yield in 2004 was between 1,6 – 1,8 ton/ha and for canola it was just over 1,4 ton/ha. During 2005 the yield showed an improvement and with wheat it was up to a maximum of 5,5 ton/ha and with canola it was between 2,8 – 2,9 ton/ha. The 2006 data showed a slight decline in the wheat yield, but it was higher than in 2004 (4,8 - >5,0 ton/ha) and for barley it was 3,8 – 3,99 ton/ha.

The conclusion can thus be drawn that the majority of soil types showed higher yields with the VRT than the SR treatment. The wheat yield (VRT treatment) also increased from 1,75 ton/ha in 2004 to a maximum of 5,5 ton/ha in 2005. A slight decline of 0,3 ton/ha was experienced in 2006. The same trend was true for canola, with just over 1,4 ton/ha realised in 2004, and 2,85 ton/ha in 2005. Barley was introduced into the crop rotation system in the third year of the trial and yields of 3,8 (VRT treatment) – 3,99 (SR treatment) ton/ha were realised.

In Chapter 5, the results of statistical and profitability analyses are shown and three statistical methods are used, namely the methods of ordinary least squares (OLS), spatial error (SER) and restricted maximum likelihood (REML). More emphasis is placed on which statistical method best suits the specific model used.

CHAPTER FIVE

STATISTICAL AND PROFITABILITY ANALYSIS

5.1 INTRODUCTION

The main aim in this chapter is to focus on the research objective, namely to determine the effect of precision phosphorus (P) application on the profitability of PA (precision agriculture) on a commercial farm in the Heidelberg district in the Western Cape Province in South Africa. In order to achieve this goal, the chapter has been divided into two main sections, namely a statistical analysis using regression models and a profitability analysis using partial budgets. Data was collected by using the variable-rate (VRT) application of P, in comparison with the single-rate (SR) application. The results obtained are presented and compared using the traditional statistical analysis method, the method of ordinary least squares (OLS), the spatial analysis method, the spatial error (SER) model and the geo-statistical approach to spatial regression, as well as the restricted maximum likelihood (REML) geo-statistics approach. The assumptions of classical statistical analyses are often violated when analysing spatial data (yield monitor data in this case) because of the correlation among neighbouring observations. By applying classical statistics to on-farm experiments, the assumption is made that observations are independent, but in the case of PA data this assumption of independence is untenable, as any yield monitor observation is clearly correlated to its neighbouring observations (Lambert, Lowenberg-DeBoer and Bongiovanni, 2003). Spatial auto-correlation is taken into account when spatial regression analysis is done and this method of analysis can overcome the limitations of classical statistical analysis. The data collected for this research have a spatial nature which requires specifically designed statistical methods. The GeoDA™ statistical package was chosen for this reason. Profitability analysis refers to the methodology used to determine the profitability differences between the VRT and SR application strategies.

The next section will focus on the statistical analysis of this study and more specifically the mean yields of the fields, diagnostic tests, the baseline model (Section 3.6.3), measures of fit and coefficient estimates. Accordingly, the best model fit will be discussed.

5.2 STATISTICAL ANALYSIS

The aim of this section is to investigate the relationship between yield and P as explanatory variable and also the effect of the two treatments (VRT and SR) on yield. The effect of the two treatments, VRT and SR, are captured in a treatment (TRT) dummy variable, which assigns a value of 1 to VRT and 0 to SR. Besides P being used as an explanatory variable, dummy variables for different soil types are also included in a regression model. The aim is to determine whether yields vary spatially and this spatial variability is captured for different soil types. In Annexure H, Table H1, a summary of the different soil types and the different symbols used in the regression model is given.

The effect of spatial autocorrelation must be taken into account because of the nature of the data collected. The data are spatially correlated and it is essential to use the methodology that takes this into account. This is the reason why the spatial econometric analysis is so important in this study. Spatial autocorrelation arises in yield monitor data from the coincidence of similarity in yield values and location between yield points. PA is analysed as a package by using the Baseline Model (Treatment Model) and it is done by assessing the statistical significance of the estimated coefficients.

5.2.1 Diagnostic tests for the Baseline Model

Maine (2006) reported that diagnostic tests on the OLS residuals determine the presence of spatial effects and also verify the optimal model. When the OLS model is run in conjunction with the weights matrix, the specification tests on spatial autocorrelation and heteroscedasticity (structural change) are acquired and this also suggests which model should be used (spatial error or spatial lag).

It was essential to determine if some of the assumptions of the classical linear regression models hold true before estimating the regression coefficient of data collected in this study. Some of these assumptions are that random variables are normally distributed and homoscedastic and that there is no autocorrelation and multicollinearity between variables. The Jarque-Bera (JB) test is used to determine normality in the error terms and thereby the hypothesis that the residuals are normally distributed is tested. The data collected for this study are cross-sectional in nature. Heteroscedasticity is most common in these kinds of data. The Breusch-Pagan (BP) test is a diagnostic test done of a regression in order to determine the presence of heteroscedasticity in the error terms. The Koenker-Bassett (KB) test in the OLS model also confirms the presence of heteroscedasticity. In Table 5.1, a summary of these various diagnostic tests for normality, multicollinearity and heteroscedasticity is provided.

TABLE 5.1: DIAGNOSTIC TESTS FOR NORMALITY AND HETEROSCEDASTICITY

Field	***L2***			***K3A***			***K5***			***K7A***		
Test	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**
Jarque-Bera (JB)	11.4294*	154.2359*	-	58.9946*	98.9809*	863.6531*	323.0742*	251.8848*	67.6576*	32.0605*	632.5137*	198.0619*
Breusch-Pagan (BP)	27.8987* 18.3958** 18.9153***	59.6836* 43.6239** 42.4853***	- - -	81.1555* 58.9028** 63.3864***	40.6417* 47.2516** 46.4072***	55.1726* 54.5730** 56.5348***	9.9591* 14.6160** 15.0960***	12.7250* 12.1737** 11.7034***	59.3813* 44.3289** 47.7036***	28.7996* 15.1413** 18.1577***	18.5870* 15.4736** 15.1433***	16.1171* 17.4702** 17.5394***
Koenker-Basset (KB)	25.8788*	36.2622*	-	56.5406*	25.2606*	20.6424*	5.3474*	7.3508*	106.0672*	40.8516*	7.9454*	9.5304*

*****OLS model

**Spatial lag model

***Spatial error model

Table 5.1 shows that in the test for normality of errors in the Baseline Model using OLS, the highest JB value for 2004 was obtained for K5, namely 323.0742. For 2005 the highest value for K7A was 632.5137, and for 2006 it was 863.6531 for K3A. The JB values for each of the four fields for each of the three years are significant at a 1 % probability level. This indicates non-normality of the error terms. The larger the BP test, the greater the evidence against homoscedasticity. The highest BP value in the OLS model for 2004 is 81.1555 (K3A), for 2005 it was 59.6836 (L2), and for 2006 it was 59.3813 (K5), while the SER model produced values of 63.3864 (K3A) for 2004, 47.2516 (K3A) for 2005 and 56.5345 (K3A) for 2006. It is interesting to note that for the SER model, field K3A produced the highest BP values for the three years. The spatial error model was better for 2004 and 2006 due to the higher BP values, which provided even greater evidence against homoscedasticity. The highest KB value for 2004 was recorded for field K3A, namely 56.5406, for 2005 it was 36.2622 (L2), and for 2006 it was 106.0672 (K5). Dealing with heteroscedasticity in spatial data presents a problem, as no standard procedure has yet been developed in this regard. All the multicollinearity condition numbers are lower than 20, the recommended maximum condition number.

Spatial autocorrelation was also expected in this type of data and the SER model was estimated to detect it. The spatial model was more appropriate for analysis so that the spatial effects could be taken into account. However, the OLS regression test had to be conducted in order to determine which spatial regression model (lag or error) would be most appropriate. Five diagnostic tests for spatial dependence are reported with the OLS regression output in GeoDa^{TM} and these include the Moran's I for the spatial error model and the lagrange multiplier (LM) and its Robust for the lag and error models. In Table 5.2 there is a summary of the results for the five diagnostic tests for each field over the three years.

TABLE 5.2: DIAGNOSTIC TESTS FOR SPATIAL DEPENDENCE

	Value											
Field	***L2***			***K3A***			***K5***			***K7A***		
Test	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**
Moran's I (error)	40.0667	43.8419	-	109.8809	41.0361	48.6230	62.7992	109.1724	141.2386	159.3169	23.2960	36.6404
Lagrange Multiplier (lag)	1127.6340	468.9049	-	2212.4411	572.4764	692.3588	2334.9557	4571.0204	10065.1965	4812.1417	460.1790	1202.8410
Robust LM (lag)	51.8383	73.9896	-	7.7388	5.9274	63.5653	0.2769	66.4559	73.2738	0.1753	5.0973	5.5007
Lagrange Multiplier (error)	1140.6991	735.2659	-	5654.5541	751.9123	861.4104	2784.9947	5322.4829	16035.7339	9229.4628	459.6740	1200.8915
Robust LM (error)	64.9033	340.3506	-	3449.8517	185.3633	232.6169	450.3159	817.9184	6043.8112	4417.4964	4.5924	3.5512

The model with the highest LM value and its robust term is the most appropriate (Table 5.2). The spatial error model appears to be the most appropriate for 2004, 2005 and 2006 for fields L2, K3A and K5. In the 2005 and 2006 production years, the spatial lag model is more appropriate for K7A. The selection of the most appropriate model for spatial differences (sub-research objective one) will be discussed in the next section.

5.2.2 Model selection for spatial differences (regression)

In ordinary regression analysis, the R-squared (also called coefficient of determination) is usually used as a measure of goodness of fit, with the model with the highest R-squared considered having the best fit and this implies that the predicted values match the observed values for the dependent variable. R-squared increases in value with additional explanatory variables and over-fitting can occur. In Table 5.3, a summary of the goodness of fit is found.

TABLE 5.3: MODEL SELECTION FOR SPATIAL DIFFERENCES

Measures of goodness of fit	L2			K3A			K5			K7A		
	2004	**2005**	**2006**	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**
R-Squared (R^2)												
OLS	0.057283	0.177986	-	0.095716	0.028195	0.047559	0.015778	0.013155	0.141170	0.066430	0.028444	0.062372
SER	0.211588	0.258012	-	0.273900	0.112948	0.117888	0.133911	0.128900	0.536611	0.270042	0.145660	0.277872
REML	-	-	-	-	-	-	-	-	-	-	-	-
Log-likelihood												
OLS	-15155	-16651.5	-	-12636.1	-12404	-13496.3	-17845.1	-20398	-17466.3	-13412.2	-15753.8	-14942.7
SER	-14991.2889	-16550.6535	-	-12462.1956	-12337.7485	-13439.0586	-17697.8202	-20248.5140	-16877.9483	-13190.7314	-15653.6982	-14728.1183
REML (Gaussian)	-14874.8407	-16431.5639		-12380.7060	-12273.1013	-13414.1757	-17606.5224	-20060.5891	-17364.6069	-12962.1164	-15637.1057	-14813.4804
REML (Spherical)	-14866.7070	-16363.4936	-	-12257.2708	-12189.6602	-13274.9946	-17469.1061	-19964.2052	-16916.5767	-12873.6591	-15586.3164	-14654.7892
REML (Exponential)	-14866.9617	-16399.4656		-12313.7897	-12258.0858	-13322.9494	-17692.4494	-20020.1671	-20187.1540	-12918.3634	-15601.0935	-14747.7004
Akaike Information Criterion (AIC)												
OLS	30334.1	33327	-	25284.3	24820.1	27004.5	35702.2	40808	34944.6	26840.3	31523.6	29901.3
SER	30006.6	33125.3	-	24936.4	24687.5	26890.1	35407.6	40509	33767.9	26397.5	31323.4	29472.2
REML (Gaussian)	29749.7	32863.1		24761.4	24546.2	26828.4	35213.0	40121.2	34729.2	25924.2	31274.2	29627.0
REML (Spherical)	29733.4	32727.0	-	24514.5	24379.3	26550.0	34938.2	39928.4	33833.2	25747.3	31172.6	29309.6
REML (Exponential)	29733.9	32798.9		24627.6	24516.2	26645.9	35384.9	40040.3	40374.3	25836.7	31202.2	29495.4
Schwartz Criterion (SC)												
OLS	30402.1	33395.2	-	25316.7	24852.3	27036.9	35737.1	40842.9	34978.2	26884.5	31568.2	29946
SER	30074.6173	33193.51334	-	24968.8641	24719.7184	26922.4583	35442.5509	40543.9385	33801.4568	26441.6680	31368.0256	29516.9148
REML	-	-	-	-	-	-	-	-	-	-	-	-

In Table 5.3 the R-squared is higher in the SER model for each of the four fields during each of the three years. The goodness of fit of the model cannot be based on R-squared alone, as it does not indicate whether the estimated partial regression coefficients are statistically different from zero (LeSage, 1998). R-squared is also not appropriate as a measure of fit in comparing spatial regression models. The Log-likelihood models become more reliable and these values measure how good or poorly the model predicts the output in the observed data. The model with the highest log-likelihood has the best fit. Table 5.3 indicates that the REML (spherical) model has the highest log-likelihood (less negative) values. However, the log-likelihood increases with additional variables, as does the R-squared, over-fitting the model. This over-fitting can be corrected by employing the akaike information criteria (AIC) (Maine, 2006). The AIC value assigned to a model is only meant to rank competing models and tell which is the best among the given alternatives, (the lower the AIC value, the better the model) (Acquah, 2009). The absolute values of the AIC for different models have no meaning. The REML (spherical) model has the lower AIC values for each of the four fields during each of the three years. The winter grain response to P on different soil types (sub-research objective two) will be discussed under the next section.

5.2.3 Winter grain response to phosphorus variation on different soil types

The results of winter grain response to phosphorus (P) variation on different soil types for the Baseline Model estimated with the OLS, SER and REML models for each field for each production year are summarised in Annexure I. The spherical model for REML is the most appropriate for each of the four fields for each of the three years, due to the fact that the AIC is the smallest (Table 5.3). The results achieved for each field for each year with the REML (spherical) model will be discussed separately in Tables 5.4 to 5.14. Table 5.4 presents the results for L2 (2004). Soil type Glenrosa (Gs1) (S1) was used as base soil for discussion of all fields except for L2 where Gs3 (S3) was used due to the fact that soil type Gs1 is not found in L2. The “Constant” represents the base soil and base treatment (SR) in kilograms (kg). The “Trt” coefficient is the yield difference between VRT and SR treatments for the base soil. The Si coefficients represent the difference between specified soil i and the base soil with SR treatment. The TRTSi interaction coefficient is the yield difference between VRT and SR for soil i versus the base soil ((Si:(VRT-SR) – Sbase (VRT-SR)).

TABLE 5.4: WHEAT RESPONSE TO PHOSPHORUS VARIATION ON DIFFERENT SOIL TYPES: L2 (2004)

	Regression output			
	REML			
	Spherical			
	Cf	Std Err.	t-Value	Pr>|t|
Constant	1570.98	97.1020	16.18	-
Trt	-99.7969	82.0126	-1.22	0.2238
S6	-17.0635	64.3721	-0.27	0.7909
S7	-14.1341	49.5061	-0.29	0.7753
S12	-271.04	89.8425	-3.02	0.0026**
S13	-14.5565	75.2637	-0.19	0.8467
S14	-25.5085	71.4158	-0.36	0.7210
TRTS6	71.0820	106.56	0.67	0.5048
TRTS7	88.9119	74.5056	1.19	0.2329
TRTS12	300.21	143.88	2.09	0.0371*
TRTS13	108.90	100.85	1.08	0.2803
TRTS14	141.84	111.95	1.27	0.2053
LAMBDA	-	-	-	-

* = 0.05

** = 0.01

Table 5.4 shows that the yield for the Coega (Cg) soil type (S12) for the SR treatment has significant statistical results with the interaction towards the reference (Glenrosa, Gs3 soil) and the coefficient is -271,04 kg/ha. This means that Gs3 produced 271,04 kg/ha more wheat than the Cg soil with the SR treatment. TRTS12 is the interaction between VRT and SR for Cg as well as the interaction between VRT and SR for Gs3 and show significant statistical results with a coefficient of 300,21 kg/ha. Therefore the Cg soil type produced 300,21 kg/ha more wheat than the Gs3 soil in the case of the VRT treatment (Cg: VRT–SR minus Gs3: VRT–SR). According to the results it appears that if the Cg soil reacted better with the VRT treatment. The other coefficients were not significant and though not discussed. Table 5.5 shows the response of canola to P variation during 2005.

TABLE 5.5: CANOLA RESPONSE TO PHOSPHORUS VARIATION ON DIFFERENT SOIL TYPES: L2 (2005)

	Regression output			
	REML			
	Spherical			
	Cf	**Std Err.**	**t-Value**	**Pr>|t|**
Constant	2762.43	131.07	21.08	-
Trt	-228.16	133.15	-1.71	0.0868
S6	10.6390	110.77	0.10	0.9235
S7	41.6905	86.9965	0.48	0.6318
S12	-239.84	152.98	-1.57	0.1171
S13	-53.835	131.50	-0.41	0.6823
S14	6.8077	121.08	0.06	0.9552
TRTS6	123.05	196.61	0.63	0.5315
TRTS7	94.1787	128.64	0.73	0.4642
TRTS12	71.9105	244.56	0.29	0.7688
TRTS13	97.3720	175.44	0.56	0.5789
TRTS14	165.12	194.22	0.85	0.3953
LAMBDA	-	-	-	-

* = 0.05

** = 0.01

According to Table 5.5, no significant statistical differences are evident with the different soil types and canola's response to the variation in P. The 2006 data were corrupted and could not be used. The results of K3A during the three years are presented in Tables 5.6 to 5.8. The Glenrosa (Gs1) soil type was used as the reference on field K3A. Table 5.6 shows wheat response to P variation on different soil types during 2004.

TABLE 5.6: WHEAT RESPONSE TO PHOSPHORUS VARIATION ON DIFFERENT SOIL TYPES: K3A (2004)

	Regression output			
	REML			
	Spherical			
	Cf	**Std Err.**	**t-Value**	**Pr>|t|**
Constant	1453.23	163.71	8.88	-
Trt	143.01	95.1004	1.50	0.1328
S2	40.8241	77.9797	0.52	0.6007
S8	54.3059	89.0987	0.61	0.5423
TRTS2	51.8859	95.4362	0.54	0.5867
TRTS8	69.5550	111.88	0.62	0.5342
LAMBDA	-	-	-	-

* = 0.05

** = 0.01

Table 5.6 shows that no significant statistical differences are evident with the different soil types and wheat's response to P variation. Table 5.7 shows the response of canola to P variation on different soil types in K3A during 2005.

TABLE 5.7: CANOLA RESPONSE TO PHOSPHORUS VARIATION ON DIFFERENT SOIL TYPES: K3A (2005)

	Regression output			
	REML			
	Spherical			
	Cf	**Std Err.**	**t-Value**	**Pr>|t|**
Constant	3000.49	176.89	16.96	-
Trt	-142.37	135.60	-1.05	0.2939
S2	-110.05	104.76	-1.05	0.2936
S8	110.14	123.29	0.89	0.3718
TRTS2	289.76	128.32	2.26	0.0241*
TRTS8	395.86	152.06	2.60	0.0093**
LAMBDA	-	-	-	-

* = 0.05

**=0.01

The average yields on the Glenrosa (Gs2) (S2) and Gamoep (Gm) (S8) soil types tested statistically significant for the difference between VRT and SR treatments. TRTS2 show that Gs2 soil produced 289,76 kg/ha more canola with the VRT treatment and for TRTS8, the Gm soil yielded 395,86 kg/ha more canola with VRT. Table 5.8 presents the results for K3A during 2006 when wheat was planted.

TABLE 5.8: WHEAT RESPONSE TO PHOSPHORUS VARIATION ON DIFFERENT SOIL TYPES: K3A (2006)

	Regression output			
	REML			
	Spherical			
	Cf	**Std Err.**	**t-Value**	**Pr>|t|**
Constant	4518.90	332.45	13.59	-
Trt	295.65	190.19	1.55	0.1203
S2	122.67	152.21	0.81	0.4204
S8	217.30	177.65	1.22	0.2214
TRTS2	-60.5589	190.18	-0.32	0.7502
TRTS8	-269.66	222.86	-1.21	0.2265
LAMBDA	-	-	-	-

* = 0.05

** = 0.01

No significant statistical differences are evident from Table 5.8 for the response of wheat to P variation on different soil types during 2006 on field K3A. The same was evident during 2004 when wheat was also planted. During 2005 canola was planted and significant statistical differences were evident for TRTS2 and TRTS8 (Table 5.7). Table 5.9 shows canola’s response to P during 2004 on K5.

TABLE 5.9: CANOLA RESPONSE TO PHOSPHORUS VARIATION ON DIFFERENT SOIL TYPES: K5 (2004)

	Regression output			
	REML			
	Spherical			
	Cf	**Std Err.**	**t-Value**	**Pr>|t|**
Constant	1333.33	60.8810	21.90	-
Trt	25.4782	54.9464	0.46	0.6429
S4	94.2647	108.11	0.87	0.3833
S13	-202.07	72.2013	-2.80	0.0052**
TRTS4	.136.20	112.21	-1.21	0.2250
TRTS13	211.91	108.92	1.95	0.0518*
LAMBDA	-	-	-	-

* = 0.05

**=0.01

Only the Etosha (Et) soil type (S13) shows significant statistical results. The Glenrosa (Gs1) soil type (the base soil type) resulted in 202,07 kg/ha more canola than the Et soil with the SR treatment. The VRT treatment on the Et soil show a positive coefficient and this means that the yield was 211,91 kg/ha more than with the Gs1 soil with VRT (Et: VRT–SR minus Gs1: VRT–SR). Table 5.10 shows the response of wheat to P variation on different soil types for K5 during 2005.

TABLE 5.10: WHEAT RESPONSE TO PHOSPHORUS VARIATION ON DIFFERENT SOIL TYPES: K5 (2005)

	Regression output			
	REML			
	Spherical			
	Cf	**Std Err.**	**t-Value**	**Pr>|t|**
Constant	5542.73	167.02	33.19	-
Trt	80.6799	151.64	0.53	0.5947
S4	-8.6146	315.70	-0.03	0.9782
S13	-175.16	180.44	-2.63	0.0085**
TRTS4	-184.49	324.99	-0.57	0.5703
TRTS13	375.84	290.53	1.29	0.1959
LAMBDA	-	-	-	-

* = 0.05

**=0.01

Table 5.10 shows that the only significant statistical difference is that of the Etosha (Et) soil type (S13) and the Glenrosa (Gs1) soil yielded 175,16 kg/ha more wheat with the SR treatment than the Et soil. Table 5.11 summarises the results during 2006 on K5.

TABLE 5.11: BARLEY RESPONSE TO PHOSPHORUS VARIATION ON DIFFERENT SOIL TYPES: K5 (2006)

	Regression output			
	REML			
	Spherical			
	Cf	**Std Err.**	**t-Value**	**Pr>|t|**
Constant	4405.22	398.60	11.05	-
Trt	-472.23	250.08	-1.89	0.0591
S4	-39.584	287.60	-0.14	0.8905
S13	-963.26	207.78	4.64	<0.0001***
TRTS4	25.4132	306.34	0.08	0.9339
TRTS13	1360.58	328.96	4.14	<0.0001***
LAMBDA	-	-	-	

* = 0.05

**=0.01

***=0.0001

As in the case during 2004 (Table 5.9) and 2005 (Table 5.10) the only significant statistical difference is evident with the Etosha (Et) soil type (S13). The SR treatment on the Et soil shows a negative coefficient and this means that the Glenrosa soil type produced 963,26 kg/ha more barley than the Et soil. With the VRT treatment (TRTS13) the coefficient is positive and this means that the Et soil produced 1 360,58 kg/ha more barley than the Glenrosa soil type with VRT. When looking at the results it looks like the Et soil reacted better than the Glenrosa soil with the VRT treatment. Table 5.12 shows the results of K7A during 2004.

TABLE 5.12: CANOLA RESPONSE TO PHOSPHORUS VARIATION ON DIFFERENT SOIL TYPES: K7A (2004)

	Regression output			
	REML			
	Spherical			
	Cf	**Std Err.**	**t-Value**	**Pr>|t|**
Constant	1210.82	136.23	8.89	-
Trt	129.12	82.3744	1.57	0.1172
S2	-19.715	45.7369	-1.09	0.2772
S4	-56.9582	82.1583	0.69	0.4882
S11	146.82	55.6569	2.64	0.0084**
TRTS2	-51.8126	98.9845	-0.52	0.6007
TRTS4	83.4732	93.8884	0.89	0.3741
TRTS11	-98.2111	82.3595	-1.19	02332
LAMBDA	-	-	-	-

* = 0.05

**=0.01

When looking at Table 5.12, the only significant statistical difference was obtained with the Cartref (Cf) soil type (S11) and the result showed that 146,82 kg/ha more canola was produced than the Glenrosa soil type under the SR treatment. Table 5.13 shows the response of wheat to P variation on different soil types during 2005 on K7A.

TABLE 5.13: WHEAT RESPONSE TO PHOSPHORUS VARIATION ON DIFFERENT SOIL TYPES: K7A (2005)

	Regression output			
	REML			
	Spherical			
	Cf	**Std Err.**	**t-Value**	**Pr>|t|**
Constant	5025.49	215.33	23.34	-
Trt	280.87	170.01	1.65	0.0987
S2	102.45	111.59	0.92	0.3587
S4	12.8689	197.37	0.07	0.9480
S11	136.70	141.49	0.97	0.3341
TRTS2	-248.79	219.30	-1.13	0.2567
TRTS4	31.7960	226.13	0.14	0.8882
TRTS11	-143.69	202.86	-0.71	0.4788
LAMBDA	-	-	-	-

* = 0.05

**=0.01

Table 5.13 shows that no significant statistical differences were obtained during 2005 with the response of wheat to P variation on different soil types for K7A. The response of barley to P variation during 2006 can be seen in Table 5.14.

TABLE 5.14: BARLEY RESPONSE TO PHOSPHORUS VARIATION ON DIFFERENT SOIL TYPES: K7A (2006)

	Regression output			
	REML			
	Spherical			
	Cf	**Std Err.**	**t-Value**	**Pr>|t|**
Constant	2852.22	109.83	25.97	-
Trt	-43.4630	111.81	-0.39	0.6975
S2	-43.1446	73.2763	0.59	0.5561
S4	-48.3742	126.67	0.38	0.7026
S11	-91.4459	88.6752	-1.03	0.3026
TRTS2	187.37	142.37	1.32	0.1883
TRTS4	152.92	145.13	1.05	0.2922
TRTS11	251.85	130.39	1.93	0.0536
LAMBDA	-	-	-	-

* = 0.05

**=0.01

As in the case during 2005 with wheat, the results of the response of barley to P variation (Table 5.14) also show no significant statistical differences during 2006. A profitability analysis conducted by using the general linear model (GLM) procedure is outlined in the following section. The coefficients estimated with the REML model (Spherical) for each field during individual years are used to determine the profitability of precision P application (sub-research objective three).

5.3 PROFITABILITY ANALYSIS

Cramer and Jensen (1994) described profitability as the surplus of receipts over expenses. Profitability is usually measured over the economic lifetime of a project. For this study, profit is calculated using two phases and formulas 1 and 2. The first phase entails profit per hectare on the basis of observed data (formulas 1 and 2). In the second phase, the REML model (Spherical) (Section 5.3.1) is used to estimate profit per hectare with the VRT and SR treatments. Separate calculations were performed with regard to VRT and SR application treatments by using formulas (1) and (2) respectively.

Profit_ha	=	Income_ha – Expenditure_ha	**(1)**
Income_ha	=	GrainPrice*(Yield/1000);	
Expenditure_ha	=	ProductionC + RPrecision + RFertiliser + InterestC(a) + InterestC(b);	

ProductionC	=	Production costs	**(a)**
RPrecision	=	Precision cost;	**(b)**
RFertiliser	=	kgFertiliser*FertiliserPrice; (P)	
InterestC(a)	=	Interest cost for precision equipment	**(c)**
InterestC(b)	=	Interest cost for fertiliser	**(d)**

Profit_ha	=	Income_ha – Expenditure_ha	**(2)**
Income_ha	=	GrainPrice*(Yield/1000);	
Expenditure_ha	=	ProductionC + RFertiliser + InterestC(b);	

ProductionC	=	Production costs	**(a)**
RFertiliser	=	kgFertiliser*FertiliserPrice; (P)	
InterestC(b)	=	Interest cost for fertiliser	**(d)**

(a) ProductionC = the variable chemical and KAN/1:0:0 (40) cost for all the other activities. (See Tables 3.5 to 3.7 in Chapter 3 for a list of all the activities and Tables J1 to J3 in Annexure J.)

(b) Table J4 in Annexure J shows the calculation of the above-mentioned cost.

(c) InterestC(a) = the interest cost calculated for the precision equipment needed. (See Table J5 in Annexure J)

(d) InterestC(b) = the interest cost calculated for the phosphate fertiliser applied. (See Table J6 in Annexure J)

Training costs and the time spent by the farmer learning how to use the equipment and analysing data – although essential – are not accounted for. In Annexure J, the calculation of all the costs is shown. The symbols (Constant, Trt, Si and TRTSi) have the same meaning as given in the model in Section 5.2.3, except that profit (ZAR/ha) is now investigated instead of yield.

The calculations are based on each of the three years' grain yield (kg/ha), grain price (ZAR/ton) and P price (ZAR/kg). The other variable costs are based on the actual activities that took place in the fields. The spherical part of the REML model of the profit analysis will accordingly be discussed.

5.3.1 Profit analysis: REML model (Spherical)

This section focuses on the spherical part of the REML model as this is the best fit model. A summary of each field during the three years is given in order to scrutinise the profit in ZAR/ha and the effect of the VRT and SR treatments on the different soil types. No profit function was used. The models were run only on the calculated profit. Table 5.15 shows the estimated profit achieved in field L2.

Table 5.15: ESTIMATED PROFITS FOR L2 DURING THREE INDIVIDUAL YEARS

	Profit – ZAR/ha					
	2004 (Wheat)		2005 (Canola)		2006	
	Estimate	**Pr > |t|**	**Estimate**	**Pr > |t|**	**Estimate**	**Pr > |t|**
Constant	1333.30	.	4022.03	.	-	-
Trt	-213.82	0.0120*	-456.21	0.0324*	-	-
S6	-18.2568	0.7850	18.3857	0.9174	-	-
S7	-4.7406	0.9268	65.1500	0.6398	-	-
S12	-281.70	0.0025**	-388.82	0.1122	-	-
S13	-9.5497	0.9028	-89.5354	0.6706	-	-
S14	-12.4305	0.8662	8.5212	0.9649	-	-
TRTS6	75.8668	0.5003	190.76	0.5442	-	-
TRTS7	73.7725	0.3409	139.77	0.4970	-	-
TRTS12	339.76	0.0233*	101.80	0.7947	-	-
TRTS13	115.44	0.2735	142.37	0.6122	-	-
TRTS14	126.03	0.2813	241.95	0.4363	-	-

* = 0.05

** = 0.01

The profit for the base soil (Gs3) with the base treatment (SR) was ZAR1 333,30/ha (2004), and for 2005 it was ZAR4 022,03/ha. There is a significant statistical difference with the VRT and SR treatments. The Trt (difference between VRT and SR treatments) for both years had P values less than 0.05. The aforementioned means that significant differences were found in comparison to the base soil (Glenrosa, Gs3). The VRT treatment was always taken as a value compared to 1. The negative coefficient means that the VRT treatment obtained a profit of ZAR213,82/ha less than that obtained with the SR treatment on Gs3 in 2004. In 2005, the profit obtained with VRT was ZAR456,21/ha less than that obtained with SR with Gs3. With the Coega (Cg) soil type

(S12) there were also significant statistical differences in 2004 when comparing the profit of the SR treatment between S12 and the Gs3 soil and the profit was ZAR281,70/ha less for the Cg soil. With the VRT treatment (TRTS12) the coefficient was positive in both years but only 2004 show significant statistical differences and this means when comparing the difference in profit of VRT and SR for the Cg soil versus the Gs3 soil, the profit was ZAR339,76/ha more for Cg. During 2005, no statistical significant differences were obtained. According to Table J6a (Annexure J), the cost difference for fertiliser applied was ZAR39,83/ha less with the VRT treatment during 2004. In Table 5.16, the estimated profits obtained on field K3A are shown during the three years under review.

Table 5.16: ESTIMATED PROFITS FOR K3A DURING THREE INDIVIDUAL YEARS

	Profit – ZAR/ha					
	2004 (Wheat)		2005 (Canola)		2006 (Wheat)	
	Estimate	Pr > |t|	Estimate	Pr > |t|	Estimate	Pr > |t|
Constant	1135.72	.	4429.73	.	5775.45	.
Trt	75.3781	0.4425	-317.97	0.1439	267.29	0.3484
S2	43.6771	0.5875	-177.42	0.2916	166.79	0.3941
S8	55.7896	0.5444	174.80	0.3766	195.91	0.3881
TRTS2	49.8948	0.6128	461.93	0.0250*	-231.87	0.3612
TRTS8	68.2776	0.5545	632.40	0.0096**	-656.31	0.0360*

* = 0.05

** = 0.01

According to Table 5.16, the profit had increased from 2004 to 2006 for the base soil with the base treatment (SR). No significant statistical differences were obtained during 2004. Soil type Glenrosa (Gs1) (S1) was used as base soil for discussion except for L2 were Gs3 (S3) was used due to the fact that soil type Gs1 is not found in L2. In 2005 significant statistical differences were found with the VRT treatment on S2 (Glenrosa, Gs2 soil type) (TRTS2) and S8 (Gamoep, Gm soil type) (TRTS8). The difference between the profits of the two treatments namely VRT and SR was ZAR461,93/ha more with the Gs2 soil versus Gs1 and with the Gm soil it was ZAR632,40/ha more. In the 2005 production year, the best statistical differences were obtained. During this year the cost per ha of fertiliser applied was ZAR16,89/ha less with the VRT treatment (Table J6b, Annexure J). During 2006 the only significant statistical difference was with TRTS8 and this means that profit on the Gm soil was ZAR656,31 less than on the Gs1 soil with the VRT treatment. This means that during 2005 the Gm soil produced higher profits with the VRT treatment, but in 2006 it produced lower profits. The same trend can be seen with the Gs2 soil type although no significant statistical differences are evident for this soil in 2006, but the profit in 2005 is higher with VRT and lower in 2006. The estimated profit obtained on field K5 (2004 to 2006) is summarised in Table 5.17.

Table 5.17: ESTIMATED PROFITS FOR K5 DURING THREE INDIVIDUAL YEARS

	Profit – ZAR/ha					
	2004 (Canola)		2005 (Wheat)		2006 (Barley)	
	Estimate	**Pr > |t|**	**Estimate**	**Pr > |t|**	**Estimate**	**Pr > |t|**
Constant	1446.98	.	5420.94	.	4851.15	.
Trt	-62.2129	0.4490	18.5298	0.9088	-929.95	0.0020**
S4	134.10	0.4069	-19.1036	0.9547	-30.8909	0.9294
S13	-302.57	0.0051**	-506.98	0.0084**	-1137.89	<0.0001***
TRTS4	-196.82	0.2409	-184.14	0.5951	-8.4111	0.9819
TRTS13	318.59	0.0504*	403.76	0.1923	1601.75	<0.0001***

* = 0.05

** = 0.01

***=0.0001

Table 5.17 shows that the profit of the base soil with the SR treatment increased from 2004 to 2005 with ZAR3 973,96/ha and then decreased with ZAR569,79/ha from 2005 to 2006. The Glenrosa (Gs1) soil type was used as base and the results for the difference between VRT and SR for this soil is ZAR929,95/ha less profit with VRT. Significant statistical differences were obtained in 2004 and 2005 on the Etosha (Et) soil type (S13). The difference in profit for SR treatments between the Et and Gs1 soil types was ZAR302,57/ha less (2004), in 2005 it was ZAR506,98/ha less and ZAR1 137,89/ha less in 2006. This means that during all three years the Et soil produced smaller profits with the SR treatment than Glenrosa. With the VRT treatment the profits on Et soil type of 2004 and 2006 showed significant statistical differences. The difference between the profits of the two treatments and the two soil types of Et and Gs1 showed that Et produced a profit of ZAR318,59/ha more in 2004 and ZAR1 601,75/ha more in 2006. The results showed that the Et soil reacted better with the VRT treatment. During 2004 and 2005 the fertiliser cost per ha was lower with the VRT treatment, but during 2006 the opposite appeared to be true, because the fertiliser cost per ha was higher with the VRT treatment (Table J6c, Annexure J). In Table 5.18, the estimated profits on K7A over the three production years are shown.

Table 5.18: ESTIMATED PROFITS FOR K7A DURING THREE INDIVIDUAL YEARS

	Profit – ZAR/ha					
	2004 (Canola)		2005 (Wheat)		2006 (Barley)	
	Estimate	Pr > |t|	Estimate	Pr > |t|	Estimate	Pr > |t|
Constant	1318.24	.	4963.19	.	2912.18	.
Trt	88.7432	0.4769	212.72	0.2413	-154.41	0.2249
S2	-75.6170	0.2741	109.41	0.3583	-42.4538	0.5979
S4	-83.1978	0.5029	13.8037	0.9478	-24.4175	0.8618
S11	220.96	0.0087**	146.82	0.3308	-135.82	0.1601
TRTS2	-108.81	0.4671	-262.96	0.2613	222.13	0.1615
TRTS4	122.80	0.3870	29.7660	0.9019	144.33	0.3684
TRTS11	-143.60	0.2488	-156.81	0.4690	259.77	0.0692

* = 0.05

** = 0.01

The same trend as shown in Table 5.17 can be seen in Table 5.18, namely the profit for the base soil with the SR treatment increased from 2004 to 2005 and then decreased from 2005 to 2006. The only significant statistical differences were those obtained on the Cartref (Cf) soil type (S11) in 2004. The difference between the profit of the SR treatment on the Cf and Glenrosa (Gs1) (base) soil types resulted in a positive coefficient and this means the profit of the Cf soil was ZAR220,96/ha more with the SR treatment than Gs1. According to Table J6d, Annexure J, the fertiliser cost per ha was higher during 2004 and 2006 with the VRT treatment.

5.4 CONCLUSION

There are significant differences to be observed between the results obtained with the OLS, SER and REML models (Annexure I) and this may have an impact on decision-making. This fact once again emphasises the importance of taking spatial effects into account. Methodologies not taking these effects into account and thus ignoring spatial dependencies of yield monitor data can cause inaccurate results and conclusions.

Profit analysis based on the application of statistical models indicates that for certain soil types in certain years the VRT treatment resulted in higher profits than the SR treatment (Tables 5.15 to 5.18). It could not be established, based on this study, that yield response to fertiliser depends on soil type, because some soil types delivered higher yields and profits during certain years and performed weaker during others years. One can thus conclude that yield responses and profits differ from year to year and also within the crop rotation system (wheat, canola and barley). The Glenrosa (Gs1 to Gs7) soil type was expected to perform better than the other soil types due to the fact that this soil is a higher potential soil (Section 3.3.1.3.1) for annual dryland crop production. However, this was not the case for all the fields under observation.

There is some resemblance between the results of this study and the profitability conclusions from PA studies as summarised in Table 2.3 by Lowenberg-DeBoer (1996a). The crop, input managed and the costs included in the profitability analysis, all have an influence on the profitability of PA. The most significant influence achieved in this study was the crop in the crop rotation system (the results differed for wheat, canola and barley), as well as the production season and the costs included. The influence of soil type on profitability could not be proved without further doubt.

In Chapter 6, this study will be concluded with a summary of the results achieved, as well as recommendations for further studies.

CHAPTER SIX

SUMMARY AND RECOMMENDATIONS

6.1 INTRODUCTION

The effect of various statistical analyses on the difference between conventional (SR) and precision application (VRT) of phosphorus (P) was investigated. Variable-rate (VRT) and standard-rate (SR) applications of P were investigated. The responses of wheat, barley and canola in a crop rotation system to these applications were investigated over a period of three years (2004 – 2006) in the Heidelberg district of the Western Cape Province in South Africa. The design and experimental procedure used did not cause major disruption to the normal farming activities. The value of VRT applications was measured by comparing the profit achieved with the application of P in the presence and absence of precision information and technology.

The results of the study indicated that the profitability of the VRT application of P can be successfully evaluated with on-farm trials in conjunction with spatial econometrics. Yield monitor and VRT P application data were analysed and spatial models taken into account due to the spatial effects inherent in this type of data. The results obtained were presented and compared using the traditional statistical analysis method namely ordinary least squares (OLS) and the spatial analysis method namely the spatial error (SER) model and the geo-statistical approach to spatial regression, as well as the restricted maximum likelihood (REML) geo-statistics approach. All the measures of goodness of fit (Table 5.1 and 5.3) indicated an increase in fit from the OLS to the SER model, with the best fit being achieved with the REML model, implying that the use of this model resulted in more accurate estimates. Tables 5.4 to 5.18 presented the results of the REML model (Spherical).

Collaboration between researchers, farmers and the business sector in order to conduct new research and to address the profitability issues of precision agriculture (PA) under local conditions is also illustrated by this study. Technological improvements such as PA technologies, and specifically the VRT application of fertiliser, can be employed to assess and demonstrate alternative management practices and this can improve the sustainability of agriculture. The following conclusions were generated in hypothesis testing:

1. Spatial econometric models resulted in more accurate estimates than those achieved with the OLS models.
2. It is evident that the winter grain yield response to P varies according to soil type, but it could not be established that yield response to fertiliser depends on a specific soil type.
3. Over a three-year period, the VRT application of P lead to higher profitability compared to the SR application of P.

6.2 SUMMARY OF REGRESSION RESULTS

Baseline model – Diagnostic tests for normality and heteroscedasticity

- The Jacque-Bera (JB) values for each of the four fields for each of the three years were significant at a 1 % probability level.
- The highest Breusch-Pagan (BP) values for the OLS model for 2004 were achieved on K3A, for 2005 it was on L2, and for 2006 it was on K5.
- Field K3A produced the highest BP values for the three years when using the SER model.
- The spatial error model performed better in 2004 and 2006 than in 2005.
- The highest Koenker-Basset (KB) value for 2004 was recorded on K3A, for 2005 it was on L2, and for 2006 it was on K5.

Baseline model – Diagnostic tests for spatial dependence

- The spatial error model produced the best results for all three production years in fields L2, K3A and K5.
- The spatial lag model was more appropriate for use in field K7A during the 2005 and 2006 production years. When a spatial lag model is recommended in crop production functions it is only an acknowledgment that there may be a problem with the structure of the data.

Model selection for spatial differences (regression)

- The R-squared tends to be higher in the SER model for each of the four fields during the three years under review.
- The model with the highest log-likelihood (the REML model) was the best fit.
- The REML model also produced lower akaike information criteria (AIC) values in each of the four fields during the three years under review.

Winter grain response to P variation on different soil types

- The spherical model for REML was the most appropriate for use in each of the four fields during the three years under review.
- During 2004 field L2, the Glenrosa (Gs3) soil produced 271,04 kg/ha more wheat than the Coega (Cg) (S12) soil with the SR treatment. When the VRT treatment was used the Cg soil (TRTS12) produced 300,21 kg/ha more wheat than the Gs3 soil. According to the results the Cg soil reacted better with the VRT treatment (see Table 5.4 in Chapter 5). With reference to Table 5.5, the 2005 production year show no statistical significant differences for canola response to P on different soil types.
- The results of field K3A show the only statistical significant difference is evident during 2005 (Table 5.7). Glenrosa (Gs2) (TRTS2) soil produced 289,76 kg/ha more canola when the VRT treatment was used and the Gamoep (Gm) (TRTS8) soil produced 395,86 kg/ha more canola. The response of wheat to P variation on

different soil types shows no statistical significant differences during 2004 and 2006 (Tables 5.6 and 5.8).

- Although three different crops were planted on field K5 during 2004, 2005 and 2006, statistical significance differences are evident for the same soil type namely Etosha (Et) (S13). During 2004 (Table 5.9), the Glenrosa (Gs1) soil has resulted in 202,07 kg/ha more canola than the Et soil with the SR treatment. With the VRT treatment the Et soil has produced 211,91 kg/ha more canola than Gs1 during 2004. The results during 2005 (Table 5.10) show that Gs1 produced 175,16 kg/ha more wheat than the Et soil with the SR treatment and in 2006 Gs1 produced 963,26 kg/ha more barley. When the VRT treatment was used during 2006 (Table 5.11) the Et soil (TRTS13) produced 1 360,58 kg/ha more barley than the Gs1 soil with the VRT treatment. The results of 2004 and 2006 shows that the Et (TRTS13) soil type reacted better than the Gs1 soil with the VRT treatment.
- The results achieved on K7A indicated that during 2004 (Table 5.12) canola's response to P show the only statistical significant difference on the Cartref (Cf) (S11) soil type and this soil has produced 146,82 kg/ha more canola than the Glenrosa (Gs1) soil. The results achieved for 2005 and 2006 (Tables 5.13 and 5.14) showed that the response of wheat and barley to P was not statistical significant for any of the soil types.
- It is thus evident that winter grain response to P on different soil types showed significant differences between the mean yields (kg/ha) achieved with the VRT and SR treatments with the VRT treatment (TRT) giving the statistically the best results on L2 (2004) (Coega soil), K3A (2005) (Glenrsa and Gamoep soils) and K5 (2004 and 2006) (Etosha soil in both years).

6.3 SUMMARY OF PROFITABILITY ANALYSIS

- With reference to Table 5.15 in Chapter 5, the profit achieved with the difference between the VRT and SR treatment (TRT) of the reference soil, namely Glenrosa (Gs3) was ZAR213,82/ha less with the VRT treatment in 2004 on L2. In 2005 the profit achieved with the VRT treatment was ZAR456,21/ha less than with SR treatment. The Coega (Cg) (S12) soil show also statistical significant differences in 2004 and the profit was ZAR281,70/ha less than the Gs3 soil with the SR treatment. With the VRT treatment (TRTS12) the profit of Cg was ZAR339,76/ha more than Gs1. During 2005 no statistical significance differences were obtained.

- The profitability results of K3A (Table 5.16) shows that in 2005, the Glenrosa (Gs1) soil was used as the reference and statistical significant differences were found with the VRT treatment on the Glenrosa (Gs2) (TRTS2) and Gamoep (Gm) (TRTS8) soil types. The Gs2 soil shows a profit of ZAR461,93/ha higher than Gs1 and on Gm it increased by ZAR632,40/ha more with the VRT treatment. During 2006 the only statistical significant difference is evident on the Gm soil when the VRT treatment was used and the profit was ZAR656,31/ha less on the Gs1 soil.
- The difference between the profit of the VRT and SR treatment (TRT) for the reference soil (Glenrosa, Gs1) shows that the VRT treatment has resulted in ZAR929,95/ha smaller profit than the SR treatment during 2006 on K5 (Table 5.17). Significant differences were achieved in 2004 and 2005 on the Etosha (Et) (S13) soil type and the profit was smaller by ZAR302,57/ha (2004), ZAR506,98/ha less (2005) and ZAR1 137,89/ha (2006) than that achieved with the Gs1 soil when using the SR treatment. When the VRT treatment was used the Et soil types (TRTS13) showed profits of ZAR318,59/ha more in 2004 and ZAR1 601,75/ha more in 2006 in comparison to the Gs1 soil. The higher profits during these two years showed that the Et soil reacted better with the VRT treatment.
- The only statistical significant differences achieved in field K7A (Table 5.18) was with the Cartref (Cf) (S11) soil type. The profit achieved on the Cf soil was ZAR220,96/ha more in 2004 than with the SR treatment on the Glenrosa soil.
- Over a three-year period (2004 to 2006), the profit per ha was higher with the VRT treatment on the following fields for the following soil types in comparison

to the reference soil (namely Glenrosa (Gs3) (L2) and Glenrosa (Gs1) (K3A, K5 and K7A):

- L2 – 2004 – Coega soil type
- K3A – 2005 – Glenrosa (Gs2) and Gamoep soil types
- K3A – 2006 – Gamoep soil type
- K5 – 2004 – Etosha soil type
- K5 – 2006 – Etosha soil type

6.4 LESSONS LEARNT

A number of factors need to be taken into account in future research of PA:

- From the analysis it was not clear whether any specific soil type resulted in better yields (profit) with the VRT treatment.

- When using the split-plot design which implies dividing the field into halves, the uneven number of observations for the different soil types could cause decision-making problems. The number of observations for different soil types in the VRT and SR half of the field were not always the same and this made decision making difficult when representative soil samples were taken in 2005 and 2006.

- There was a big variation in the P-levels over the three-year period.

- The pH level of the soil could also play a role in the availability of P to the crop. The pH level of the soils had been tested but not corrected. P is more available at pH levels of 6,0 to 8,0 and >8,5.

- The four fields identified for the research were not next to each other.

- Data over multiple crop seasons could not be pooled as it was essential to have data at the same location every season. The fact that there were several crops in the data set also complicated the analysis methods used and a year-by-year analysis was therefore done. Differences in drainage capabilities in various areas of the field could have an impact on the potential of the soil, depending on the rainfall amount and distribution in a particular year.

A crop rotation system (see Section 3.3.1.4, Table 3.4) was followed and it was nearly impossible to pool data for the three years as different crops were cultivated and each crop has specific needs regarding fertiliser requirements as well as yield.

Farming is part of a broader environment and it is not possible to control all factors in agriculture as most of these factors are beyond the control of individual farmers.

6.5 LIMITATIONS

Data over the three crop seasons for the same crop could not be pooled. To pool data over multiple crop seasons it is essential to have the data at the same location every season. However, this was not possible as the four experimental fields were situated on two farms. With this limitation acknowledged, the data over two years for the same location (field) were combined under Section 4.2.1.2 in Chapter 4 and the yield distribution was analysed.

6.6 CONCLUSION

The results presented apply to fields L2, K3A, K5 and K7A on the farms Môrelig and Duinerug and it was found that grain responses to P varied from farm to farm, from crop to crop, and even from field to field. Conclusions can thus only be made with regard to the fields studied and no generalisations are possible. The VRT application of P resulted in an increase in yield from the first to the third year on these fields. Three of the four fields showed a statistical significant higher profit when the VRT treatment was used during different study years. As management information and knowledge increased over the three-year study period, better decisions could be made and this also had an effect on the yields obtained. The results of this study were used to adapt management practices as time went on.

BIBLIOGRAPHY

Acquah, H. D. 2009. Comparison of Akaike information criterion (AIC) and Bayesian information criterion (BIC) in selection of an asymmetric price relationship. Department of Agricultural Economics and Extension, University of Cape Coast, Cape Coast, Ghana. E-mail: henrydegraftacquah@yahoo.com. *Journal of Development Agricultural Economics*, 2(1):001-006.

Adrian, A. M., Norwood, S. H. & Mask, P. L. 2005. Producers' perceptions and attitudes toward precision agriculture technologies. *Computers and Electronics in Agriculture*, 48(3):256-271.

Agenbag, G. A. & Tolmay, J. 2008. *Soil tillage guidelines.* Guidelines for the production of small grains in the winter rainfall region. Department of Agronomy and Pastures. University of Stellenbosch, Stellenbosch, South Africa.

Ag Fact Sheet, 2003. *Agriculture: Reasons to celebrate* [online]. Available from: http://www.agday.org/media/agfactsheet.htm [Accessed 21 August 2003].

AGR343. 2004. *Grain production.* Agronomy lecture notes. Cape Institute for Agricultural Training, Elsenburg, South Africa.

Allemann, J. (AllemannJ.SCI@ufs.ac.za), 4 September 2007. *RE: Proefontwerp.* E-mail to E. C. Hough (ellanah@elsenburg.com).

Anderson, D. 2007. *How to conduct research on your farm or ranch* [online]. University of Illinois. Available from: http://www.sare.org/publications/research/crops_research.htm [Accessed 28 August 2007].

Anselin, L., Bongiovanni, R. & Lowenberg-DeBoer, J. 2004. A spatial econometric approach to the economics of site-specific nitrogen management in corn production. *American Journal Agricultural Economics*, 86(3):675-687.

ARC-guidelines. 2008. *Production of small grains in the winter rainfall region. Guidelines 2008.* ARC – Small Grain Institute, Bethlehem, South Africa.

Arnholt, M. W. 2001. *Evaluation of adoption and uses of precision farming technologies.* Master of Agricultural thesis, Environmental, and Development Economics in the Graduate School of the Ohio State University.

Auernhammer, H. 2002. The role of mechatronics in crop product traceability. *Agricultural Engineering International: The CIGR Journal of Scientific Research and Development.* Invited overview paper. Vol. 4. October, 2002. Presented at the club of Bologna meeting, July 27, 2002. Chicago, IL., USA.

Auernhammer, H. & Muhr, T. 1991. GPS in a basic rule for environment protection in agriculture. *Automated Agriculture for the 21st Century*. Institut fuer Landtechnik, Technical University Munich, Germany.

Babcock, B. A. & Pautsch, G. R. 1998. Moving from uniform to variable fertilizer rates on Iowa corn: Effects on rates and returns. *Journal of Agricultural and Resource Economics*, 23(2):385-400.

Batte, M. T. 1999. *Precision farming – factors influencing profitability*. Presented at the Northern Ohio Crops Day, Wood County, Ohio, 21 January 1999.

Batte, M. T. 2003. *Agricultural, environmental, and development economics. Economics of precision farming* [online].
Available from: http://www-agecon.ag.ohio-state.edu/programs/VanBuren/Research-PrecisionFarming.htm [Accessed 7 May 2003].

Boehlje, M. 2002. *U.S. agriculture in an increasingly competitive global market.* [IN 47907-2056. Staff Paper #02-06]. Department of Agricultural Economics, Purdue University, West Lafayette.

Bongiovanni, R. & Lowenberg-DeBoer, J. 2001. Precision agriculture: Economics of nitrogen management in corn using site-specific crop response estimates from a spatial regression model. 11 May 2001. Department of Agricultural Economics, Purdue University, West Lafayette.

Brink, P. (Pieter.Brink@yara.com), 17 September 2008. *RE: Inligting benodig.* E-mail to E. C. Hough (ellana@mkb.co.za).

Bullock, D. S. & Lowenberg-DeBoer, J. 2007. Using spatial analysis to study the values of variable rate technology and information. *Journal of Agricultural Economics*, 58(3):517-535. 2007.

Burger, C. 2009. Personal communication. (Precision agriculture specialist, Nvirocrop, South Africa).

Burger, C. 2010. Personal communication. (Precision agriculture specialist, Nvirocrop, South Africa).

Carr, P. M., Carlson, G. R., Jacobsen, J. S., Nielsen, G. A. & Skogley, E. O. 1991. Farming soils, not fields: A strategy for increasing fertilizer profitability. *Journal of Production Agriculture*, 14(1):57-61.

Christensen, L. & Krause, K. 1995. Precision farming: Harnessing technology. *Agricultural Outlook*. Economic Research Service, USDA.

Clay, D. E., Carlson, C. G, Chang, J., Clay, S. A., Malo, D. D., Ellsbury, M. M. & Lee, J. 2003. *Systematic evaluation of precision farming soil sampling requirements* [online]. Available from: http://www.abs.sdstate.edu/abs/precisionfarm/Precfc1.htm [Accessed 9 May 2003].

Coates, C., Horsburgh, C. & Gleason, T. 2002. *The economics of precision farming* [online]. Available from: http://asuwlink.uwyo.edu/~coates/epf.htm [Accessed 7 May 2003].

Coetsee, J. 2003. Presisie-wingerdkunde stoot gehalte op. *Landbouweekblad*. 24 Oktober 2003.

Cramer, G. L. & Jensen, C. W. 1994. *Agricultural economics and agribusiness*. (6th ed.). New York: John Wiley & Sons.

Crozier, C. R. & Heiniger, R. W. 1998. *Soil facts. Soil sampling for precision farming systems* (AG439-36) [online]. North Carolina Cooperative Extension Service. Available from: http://www.soil.ncsu.edu/publications/Soilfacts/AG-439-36/AG-439-36.pdf [Accessed 24 February 2010].

David, G., Casady, W. & Massey, R. 1998. *Precision agriculture: An introduction.* WQ450, New. University of Missouri Extension. Available from: http://extension.missouri.edu/publications/DisplayPub.aspx?P=WQ450 [Accessed 20 July 2010].

Davis, R. F., Harris, G. H., Roberts, P. M. & MacDonald, G. E. 1999 *Designing research and demonstration tests for farmers' fields* [online]. Cooperative Extension Service. [Bulletin 1177, May 1999]. The University of Georgia College of Agricultural and Environmental Sciences.
Available from: http://pubs.caes.uga.edu/caespubs/pubcd/B1177-w.htm [Accessed 28 August 2007].

Deberten, D. L. 1986. *Agricultural production economics.* New York: MacMillan Publishing Co.

Department of Agriculture, Western Cape. 2009. *Agricultural statistics in brief* [online]. Available from: http://www.elsenburg.com/economics/statistics/start.htm [Accessed 5 May 2009].

Doerge, T. 2002. Yield monitors create on- and off-farm profit opportunities [online]. *Precision Update*, 9(14). Available from: http://www.pioneer.com/canada/crop_management/yield_monitors_canada.htm [Accessed 12 February 2004].

Elstein, D. 2003. *Management zones help in precision agriculture.* Agricultural Research Service (ARS), Pretoria, South Africa.

Engineering Statistics Handbook, 2004. *Exploratory data analysis* [online]. Available from: http://www.itl.nist.gov/div898/handbook/eda.eda.htm [Accessed 21 April 2008].

English, B. C., Roberts, R. K. & Sleigh, D. E. 2000. *Spatial distribution of precision farming technologies in Tennessee.* [Research report 00-08, February 2000]. Department of Agricultural Economics and Rural Sociology, University of Tennessee.

Fiez, T. E., Miller, B. C. & Pan, W. L. 1994. Assessment of spatially variable nitrogen fertilizer management in winter wheat. *Journal of Production Agriculture*, 7(1):17-18, 86-93.

Fleming, K. L., Westfall, D. G. & Wiens, D. W. [s.a.]. Field testing management zones for VRT. *Site-specific management guidelines* [SSMG-21]. Published by the Potash & Phosphate Institute (PPI). Coordinated by South Dakota State University

(SDSU). Sponsored by the United Soybean Board (USB) and the Foundation for Agronomic Research (FAR). For more information www.ppi-far.org.ssmg

Florida Institute of Phosphate Research. 2004. *Phosphate and organic fertilization, History of phosphate fertilizer production and Introduction: phosphate as an essential mineral* [online]. Available from: http://www1.fipr.state.fl.us/Phosphate [Accessed 12 March 2008].

Fountas, S., Pedersen, S. M. & Blackmore, S. [s.a.] *ICT in precision agriculture – diffusion of technology*. Department of Crop Sciences and Rural Environment, University of Thessaly, Greece, Danish Research Institute of Food Economics, The Royal Veterinary and Agricultural University, Denmark, Institute of Agricultural Sciences, The Royal Veterinary and Agricultural University, Denmark.

Frick, D. 2003. *KEE technologies – Electronic systems for harsh environments* [online]. Available from: http://www.kee.com.au/news/news.htm [Accessed 9 May 2003].

Gandonou, J., Stombaugh, T. S., Dillon, C. R. & Shearer, S. A. 2001. *Precision agriculture: A break-even acreage analysis* [Paper Number: 01-1029]. The Society for Engineering in Agricultural, Food and Biological Systems, Sacramento Convention Center, Sacramento, California, USA, 30 July – 1 August 2001. Written for presentation at the 2001 American Society of Agricultural Engineers Annual (ASAE) internationally meeting.

Genis, A. 2009. Ou masjinerie is tydbom. *Landbouweekblad*, 15 Mei 2009.

Gildenhuys, T. 2003. Personal communication (Farmer, Heidelberg region of the Western Cape, South Africa).

Gildenhuys, M. 2009. Personal communication (Farmer, Heidelberg region of the Western Cape, South Africa).

Godwin, R. J. 2000. *Precision farming – a multidisciplinary approach for cereal production*. Keynote speech for SEAg2000 "Growing Links", The Institution of Engineers, Adelaide, Australia, 2-5 April 2000. Published in *Landwards*, Summer 2000, 55(2):4-9.

Gold, M. V. 1999. *Sustainable agriculture: Definitions and terms.* [Special Reference Briefs Series no. SRB 99-02. Updates SRB 94-05. September 1999]. Alternative Farming Systems Information Center, National Agricultural Library, Agricultural Research Service, U.S. Department of Agriculture. Beltsville, MD.

Gouws, A. 2002. *Presisiebemesting haal raaiwerk uit beplanning* [online]. Available from: http://15.111.1.42/cgi/nph-bwcgis/LBW [Accessed 7 June 2002].

Grego, S. 2001. *Introduction to phosphate as a fertilizer* [online]. Available from: http://www1.fipr.state.fl.us/PhosphatePrimer [Accessed 12 March 2008].

Griffin, T. W., Brown, J. P. & Lowenberg-DeBoer, J. 2005. *Yield monitor data analysis: Data acquisition, management and analysis protocol* [Version 1, August 2005]. Department of Agricultural Economics, Purdue University.

Griffin, T. W., Brown, J. P. & Lowenberg-DeBoer, J. 2007. *Yield monitor data analysis protocol: A primer in the management and analysis of precision agriculture data*. [Version 2, June 2007]. Department of Agricultural Economics, Purdue University.

Griffin, T. W. & Lowenberg-DeBoer, J. 2008. *Spatial analysis of precision agriculture data: Role of extension*. Selected paper presented at the Southern Agricultural Economics Association Annual Meeting, Dallas, TX, February 2-6, 2008.

Griffin, T.W., Lowenberg-DeBoer, J., Lambert, D.M., Peone, J., Payne, T. & Daberkow, S.G. 2004. *Adoption, profitability, and making better use of precision farming data*. Staff paper#04-06. Department of Agricultural Economics, Purdue University.

Grisso, R., Alley, M., Phillips, S. & McClellan, P. 2009. *Interpreting yield maps – "I gotta yield map – now what?"* [online]. Virginia Cooperative Extension, College of Agriculture and Life Sciences, Virginia Polytechnic Institute and State University. Available from: http://pubs.ext.vt.edu/442/442-509/442-509.html [Accessed 18 February 2010].

Groenewald, A. 1999. Jongste tegnologie vir kunsmistoediening ingespan. *Landbou-weekblad*, 22 October 1999.

Helm, C. 2005. Precision farming in South Africa. *Proceedings of FarmTech 2006. Global Perspectives, Local Knowledge*. pp. 76-79. Foundation of Alberta. Held at Mayfield Inn & Suites, Edomonton, Canada.

Herbert, S., Hashemi, M., Chickering-Sears, C. & Weis, S. [s.a.] *Guidelines to nitrogen application on agronomic crops in Massachusetts* [online]. Fact sheet. UMass Extension Crops, Dairy, Livestock, Equine. Available from: http://www.umass.edu/cdl. [Accessed 30 October 2009].

Holmes, P. M. 2005. Results of a lucerne old-field restoration experiment at the Fynbos-Karoo interface. *South African Journal of Botany* 71(3&4): 326-338[online]. Available from: http://www.nisc.co.za/oneAbstract?absId=1338&print=true [Accessed 28 August 2007].

Hugo, M. L., Viljoen, A. T. & Meeuwis, J. M. 1997. *The ecology of natural resource management. The quest for sustainable living. A text for South African students*. Pretoria: Kagiso.

Jaiswal, J. P. 2009. Soil requirements in wheat. Posted in *Soil Wheat India*. 24 March 2009. Available from: http://agropedia.iitk.ac.in/?q=content/soil-requirement-wheat [Accessed 18 February 2010].

Johannsen, C. J., Arvik, J. H. & Berglund, J. 1996. Information requirements for agriculture: The next decade [online]. *Proceedings of the Workshop on Remote Sensing for Agriculture in the 21st Century*, 23-25 October 1996. Available from: http://www.cstars.ucdavis.edu/projects/ag-21/ag21files/cjohann.html [Accessed 19 February 2001].

Khanna, M., Epouhe, O. F. & Hornbaker, R. 1999. Site-specific crop management: Adoption patterns and incentives. *Review of Agricultural Economics*, 21(2):455-472.

Kleinjan, J., Chang, J., Wilson, J., Humburg, D., Carlson, G., Clay, D. & Long, D. 2004. *Cleaning yield data*. Available from: http://plantsci.sdstate.edu/precisionfarm/paper/papers/Cleaning%20Yield%20Data.pdf. [Accessed 5 March 2010].

Kowalski, S. M. & Potcher, K. J. 2003. *How to recognize a split-plot experiment.* Experimental Design. Quality Progress Discussion Board. Available from: http://www.asq.org or e-mail at editor@asq.org.

Lambert, D. & Lowenberg-DeBoer, J. 2000. *Precision agriculture profitability review*. Site-specific Management Center, School of Agriculture, Purdue University.

Lambert, D. M., Lowenberg-DeBoer, J. & Bongiovanni, R. 2003. *Spatial regression models for yield monitor data: A case study from Argentina.* Paper presented at the American Agricultural Economics Association Annual Meeting, Montreal, Canada, July 27-30, 2003.

Lambert, D. M., Lowenberg-DeBoer, J. & Bongiovanni, R. 2004. A comparison of four spatial regression models for yield monitor data: A case study from Argentina. *Precision Agriculture* (5):579-600.

Leedy, P. D. & Ormrod, J. E. 2005. *Practical research: Planning and design.* 8th edition. New Jersey: Prentice Hall.

Le Roux, P. A. L. 2008. Personal communication. (Lecturer in soil science. Department of Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein, South Africa).

Lenz, D. 1996. *Calculating profitability of grid soil sampling and variable rate fertilizing for sugar beets.* Proceedings of the Third International Conference on Precision Agriculture, June 23-26, 1996. Minneapolis, Minnesota.

LeSage, J. P. 1998. *Spatial econometrics.* MATLAB Guide. Department of Economics, University of Toledo.

Link, J., Graeff, S., Batchelor, W. D. & Claupein, W. 2006. Evaluating the economic and environmental impact of environmental compensation payment policy under uniform and variable-rate nitrogen management. *Agricultural Systems*, 91(1-2):135-153.

Lowenberg-DeBoer, J. 1996a. *Economics of precision farming: Payoff in the future* [online]. Purdue University. Available from: http://pasture.ecn.purdue.edu/~mmorgan/PFI/pfiecon.html [Accessed 26 June 2003].

Lowenberg-DeBoer, J. 1996b. Precision farming and the new information technology: Implications for farm management, policy, and research: Discussion. *American Journal of Agriculture Economics*, 78(5):1281-1284.

Lowenberg-DeBoer, J. 2003. Precision farming or convenience agriculture [online]. *Proceedings of the 11th Australian Agronomy Conference*, Geelong, 2003. Available from: http://www.regional,org.au/au/asa/2003/i//6/lowenberg.htm [Accessed 26 June 2003].

Lowenberg-DeBoer, J. & Erickson, B. 2010. *The search for the killer app. Precision farming in Africa.* GJIA. Georgetown. Journal of International Affairs. Summer/Fall 2010.

Maine, N. 2006. *The profitability of precision agriculture in the Bothaville district*. Ph.D. thesis, Department of Agricultural Economics (Agricultural Management), Faculty of Natural and Agricultural Sciences, University of the Free State, Bloemfontein, South Africa.

Maine, N., Nell, W. T., Alemu, Z. G. & Barker, C. 2006. *Economic analysis of N and P applications under variable rate and whole field strategies in the Bothaville district* [online]. Department of Agricultural Economics (Agricultural Management), University of the Free State, Bloemfontein, South Africa. Available from: http://www.farmingsuccess.com/economic.htm [Accessed 31 August 2007].

Matela, N. 2002. *The status of precision agriculture in cash crop production in South Africa.* M. Agric. dissertation, University of the Free State, Bloemfontein, South Africa.

McCann, B. L., Pennock, D. J., Van Kessel, C. & Walley, F. L. 1996. The development of management units for site-specific farming. *Proceedings of the Third International Conference on Precision Agriculture*, June 23-26, 1996. Minneapolis, Minnesota.

Murakami, E., Saraiva, A. M., Ribeiro Jnr L. C. M., Cugnasca, C. E., Hirakawa, A. R., & Correa, P. L. P. 2007. An infrastructure for the development of distributed service-oriented information systems for precision agriculture. *Computers and Electronics in Agriculture*, 58(1):37-48.

Murdoch, J. (jacquesm@elsenburg.com), 23 August 2007. *RE: Statistiek oor graan produksie.* E-mail to E. C. Hough (ellanah@elsenburg.com).

National Agricultural Marketing Council. *Input cost monitor: The story of potatoes.* Strategic positioning of South African Agriculture in dynamic global markets. March 2009. Pretoria: NAMC.

Nell, W. T., Maine, N. & Basson, P. M. 2006. Africa, Part III: Current status: In: A. Srinivasan (Ed.), *Handbook of precision agriculture: Principles and applications*. New York: Food Products Press, Chapter 17:465-500.

Nell, W. T. & Napier, R. J. 2009. *Strategic approach to farming success*. Second revised edition. Bloemfontein, South Africa: Wim Nell, Agricultural Management Consultant.

NJF Seminar No. 336. 2002. *Implementation of precision farming in practical agriculture*. Summary of the seminar and final discussions at the NJF (Nordic

Association of Agricultural Scientists Seminar No. 336 on 10-12 June 2002, Skara Stadshotell, Skara, Sweden.

News Announcements. 2003. Council for scientific and industrial research (CSIR) Satellite Applications Centre (SAC). Available from: http://www.sac.co.za/announcements/main.html [Accessed 21 August 2003].

Oberholzer, B. 2004. *Soil survey of portions of the farms Môrelig and Duinerug near Heidelberg in the Western Cape*. March 2004. Soil survey report.

Oberholzer, B. 2007. Reasons and procedures for soil preparation. *Wynboer*. *A Technical Guide for Wine Producers.* Paarl, South Africa.

OMAFRA Staff. 1 March 2002. On-farm trials. In: *Agronomy Guide for Field Crops* (Chapter 1) [online]. Ministry of Agriculture, Food and Rural Affairs. Available from: http://www.omafra.gov.on.ca/english/crops/pub811/1oftrials.htm [Accessed 16 August 2007]

Oriade, C. A., King, R. P., Forcella, R. & Gunsolus, J. L. 1996. A bioeconomic analysis of site-specific management for weed control. *Review of Agricultural Economics*, 18:523-535.

Pautsch, G. R., Babcock, B. A. & Breidt, F. J. 1998. *Optimal sampling under a geostatistical model*. CARD Working Paper 98-WP 200. October 1998. Center for agricultural and rural development (CARD) at Iowa State University.

Powers, L. A., Dillon, C. R., Issacs, S. G. & Shearer, S. A. 2003. *Risk management in precision agriculture.* Selected paper presented at the Southern Agricultural Economics Association Annual Meeting, Mobile, Alabama, February 1-5, 2003.

Pretorius, L. 2000. Presisieboerdery bring nuwe woema vir mieliebedryf, *Landbou-weekblad* [online]. Available from: http://152.111.1.42/cgi/nph-bwcgis/LBW [Accessed 21 Januarie 2000].

Pretorius, L. 2001. Boer met 'n plan: Pioneer-mielieman se presisieboerdery, *Landbouweekblad* [online]. Available from: http://152.111.1.42/cgi/nph-bwcgis/LBW [Accessed 16 November 2001].

Project Proposal S-283. 1998. *Develop and assess precision farming technology and its economic and environment impacts* [online]. Project number: S-283 (Southern regional project). Available from: http://www.bae.uky.edu/precag/PrecisionAg/Reports/S283/s283_prop.htm [Accessed 5 December 2006].

PNS (Proteiennavorsingstigting). 2008. Canola Handleiding (Canola Manual). Rivonia, Johannesburg, South Africa.

Queensland Government. 1995-2010. *Precision farming in the northern grains region: Using variable rate technology (VRT) in cropping land.* The State of Queensland: Department of Employment, Economic Development and Innovation. Available from: http://www2.dpi.qld.gov.au/fieldcrops/14216.html. [Accessed 20 July 2010].

Rainbow, R. [s.a.] *Getting into precision agriculture*. Southern Precision Agriculture Association (SPAA). Executive and Scientific Officer. Available from: http://www.bcg.rog.au/resources/rainbow2.pdf [Accessed 5 May 2010].

Rehm, G. W., Lamb, J. A., Davis, J. G. & Malzer, G. L. 1996. P and K grid sampling: What does it yield us? *Proceedings of the Third International Conference on Precision Agriculture*, June 23-26, 1996, Minneapolis, Minnesota.

Reichenberger, L. 2003. Learn the most from yield maps. Farmers share findings of new technology. *Successful Farming*. Precision Ag. Agro Connect. December 2003.

Rilwani, M. L. & Ikhuoria, I. A. 2006. Precision farming with geoinformatics: A new paradigm for agricultural production in a developing country. *Transactions in GIS*, 10(2):177-197.

Roberts, R. K., English, B. C. & Larson, J. A. 2002. Factors affecting the location of precision farming technology adoption in Tennessee [online]. *Journal of Extension*, 10(1). Available from: http://www.joe.org/joe/2002/february/rb3.html [Accessed 26 June 2003].

Robinson, E. 2005. *Variable-rate phosphate helps rice* [online]. Delta Farm Press. Available from: http://www.printthis.clickability.com/pt/cpt?action=cpt&title=Variable-rate+phosphate [Accessed 25 February 2005].

SAB Maltings (Pty.) Ltd. 2008. *Barley recommendations*. ARC – Small Grain Institute. South African Barley Breeding Institute (SABBI), Bethlehem, South Africa.

Sadler, E. J., Jones, J. W. & Sudduth, K. A. 2007. Modelling for precision agriculture: how good is good enough, and how can we tell? *Precision Agriculture*, '07:241-248. United States Department of Agriculture (USDA) – Agriculture Research Service (ARS), Columbia, MO 65211. University of Florida, Gainesville, FL 32611. United States of America.

SAS OnlineDoc™: Version 8. [s.a.] Chapter 30:1477-1538. *The GLM Procedure*. Available from: www.uc/edu/sashtml/ [Accessed 5 March 2010].

Schoeman, B. USDA agricultural projections to 2018. Projections Markets, *SA Graan/Grain*. April 2009.

Shearer, S. A., Fulton, J. P., McNeill, S. G., Higgins, S. F. & Mueller, T. G. [s.a.] *Elements of precision agriculture: Basics of yield monitor installation and operation.* Cooperative Extension Service, University of Kentucky, College of Agriculture.

Snyder, C., Schroeder, T., Havlin, J. & Kluitenberg, G. 1996. An economic analysis of variable rate nitrogen management. *Proceedings of the Third International Conference on Precision Agriculture*, June 23-26, 1996. Minneapolis, Minnesota.

Soil classification working group. 1991. *Soil Classification. A Taxonomic System for South Africa.* Research Institute for Soil and Irrigation. Department of Agricultural Technical Services, Pretoria.

Solohub, M. P., Van Kessel, C. & Pennock, D. J. 1996. The feasibility of variable rate N fertilization in Saskatchewan. *Proceedings of the Third International Conference on Precision Agriculture*, June 23-26, 1996. Minneapolis, Minnesota.

Southern Precision Agriculture Association (SPAA). [s.a.] *Finding the dollar return from PA.* Available from: http://www.spaa.com/au

Srinivasan, A. 1998. *Relevance of precision farming technologies to sustainable agriculture in Asia and the Pacific* [online]. Geospatial Analysis Center, Regional Science Institute. Available from: http://www.sristi.org.in/mtsa/s_7_4.htm [Accessed 19 February 2004].

Staben, M. L., Ellsworth, J. W., Sullivan, D. M., Horneck, D., Brown, B. D. & Stevens, R. G. 2003. *Monitoring soil nutrients using a management unit approach*. A Pacific Northwest Extension Publication (PNW 570-E), Oregon State University, University of Idaho, Washington State University. Available from: http://extension.oregonstate.edu/catalog/pdf/pnw/pnw570-e.pdf [Accessed 25 February 2010].

Stats SA. 2002. *Number of farming units and gross farming income by province.* Pretoria, South Africa.

Statistical Services Centre. 2007. On-farm trials – Some biometric guidelines. *Statistical good practice guidelines* [online]. Statistical Services Centre, University of Reading. Available from http://www.reading.ac.uk/ssc/publications/guides/topoft.html [Accessed 16 August 2007]

Stombaugh, T. S., Mueller, T. G., Shearer, S. A., Dillon, C. R. & Henson, G. T. 2001. *Guidelines for adopting precision agriculture practices.* Cooperative Extension Service. University of Kentucky, College of Agriculture.

Swinton, S. M. 2004. *Precision farming as green and competitive* [online]. Department of Agricultural Economics, Michigan State University. Available from: http://www.aec.msu.edu/agecon/smith_endowment/documents/swinton.htm [Accessed 12 February 2004].

Swinton, S.M. & Lowenberg-DeBoer, J. [s.a.] *Global adoption of precision agriculture technologies: Who, when and why?* Department of Agricultural Economics, Michigan State University, USA. E-mail: swintons@msu.edu. Department of Agricultural Economics, Purdue University, USA. E-mail: lowenberg-deboer@agecon.purdue.edu.

Swinton, S. M. & Lowenberg-DeBoer, J. 1998. Profitability of site-specific farming. *Site-specific management guidelines*. SSMG-3. Published by the potash and phosphate institute (PPI). Coordinated by South Dakota State University (SDSU).

Taylor, O. 1998. Yield monitors are marketing tools. *Soybean Digest,* October, p. 6.

Thrikawala, S., Weersink, A., Kachanoski, G. & Fox, G. 1999. Economic feasibility of variable-rate technology for nitrogen on corn. *American Journal of Agricultural Economics*, 18:914-927.

Valenzuela, H. & Smith, J. 2002. *Barley. Sustainable agriculture green manure crops*. August 2002 (SA-GM-3). Cooperative Extension Service, College of Tropical Agriculture and Human Resources, University of Hawai'i at Månoa, Departments of Tropical Plant and Soil Sciences and Natural Resources and Environmental Management.

Van der Merwe, D. 2009. Personal communication. (GIS specialist. Department of Agriculture: Elsenburg, Western Cape, South Africa.).

Van Rooyen, C. 2003. Presisieboerdery reik na nuwe hoogtes [online]. *Landbouweekblad*. Available from: http://152.111.1.42/cgi/nph-bwcgis/LBW [Accessed 18 Julie 2003].

Van Rooyen, C. 2004. *Nuus*: Misstofvereniging-kongres – Presisieboerdery neem toe [online]. *Landbouweekblad.* Available from: http://152.111.1.42/cgi/nph-bwcgis/LBW [Accessed 2 Julie 2004].

Van Rooyen, C. 2007. Kunsmis se pryse en verkope gaan styg. *Landbouweekblad*. 22 Junie 2007.

Van Rooyen, C. & Jordaan, J. 2002. Presisieboerdery kan werk, maar verg beplanning [online]. *Nampo-Oesdag, Bylae tot Landbouweekblad*: Available from: http://152.111.1.42/cgi/nph-bwcgis/LBW [Accessed 3 Mei 2002].

Venter, Annelie. 2008. Personal communication. (Scientist, Agricultural Research Council, Institute for soil, climate and water, Pretoria, South Africa.)

Weiss, M. D. 1996. Precision farming and spatial economic analysis: Research challenges and opportunities. *American Journal of Agricultural Economics*, 78:1275-1280. American Agricultural Economics Association.

Wentzel, R. (WentzelR@arc.agric.za), 20 April 2009. *RE: FWD:Weerdata.* E-mail to E. C. Hough (ellana@mkb.co.za).

Whitcomb, P. & Kraber, S. 2002. *PCR process optimized via split-plot DOE.* Stat-Ease Inc. Minneapolis. Available from: http://www.statease.com/pubs/pcr_via_split-plot.pdf [Accessed 26 July 2010].

Whitley, K. M., Davenport, J. R. & Manley, J. R. 2000. Differences in nitrate leaching under variable and conventional nitrogen fertilizer management in irrigated potato systems. *Proceedings of the 5th International Conference on Precision Agriculture*, Bloomington, Minnesota, USA, 16-19 July, 2000. Editors: Robert, P. C., Rust, R. H. & Larson, W. E.

Wittry, D. J. & Mallarino, A. P. 2004. Comparison of uniform- and variable-rate phosphorus fertilization for corn-soybean rotations. *Agronomy Journal*, 96:26-33.

Wollenhaupt, N. C. & Buchholz, D. D. 1993. Profitability of farming by soils. In P. C. Robert, R. H. Rust & W. E. Larso n(Eds.), *Proceedings of soil specific crop management: A workshop on research and development issues*, pp. 199-211, April 14-16, 1992. Minneapolis, MN. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Yara [s.a.] *Basic soil and plant nutrition manual* [online]. Yara International ASA, Bygdøy allé 2, N-0202, Oslo, Norway. Available from: http://www.yara.com [Accessed 24 February 2010]

Zeilinga, V. 2004. *Evaluering van verskillende metodes om bestuursone in die sentrale akkerboustreek te identifiseer*. M. Agric. dissertation, University of the Free State, Bloemfontein, South Africa.

LIST OF ANNEXURES

ANNEXURE E

ANNEXURE F

ANNEXURE G

ANNEXURE H

ANNEXURE I

ANNEXURE J

Annexure A

TABLE A1: COST FOR HIRING EQUIPMENT

	ZAR (for four fields)
Equipment for soil profiles	3 517,47
Consultant	2 405,40
TOTAL	5 922,87

TABLE A2: COST FOR PHYSICAL AND CHEMICAL ANALYSIS OF SOIL SAMPLES FOR 2004

4 fields (106 ha)	
165 soil samples	
	PHYSICAL ANALYSIS (ZAR)
ZAR20,00 per analysis	3 300,00
Subtotal	3 300,00
	CHEMICAL ANALYSIS (ZAR)
ZAR46,50 per standard sample	7 672,50
ZAR27,00 (N)	4 455,00
ZAR11,00 (Boron)	1 815,00
ZAR7,00 each (Copper, Zink and Magnesium)	3 465,00
ZAR20,00 (Sulphur)	3 300,00
Subtotal	20 707,50
TOTAL	**24 007,50**

TABLE A3: COST FOR PHYSICAL AND CHEMICAL ANALYSIS OF SOIL SAMPLES FOR 2005

4 fields (106 ha)	
35 soil samples	
	CHEMICAL ANALYSIS (ZAR)
ZAR46,50 per standard sample	1 627,50
ZAR27,00 (N)	945,00
ZAR11,00 (Boron)	385,00
ZAR7,00 each (Copper, Zink and Magnesium)	735,00
ZAR20,00 (Sulphur)	700,00
TOTAL	**4 392,50**

TABLE A4: COST FOR PHYSICAL AND CHEMICAL ANALYSIS OF SOIL SAMPLES FOR 2006

4 fields (106 ha)	
35 soil samples	
	CHEMICAL ANALYSIS (ZAR)
ZAR46,50 per standard sample	1 627,50
ZAR27,00 (N)	945,00
ZAR11,00 (Boron)	385,00
ZAR7,00 each (Copper, Zink and Magnesium)	735,00
ZAR20,00 (Sulphur)	700,00
TOTAL	**4 392,50**

Annexure B

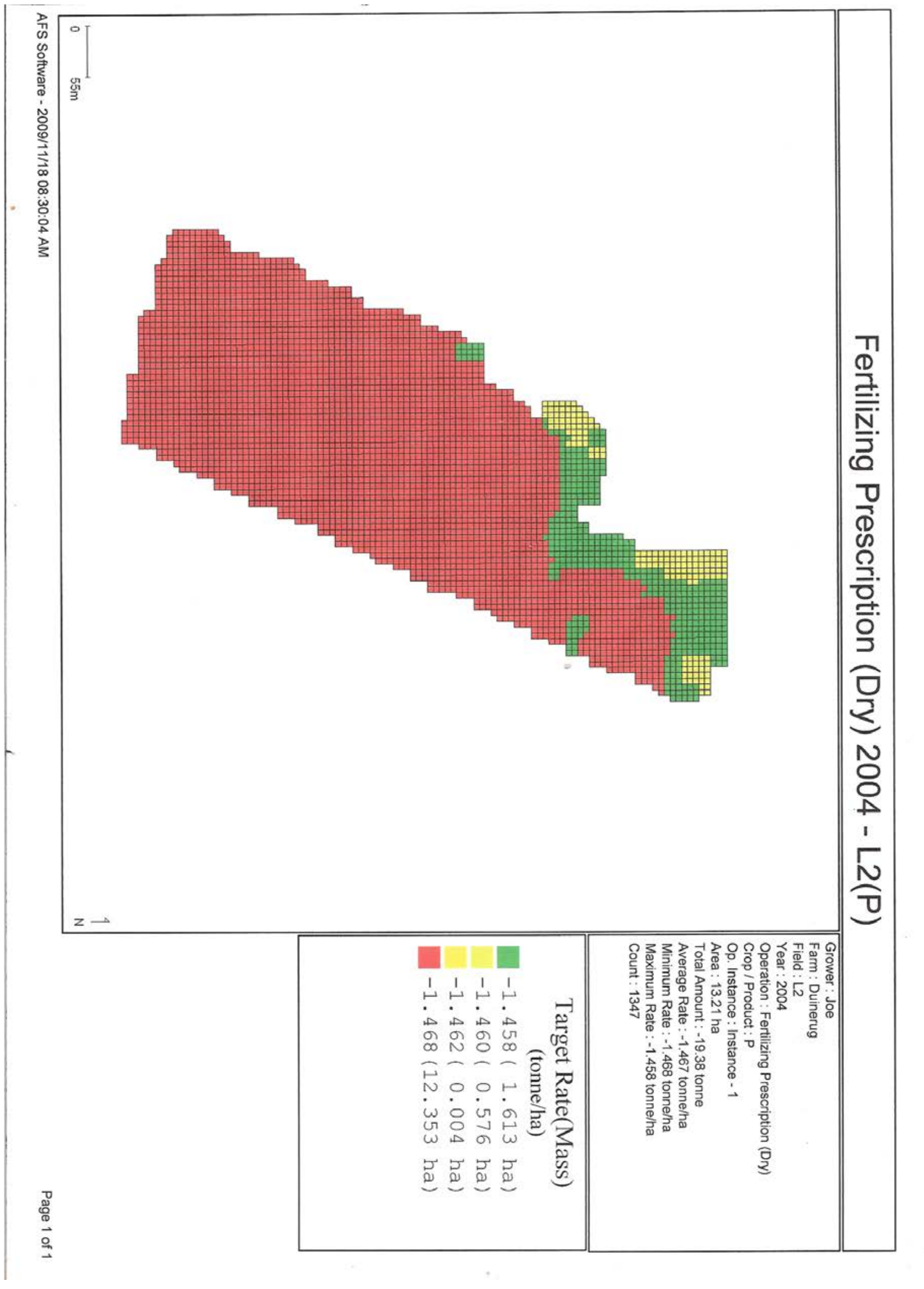


Figure B1: Application map (L2 – 2004)

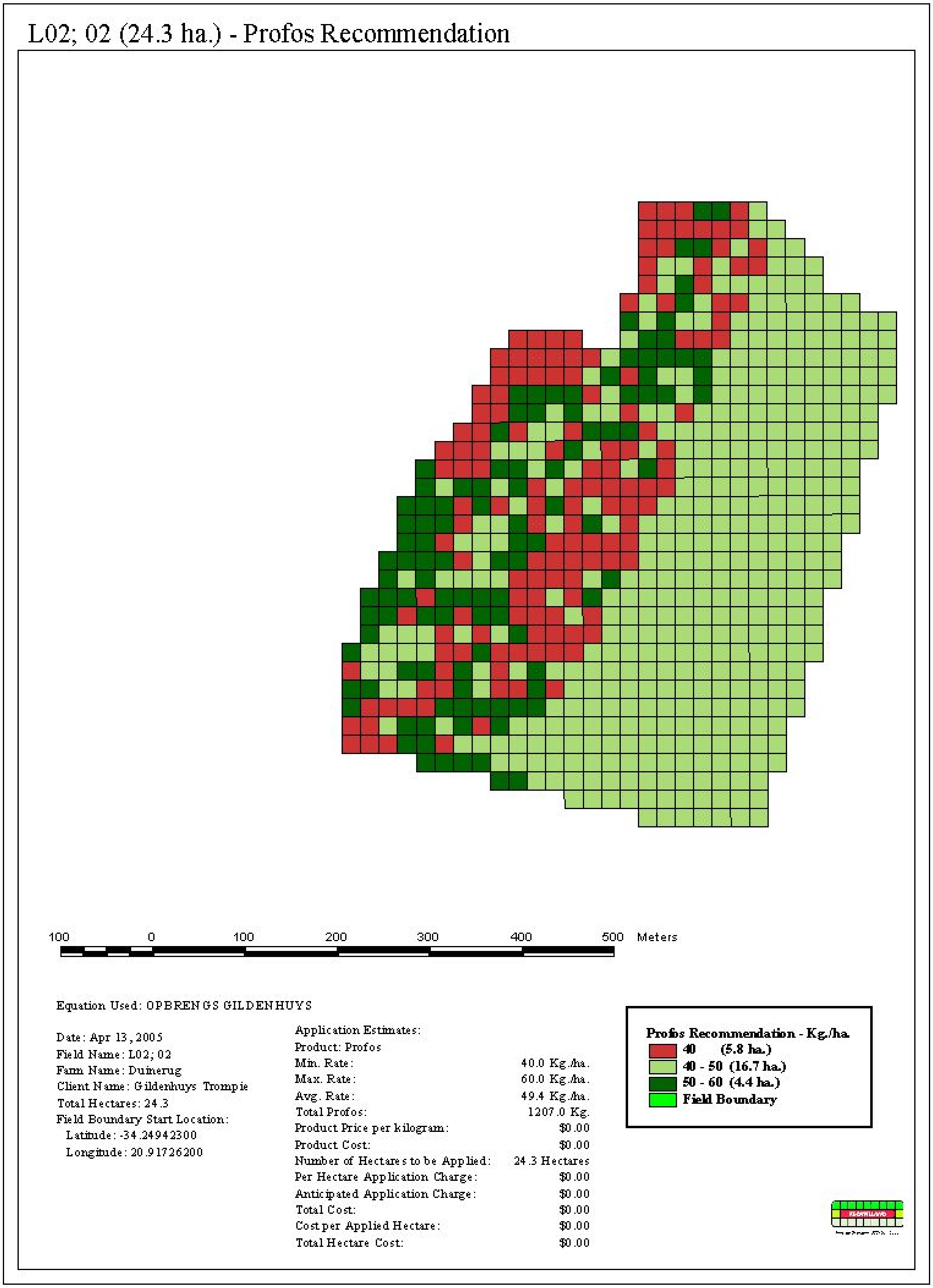


Figure B2: Application map (L2 – 2005)

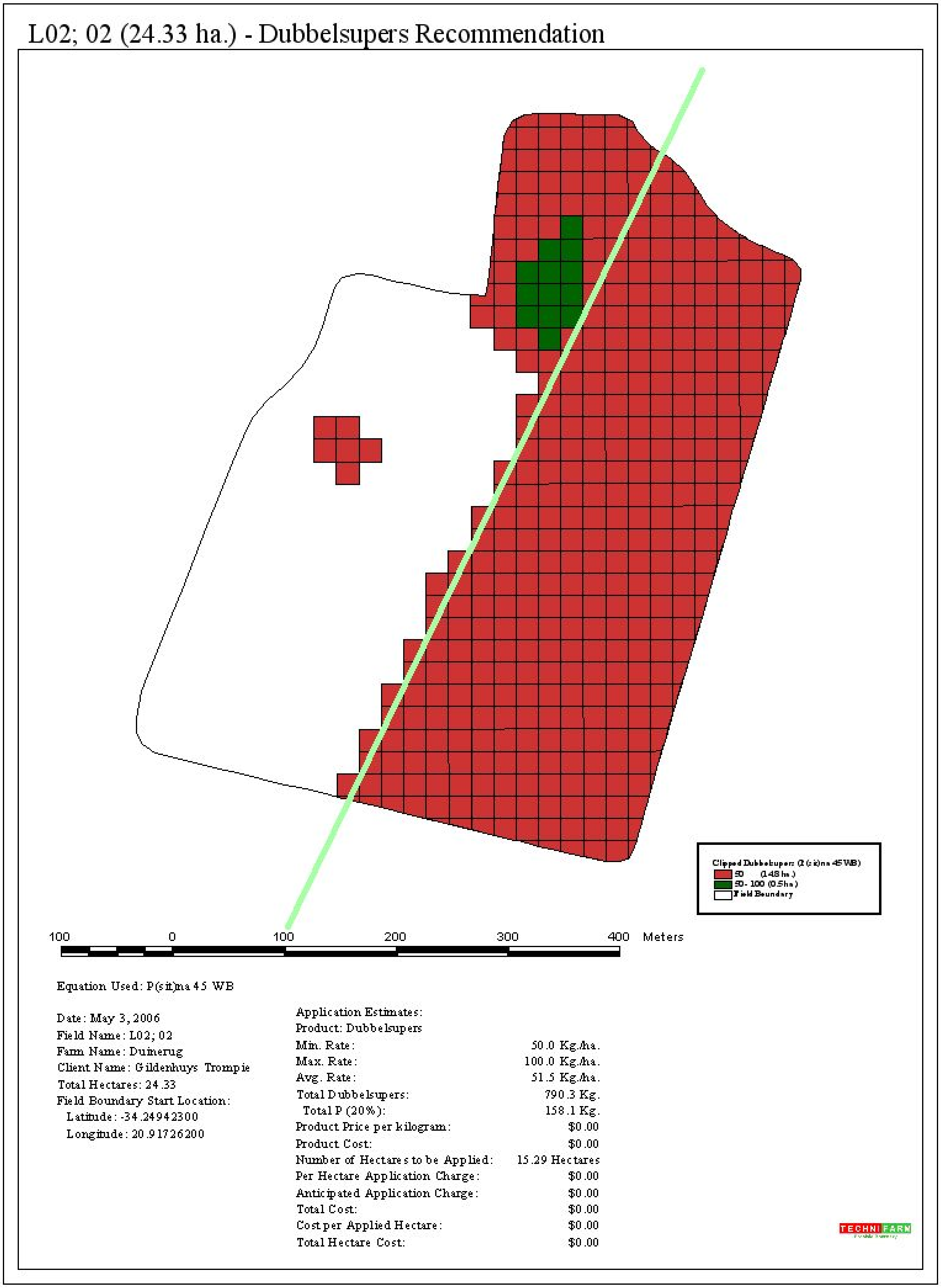


Figure B3: Application map (L2 – 2006)

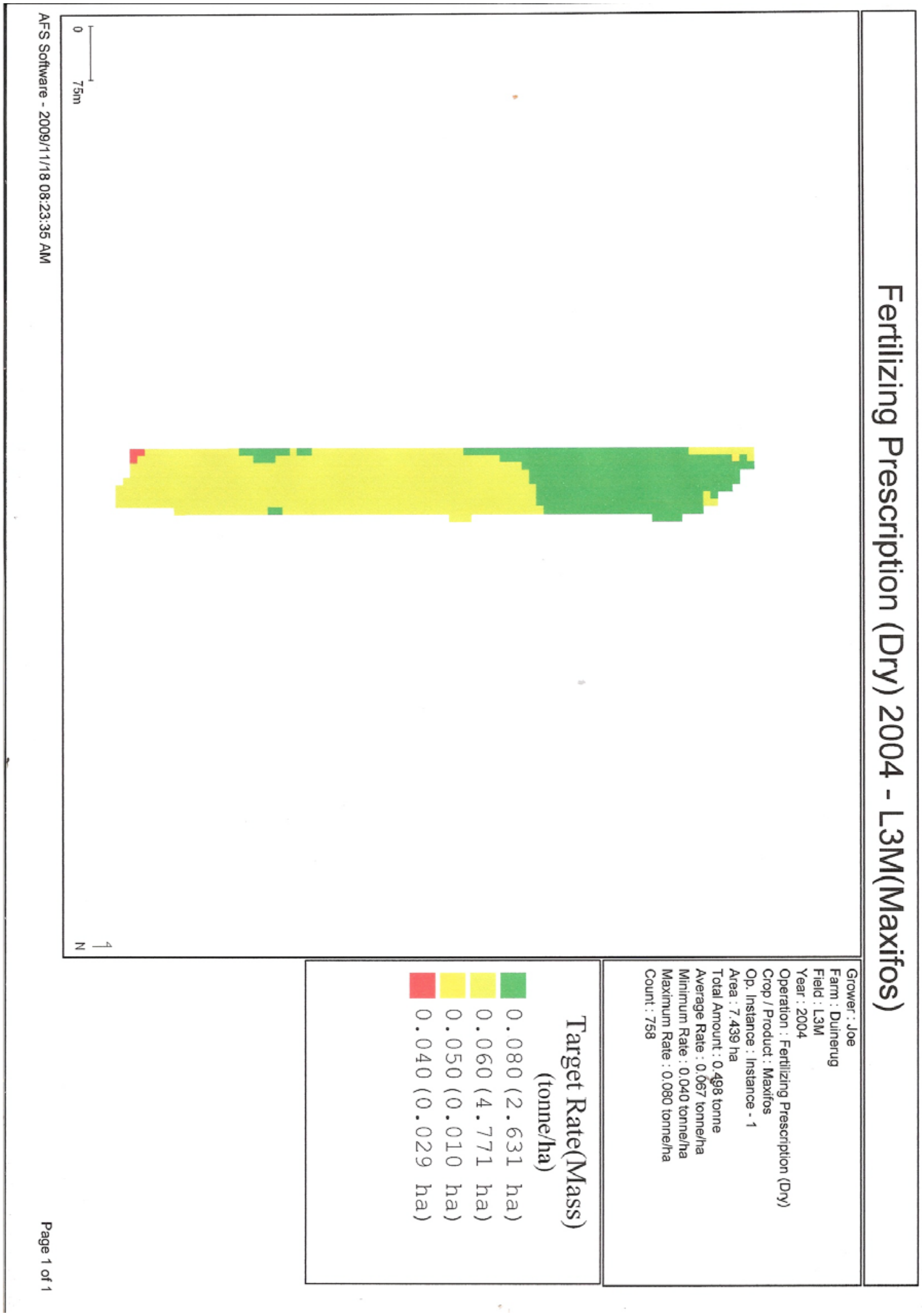


Figure B4: Application map (K3A – 2004)

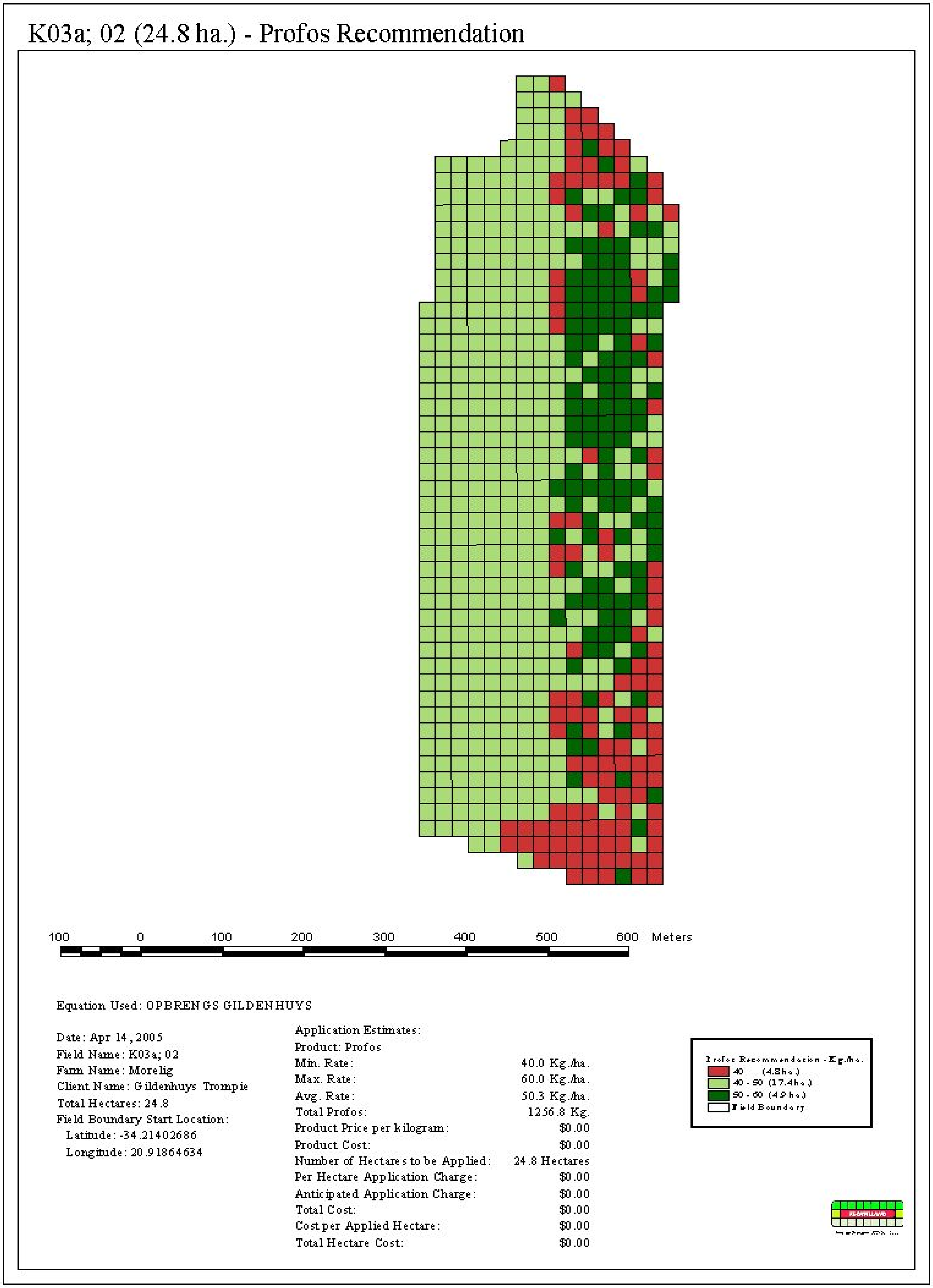


Figure B5: Application map (K3A – 2005)

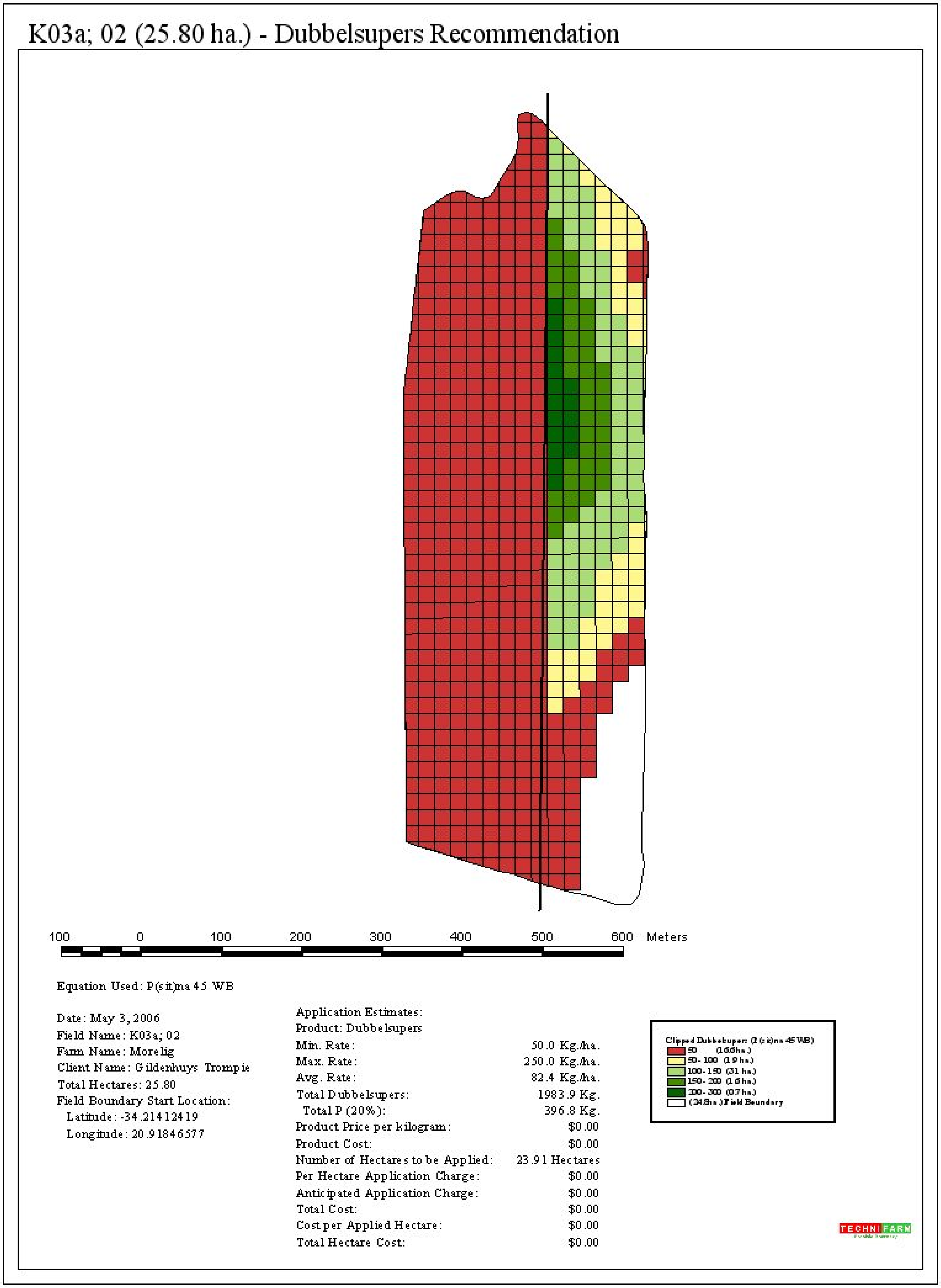


Figure B6: Application map (K3A – 2006)

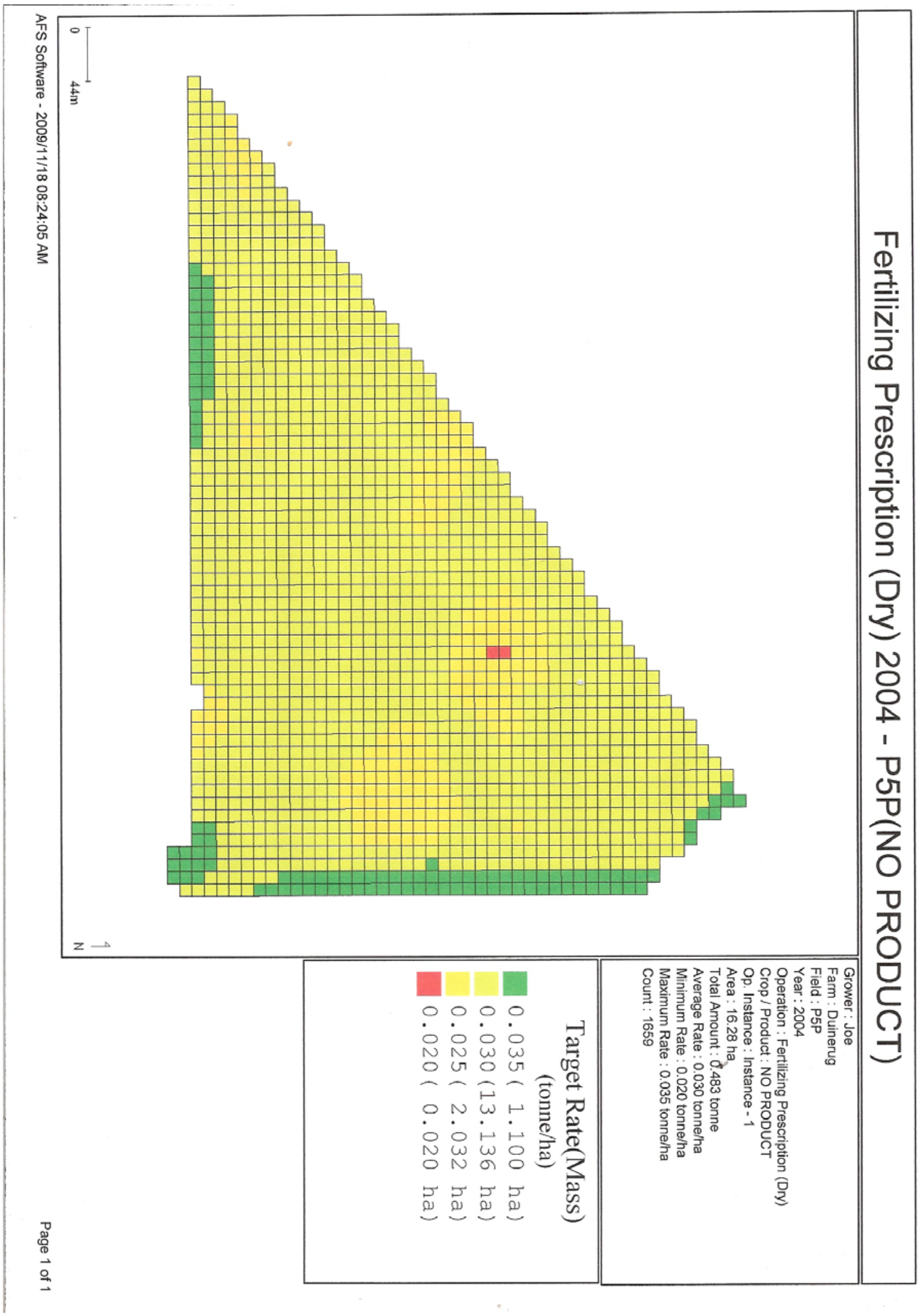


Figure B7: Application map (K5 – 2004)

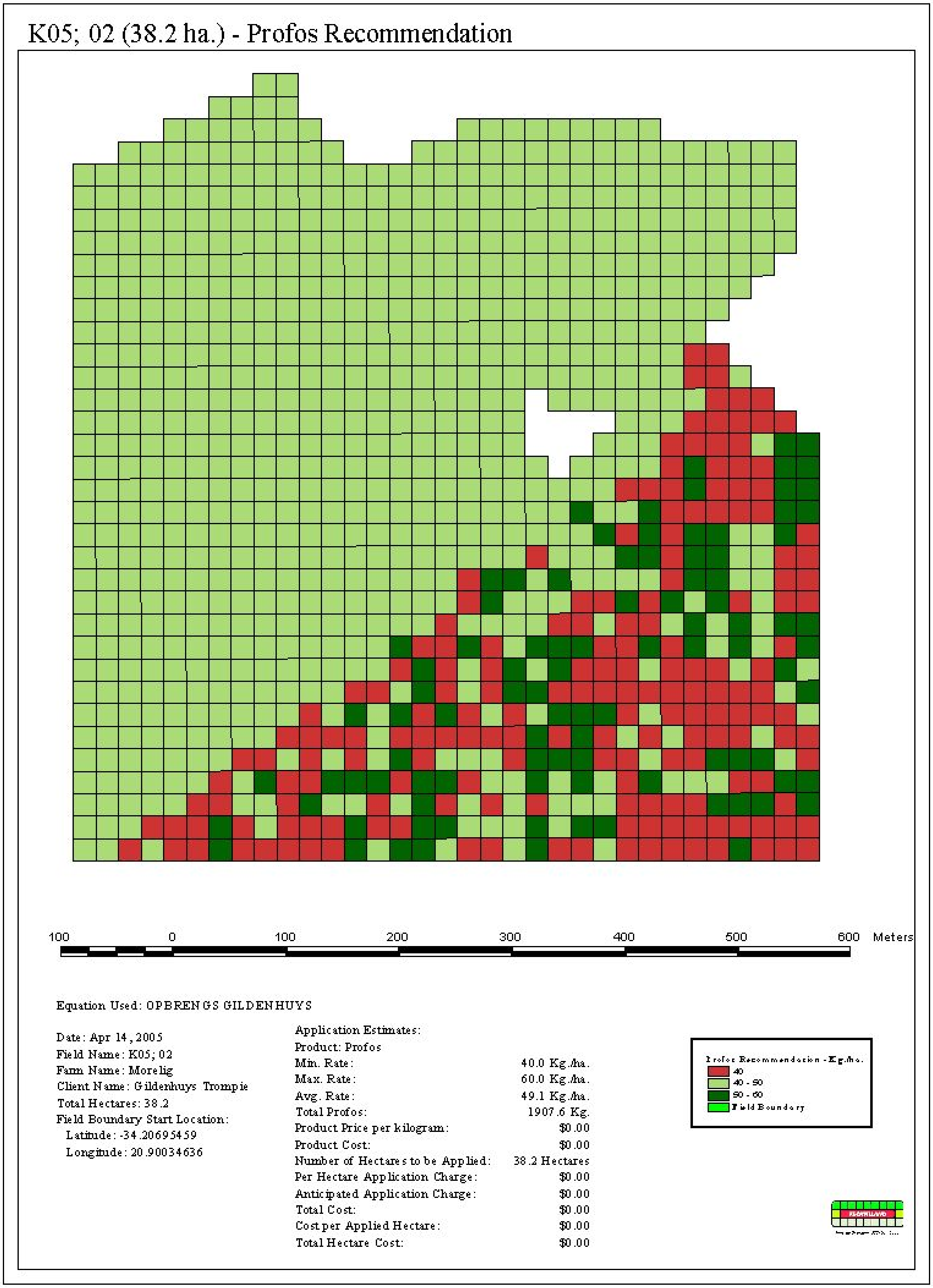


Figure B8: Application map (K5 – 2005)

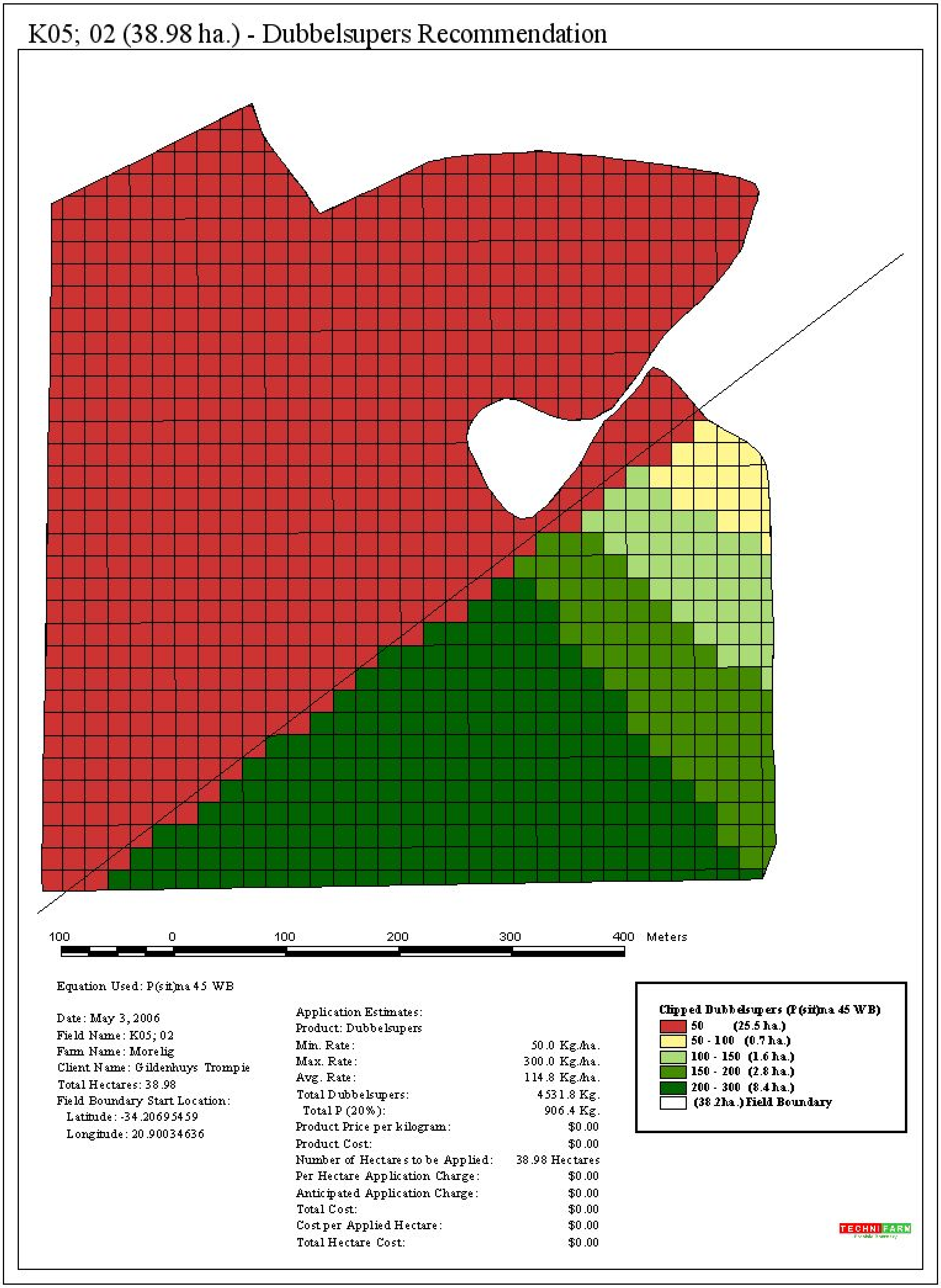


Figure B9: Application map (K5 – 2006)

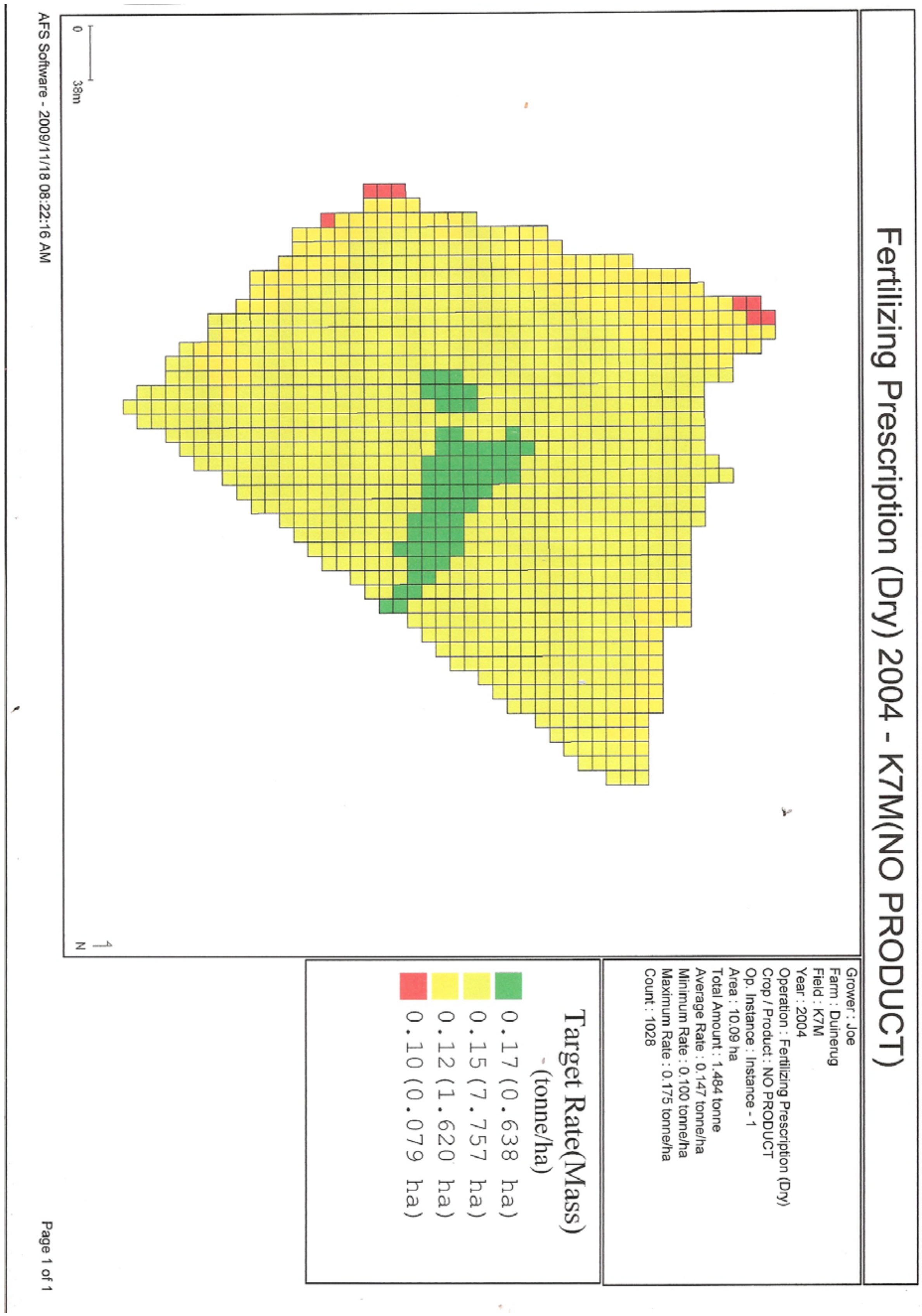


Figure B10: Application map (K7A – 2004)

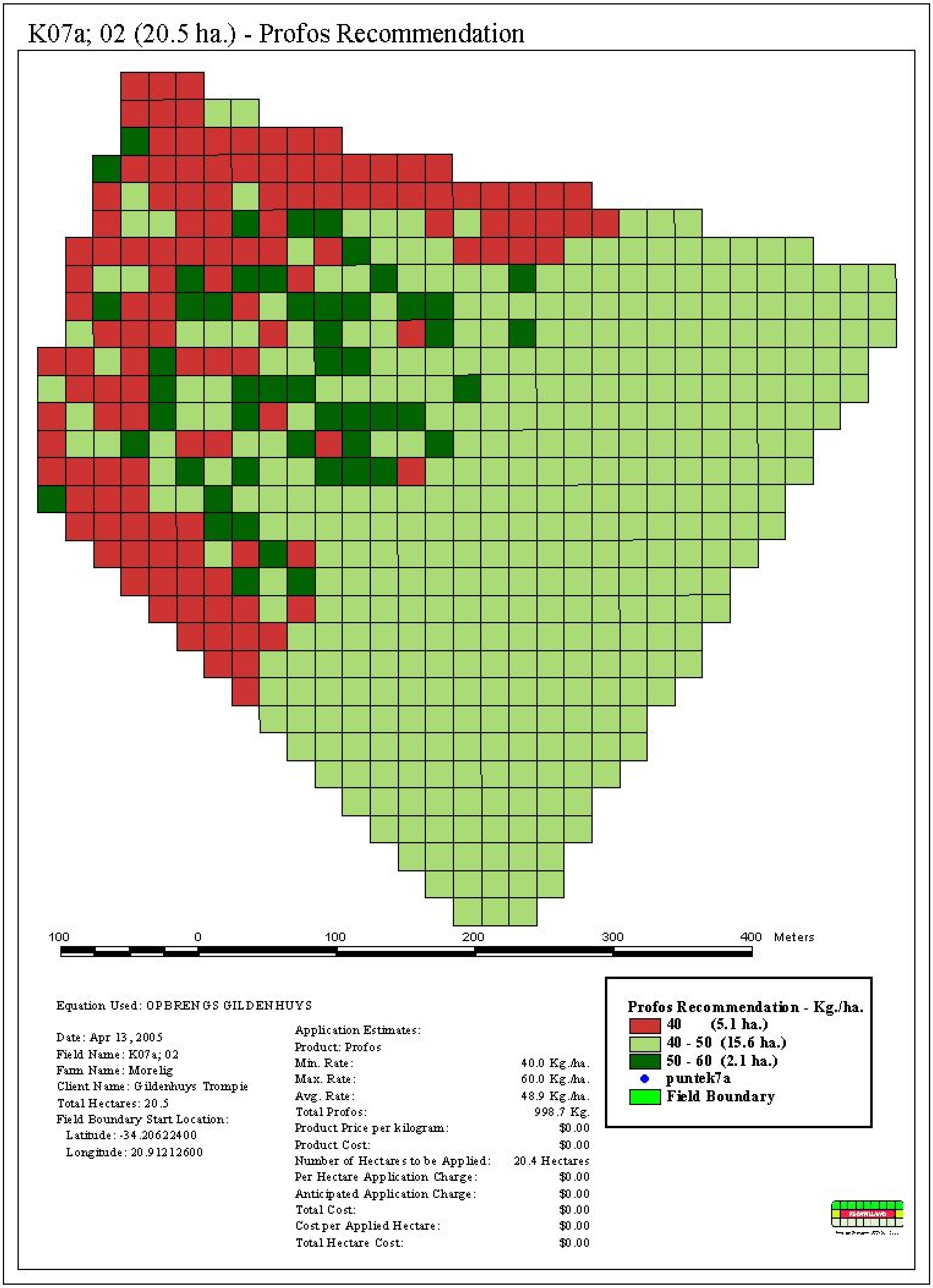


Figure B11: Application map (K7A – 2005)

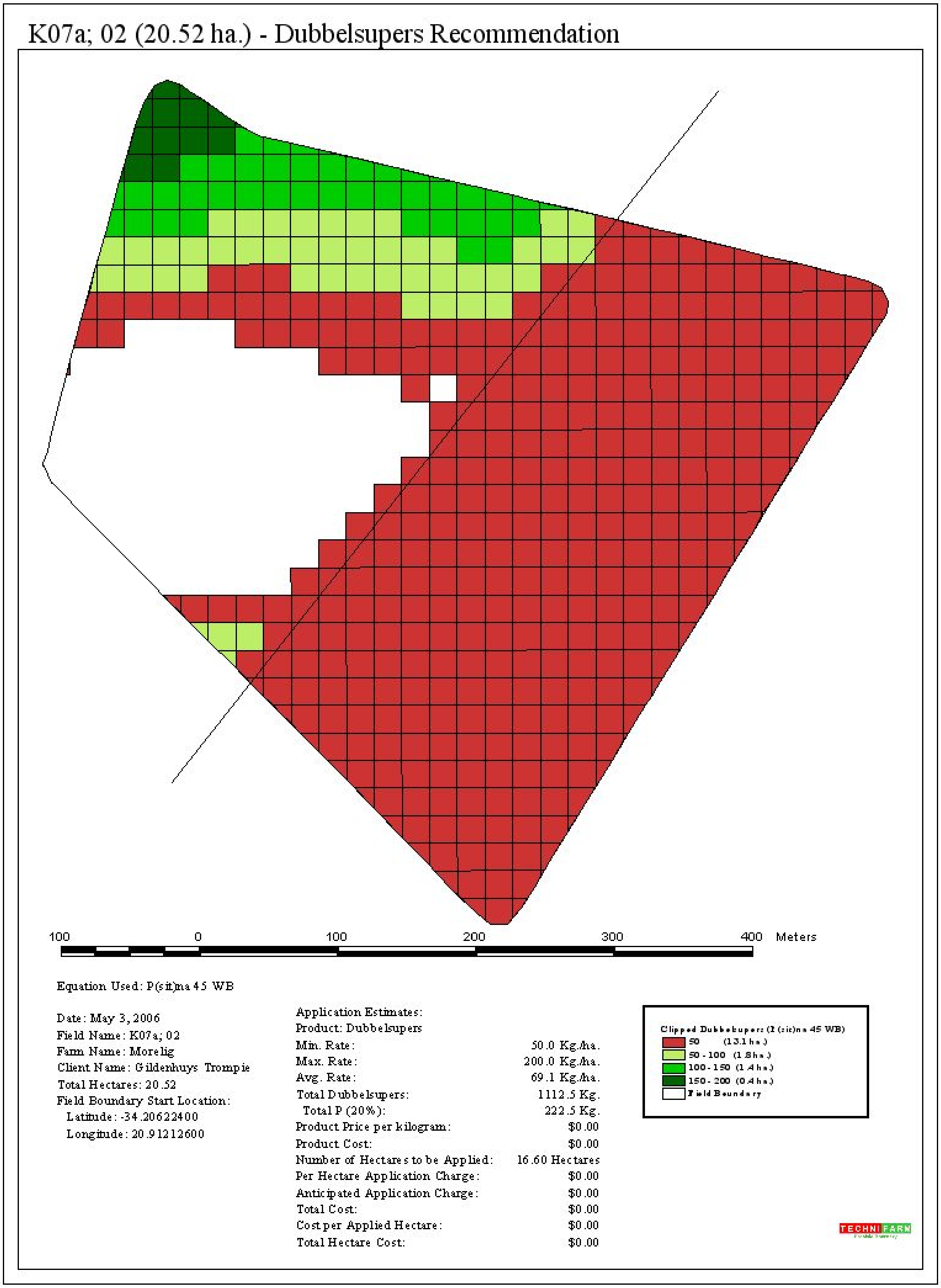


Figure B12: Application map (K7A – 2006)

Annexure C

TABLE C1: P-LEVELS (mg/kg) FOR L2 FOR THREE YEARS

Soil sample no	***2004***	***2005***	***2006***
1	86		
2	88		
3	80		
4	80		
5	126		
6	**107**	**125**	**88**
7	**84**	**93**	**70**
8	60		
9	90		
10	222		
11	69		
12	**61**	**46**	**57**
13	109		
14	90		
15	**73**	**60**	**54**
16	73		
17	**77**	**74**	**67**
18	113		
19	**51**	**64**	**37**
20	**45**	**115**	**56**
21	62		
22	**72**	**66**	**35**
23	58		
24	87		
25	61		
26	42		

TABLE C2: P-LEVELS (mg/kg) FOR K3A FOR THREE YEARS

Soil sample no	***2004***	***2005***	***2006***
1	**49**	**48**	**47**
2	39		
3	36		
4	27		
5	28		
6	57		
7	**56**	**49**	**39**
8	37		
9	44		
10	52		
11	35		
12	**30**	**39**	**21**
13	23		
14	35		
15	**62**	**36**	**31**
16	39		
17	99		
18	55		
19	65		
20	56		
21	**45**	**19**	**36**
22	**50**	**58**	**12**
23	57		
24	46		
25	**50**	**94**	**16**
26	42		
27	46		
28	**50**	**78**	**37**
29	50		
30	48		
31	44		
32	**62**	**64**	**19**
33	52		
34	55		

TABLE C3: P-LEVELS (mg/kg) FOR K5 FOR THREE YEARS

Soil sample no	***2004***	***2005***	***2006***
1	38		
2	63		
3	20		
4	17		
5	19		
6	**23**	**30**	**16**
7	39		
8	15		
9	20		
10	27		
11	**31**	**38**	**14**
12	32		
13	28		
14	43		
15	**52**	**27**	**23**
16	17		
17	**24**	**23**	**14**
18	40		
19	45		
20	38		
21	44		
22	38		
23	36		
24	24		
25	23		
26	25		
27	34		
28	40		
29	45		
30	25		
31	**41**	**43**	**20**
32	**40**	**47**	**35**
33	54		
34	30		
35	**35**	**37**	**17**
36	31		
37	**25**	**38**	**23**
38	26		
39	**31**	**71**	**44**
40	51		
41	28		
42	45		

TABLE C4: P-LEVELS (mg/kg) FOR K7A FOR THREE YEARS

Soil sample no	***2004***	***2005***	***2006***
1	**25**	**62**	**24**
2	35		
3	20		
4	67		
5	55		
6	47		
7	**32**	**55**	**33**
8	19		
9	**30**	**35**	**26**
10	23		
11	**48**	**120**	**65**
12	24		
13	68		
14	93		
15	**53**	**158**	**50**
16	52		
17	**34**	**65**	**52**
18	36		
19	25		
20	29		
21	43		
22	**31**	**32**	**30**
23	26		
24	**37**	**42**	**36**
25	**45**	**47**	**30**
26	39		
27	30		
28	69		

Annexure D

TABLE D1: pH-LEVELS FOR L2 FOR THREE YEARS

Soil sample no	***2004***	***2005***	***2006***
1	5.7		
2	5.7		
3	5.7		
4	5.6		
5	6.7		
6	**7.4**	**7.2**	**7.5**
7	**7.7**	**7.6**	**7.0**
8	5.5		
9	7.1		
10	6.2		
11	5.8		
12	**5.5**	**5.3**	**5.7**
13	5.4		
14	5.6		
15	**5.7**	**5.2**	**5.9**
16	5.4		
17	**5.7**	**5.4**	**5.5**
18	5.9		
19	**5.4**	**5.5**	**5.4**
20	**4.6**	**5.3**	**6.8**
21	5.2		
22	**5.5**	**5.3**	**5.1**
23	5.7		
24	5.1		
25	5.6		
26	5.5		

TABLE D2: pH-LEVELS FOR K3A FOR THREE YEARS

Soil sample no	***2004***	***2005***	***2006***
1	**5.7**	**6.5**	**5.3**
2	5.5		
3	5.3		
4	5.5		
5	5.0		
6	5.4		
7	**5.8**	**5.2**	**5.5**
8	5.6		
9	5.1		
10	5.6		
11	5.5		
12	**5.5**	**4.7**	**5.3**
13	5.2		
14	6.9		
15	**5.2**	**4.8**	**6.0**
16	5.7		
17	7.5		
18	5.3		
19	5.8		
20	5.3		
21	**6.2**	**5.4**	**5.2**
22	**5.9**	**5.2**	**5.1**
23	5.2		
24	5.2		
25	**5.1**	**4.8**	**5.5**
26	5.5		
27	5.8		
28	**5.3**	**5.0**	**5.7**
29	5.6		
30	5.7		
31	5.4		
32	**5.5**	**5.2**	**6.2**
33	5.6		
34	5.7		

TABLE D3: pH-LEVELS FOR K5 FOR THREE YEARS

Soil sample no	***2004***	***2005***	***2006***
1	5.2		
2	6.2		
3	5.3		
4	5.4		
5	5.2		
6	**5.3**	**5.3**	**5.6**
7	5.8		
8	5.4		
9	5.3		
10	5.0		
11	**4.9**	**4.8**	**5.2**
12	5.1		
13	5.4		
14	5.1		
15	**5.0**	**6.7**	**5.5**
16	5.2		
17	**5.1**	**5.3**	**5.5**
18	4.9		
19	6.4		
20	5.6		
21	7.9		
22	5.1		
23	5.1		
24	5.1		
25	5.0		
26	5.2		
27	5.2		
28	5.0		
29	5.1		
30	5.1		
31	**5.2**	**5.1**	**5.3**
32	**4.9**	**4.3**	**5.1**
33	6.3		
34	5.1		
35	**5.2**	**4.5**	**5.2**
36	5.0		
37	**5.1**	**4.9**	**5.2**
38	5.3		
39	**5.2**	**4.8**	**5.4**
40	5.0		
41	4.9		
42	5.1		

TABLE D4: pH-LEVELS FOR K7A FOR THREE YEARS

Soil sample no	***2004***	***2005***	***2006***
1	**5.3**	**5.3**	**5.7**
2	5.3		
3	5.3		
4	5.4		
5	5.2		
6	5.4		
7	**5.4**	**5.4**	**5.5**
8	5.6		
9	**5.5**	**4.9**	**5.7**
10	5.4		
11	**5.0**	**4.9**	**5.5**
12	5.1		
13	5.3		
14	5.0		
15	**5.4**	**4.7**	**5.2**
16	5.5		
17	**5.5**	**4.8**	**5.4**
18	5.3		
19	5.1		
20	5.4		
21	5.5		
22	**5.5**	**5.1**	**5.3**
23	5.3		
24	**5.3**	**5.8**	**5.8**
25	**5.3**	**5.6**	**5.8**
26	5.2		
27	5.3		
28	5.4		

Annexure E

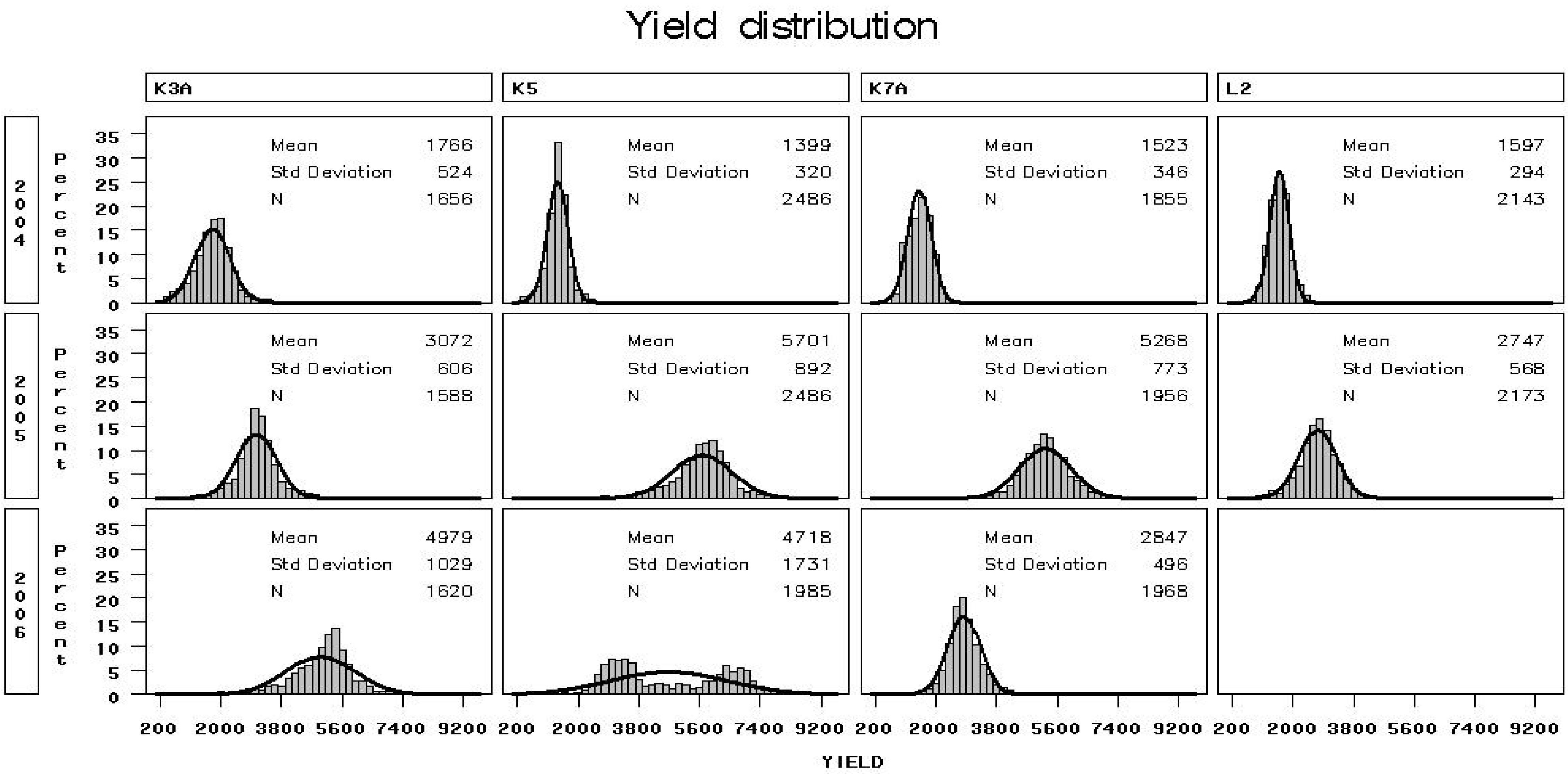


Figure E1: Summary of yield distribution

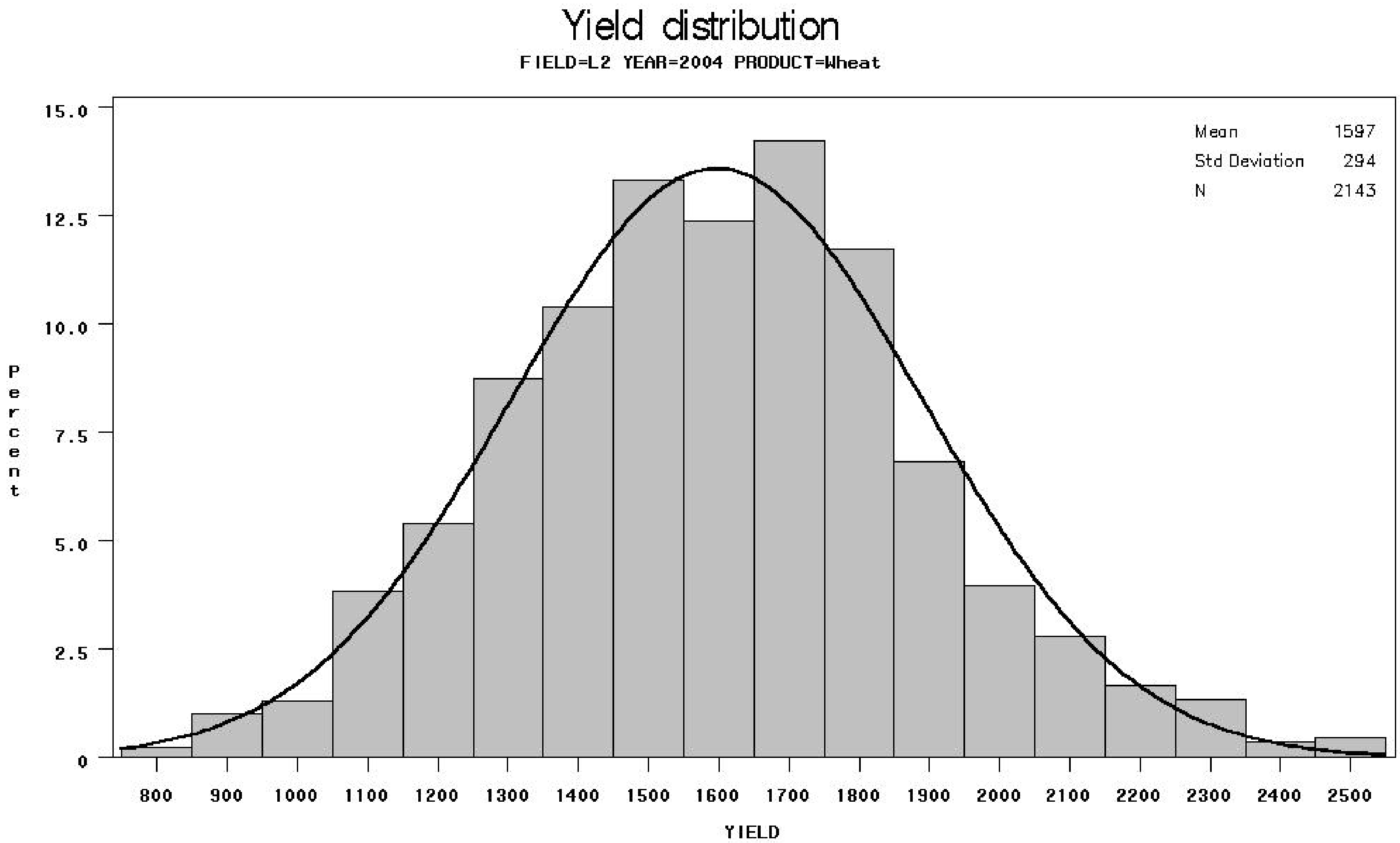


Figure E2: Yield distribution (L2 – 2004)

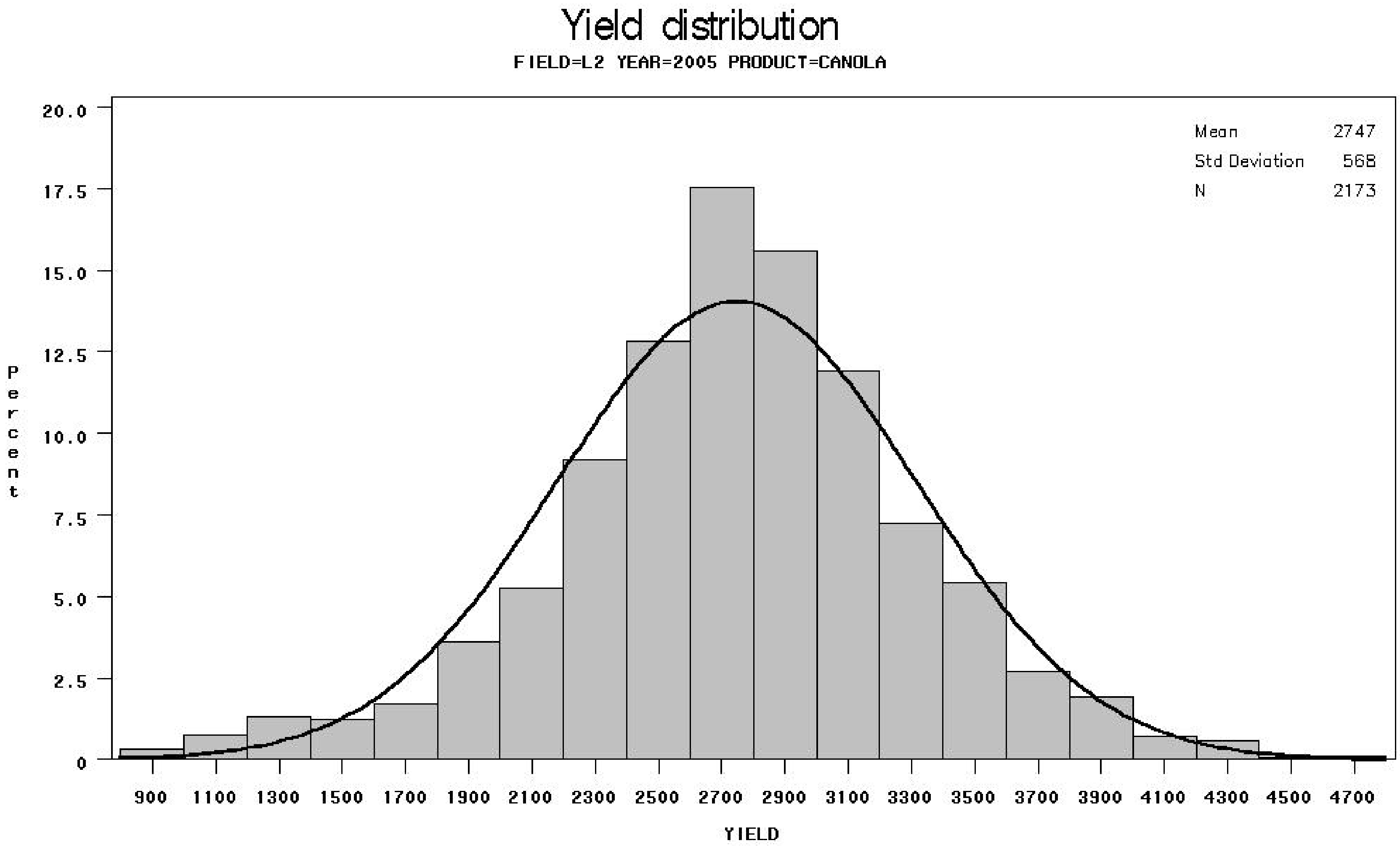


Figure E3: Yield distribution (L2 – 2005)

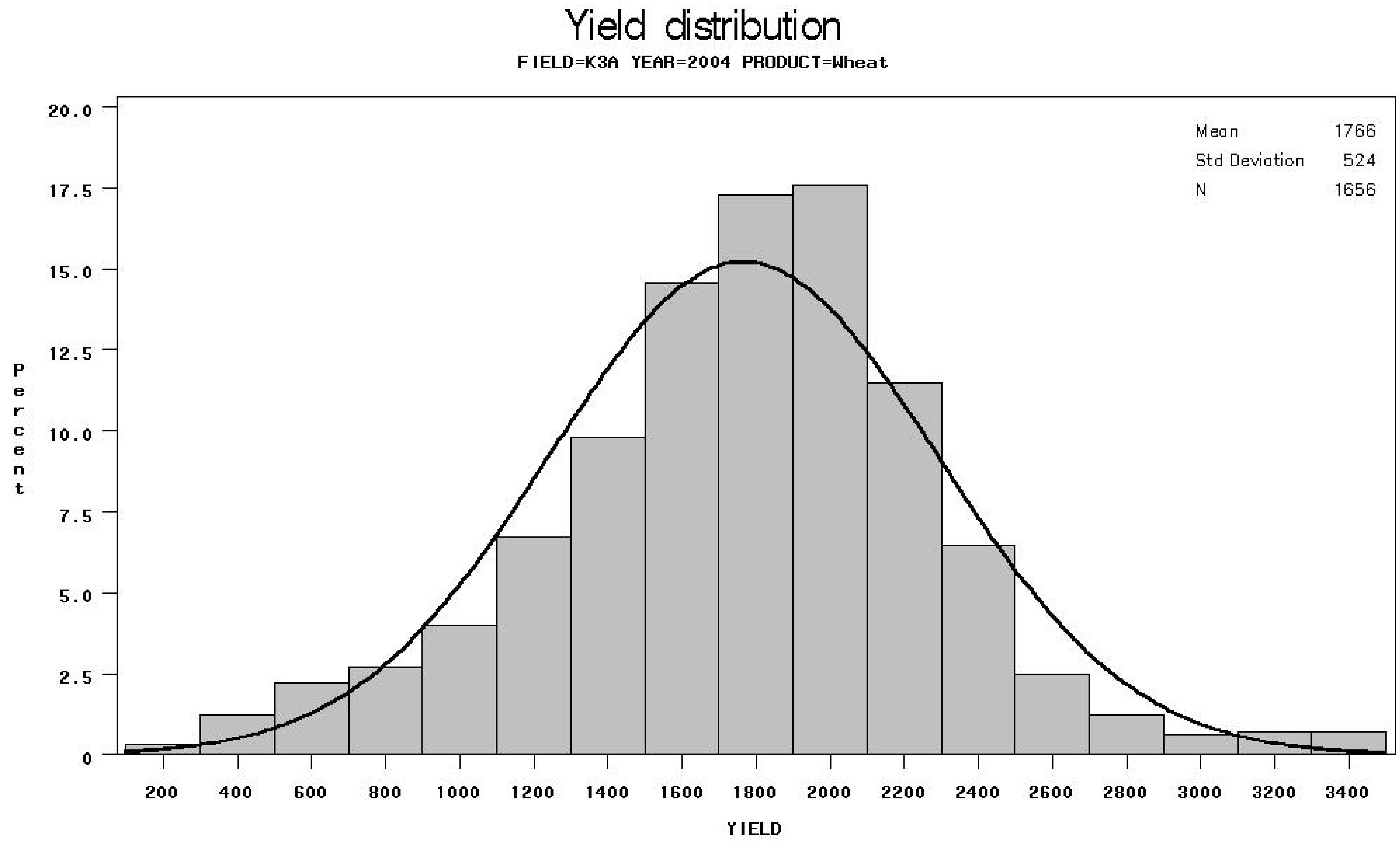


Figure E4: Yield distribution (K3A – 2004)

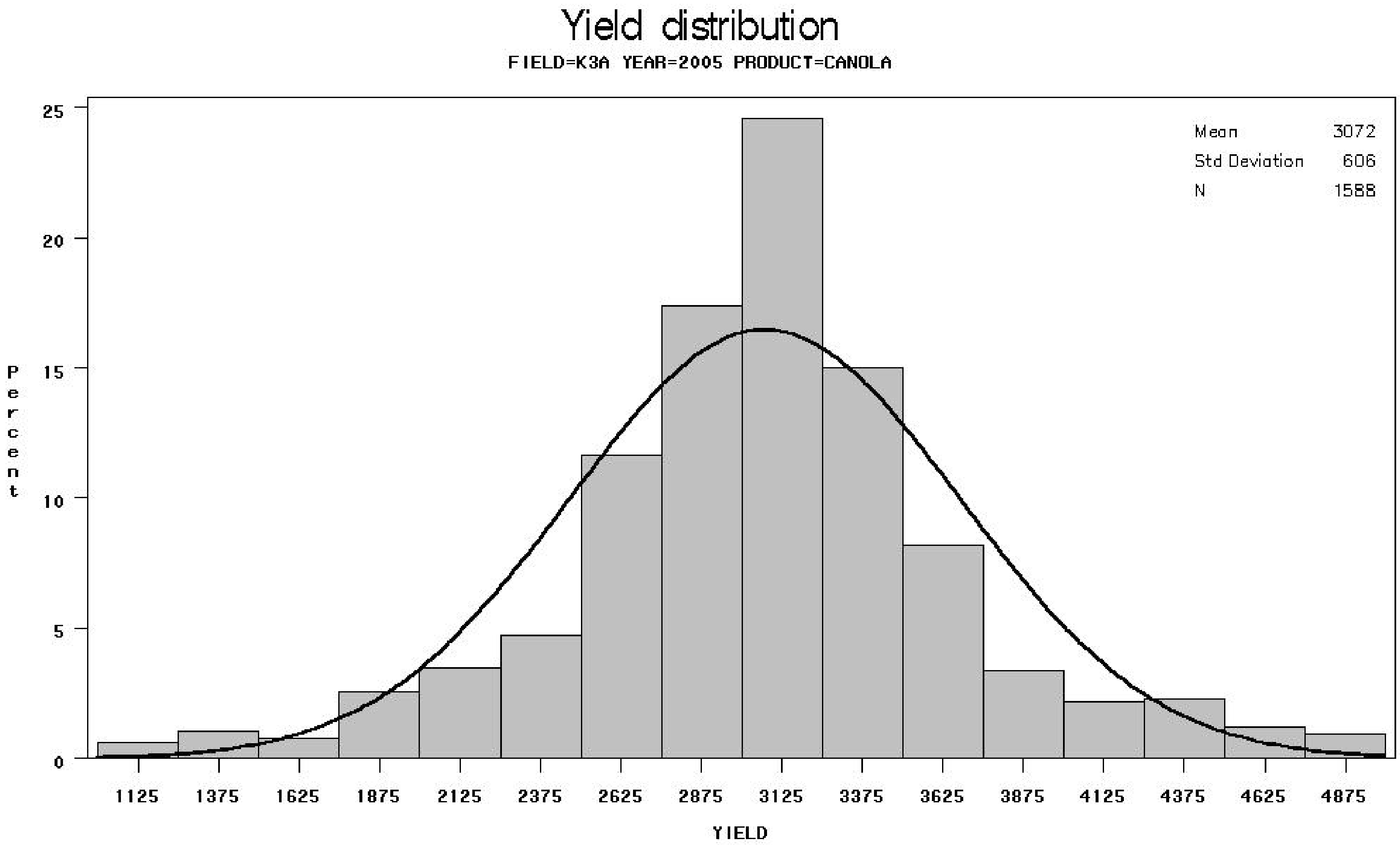


Figure E5: Yield distribution (K3A – 2005)

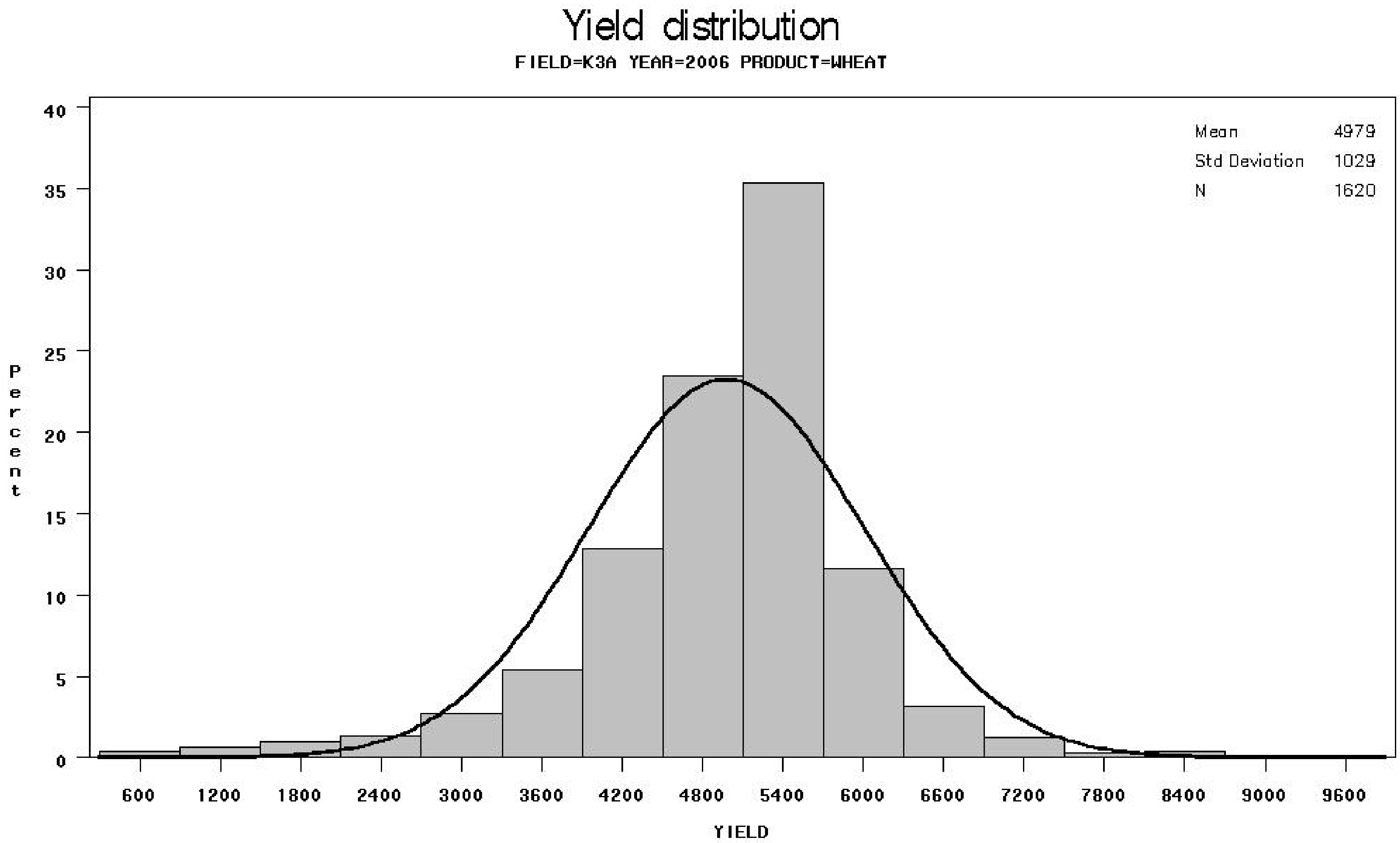


Figure E6: Yield distribution (K3A – 2006)

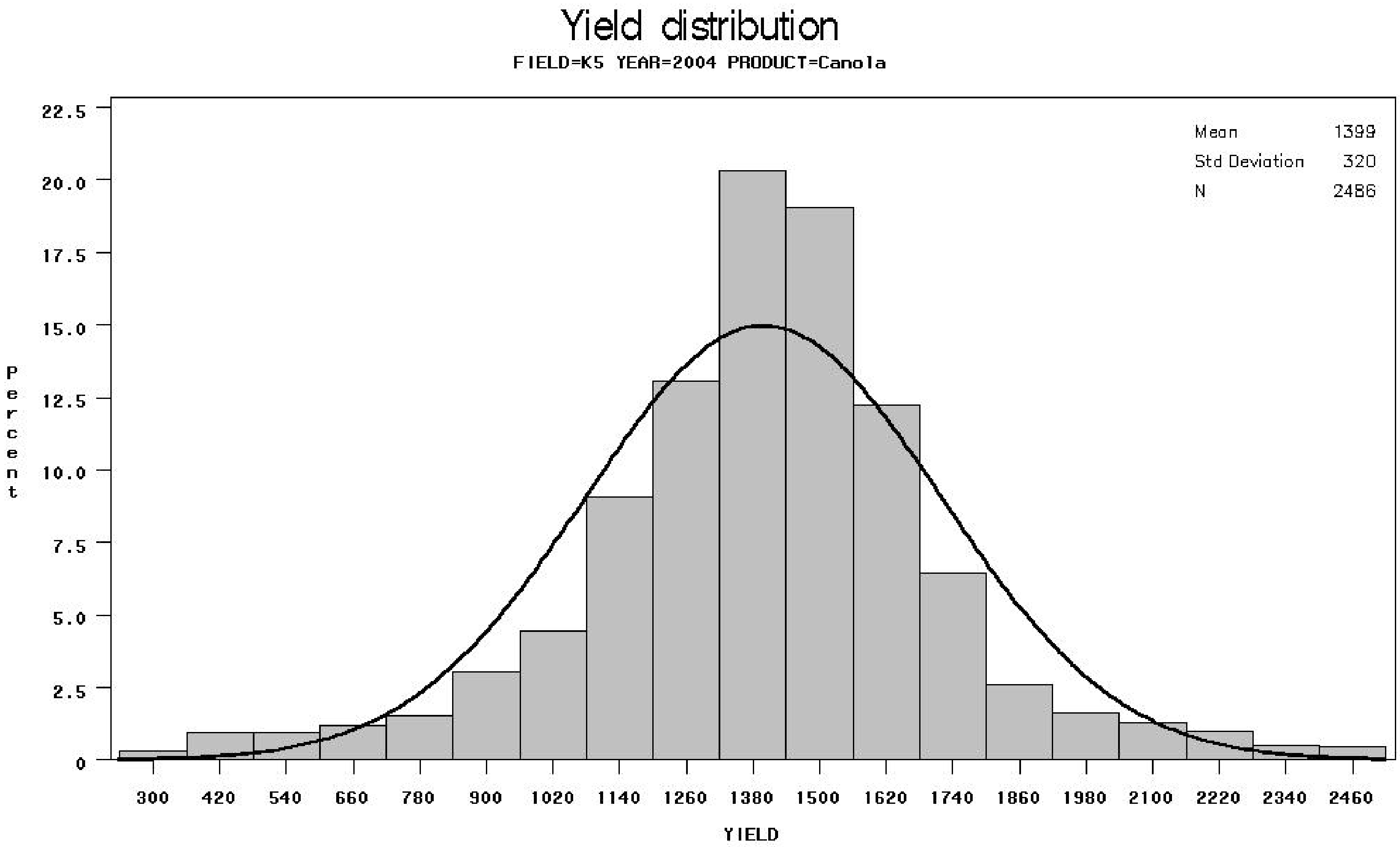


Figure E7: Yield distribution (K5 – 2004)

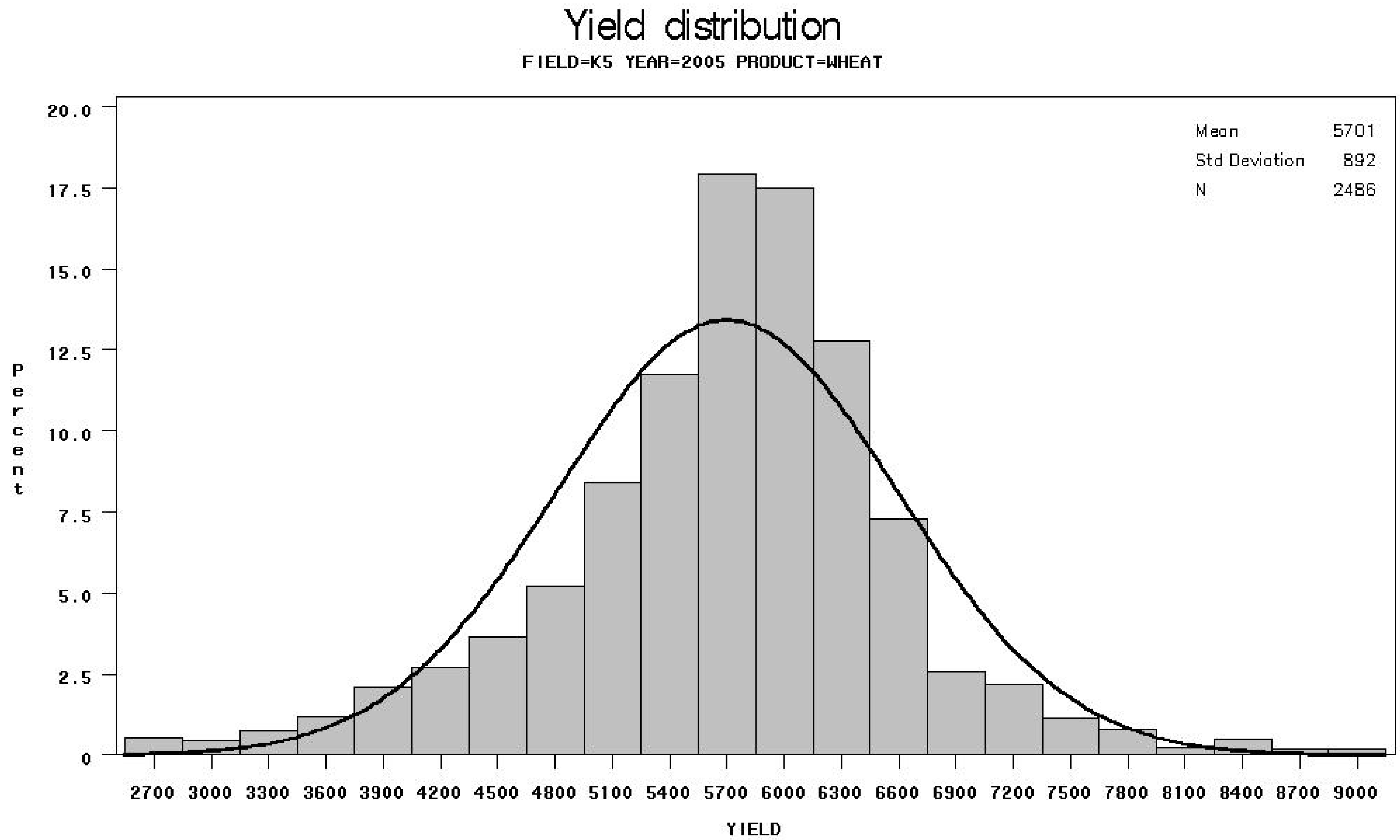


Figure E8: Yield distribution (K5 – 2005)

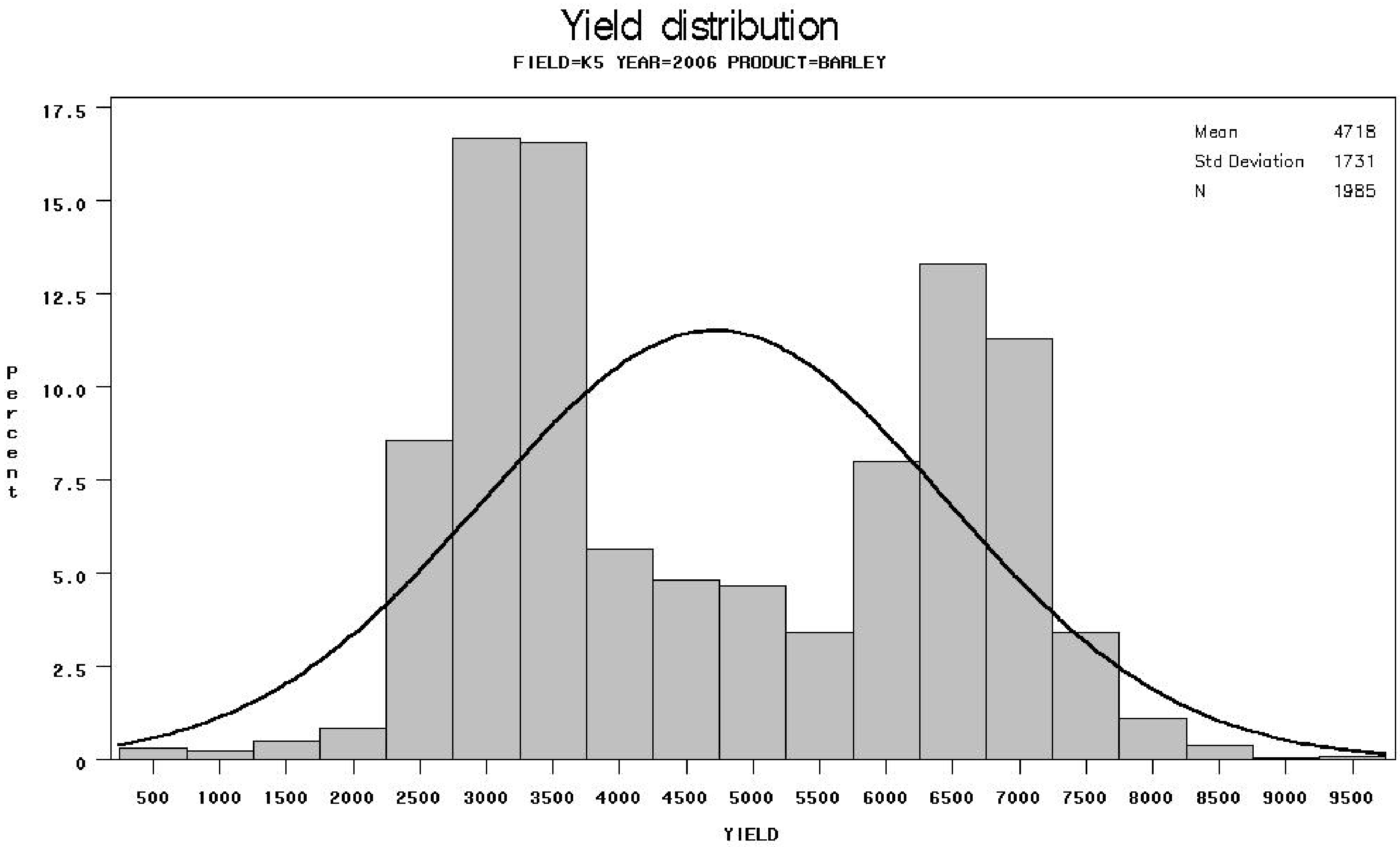


Figure E9: Yield distribution (K5 – 2006)

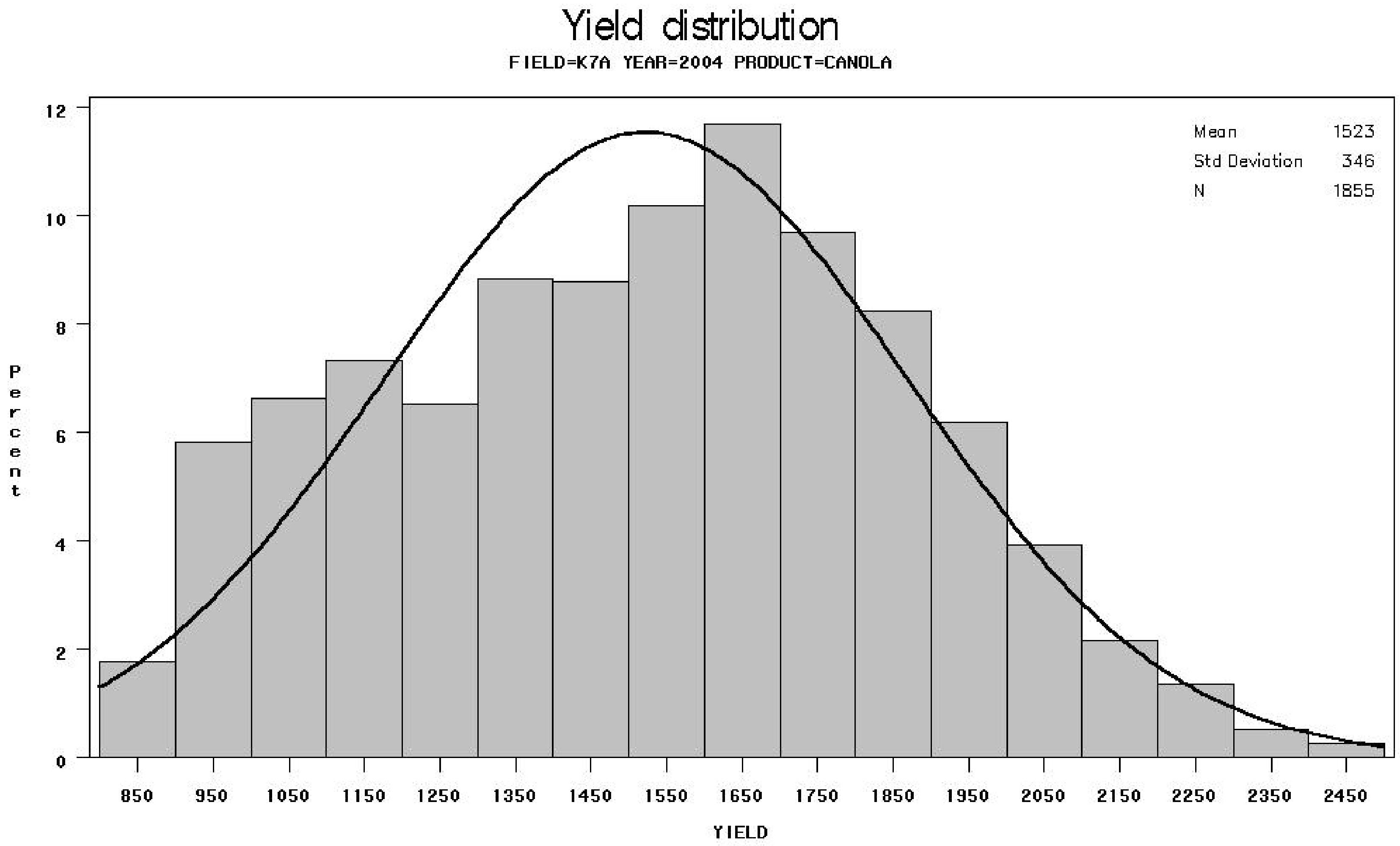


Figure E10: Yield distribution (K7A – 2004)

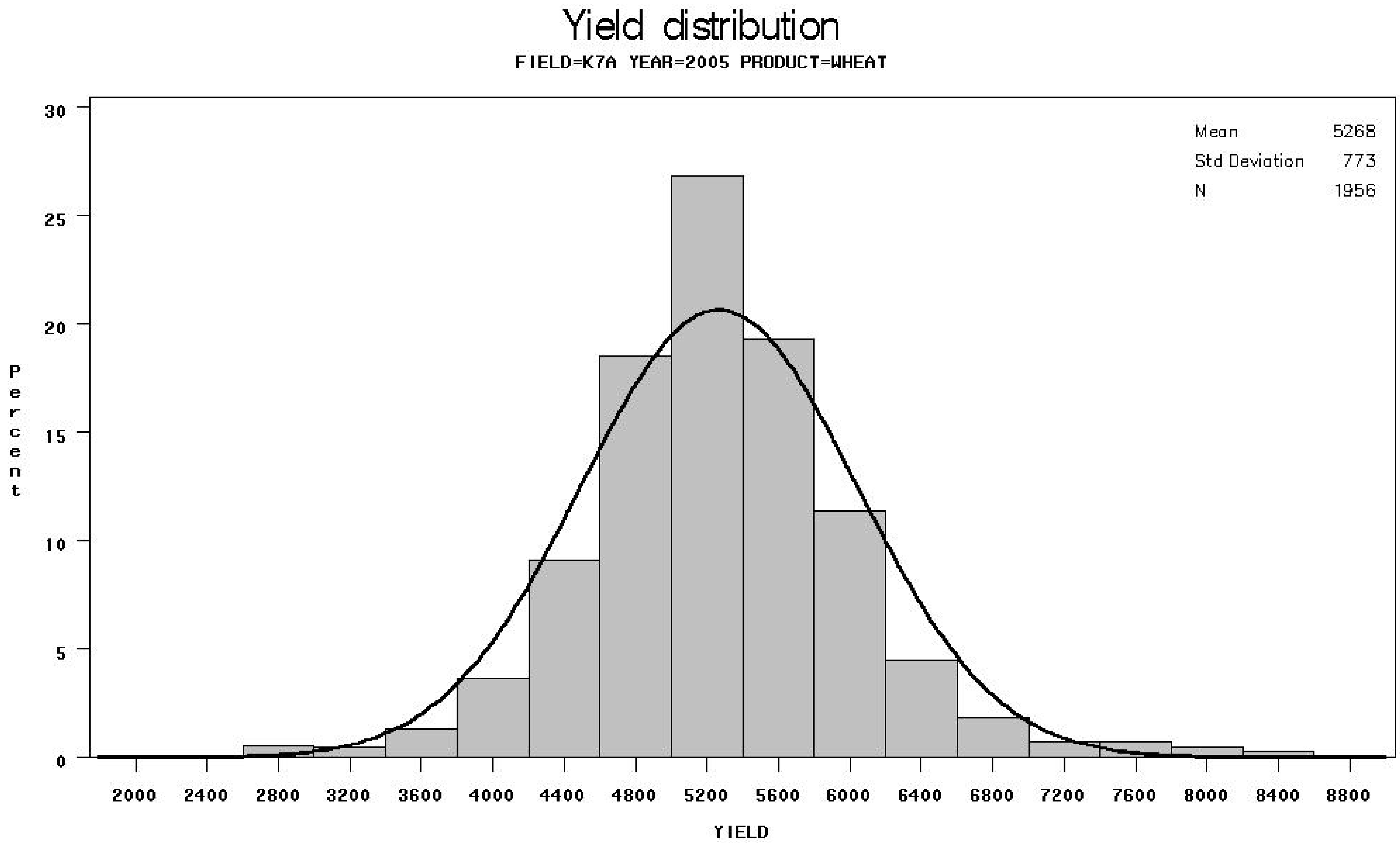


Figure E11: Yield distribution (K7A – 2005)

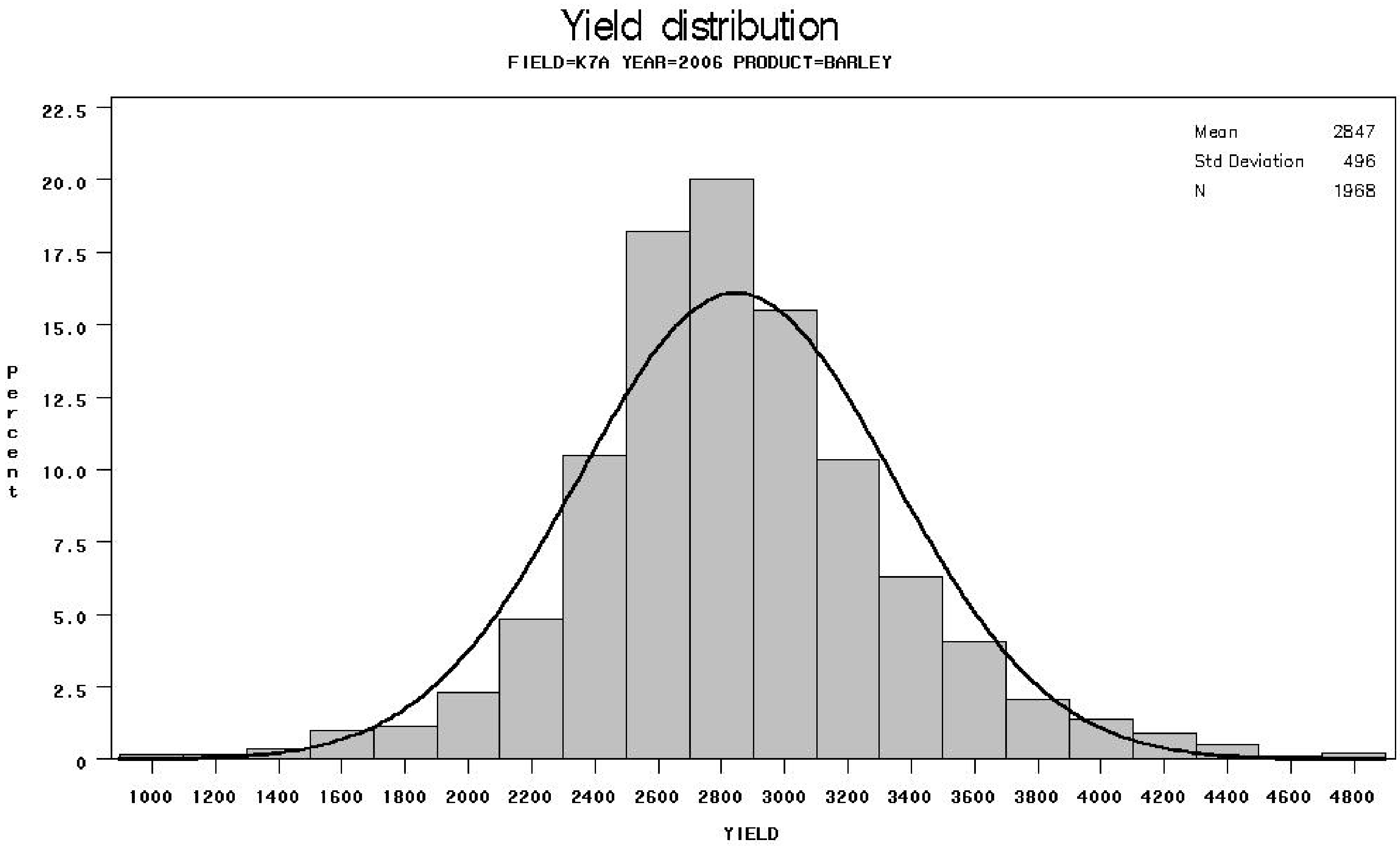


Figure E12: Yield distribution (K7A – 2006)

Annexure F

Annexure G

TABLE G1: MEAN YIELD OF FIELDS

Field		**L2**			**K3A**			**K5**			**K7A**		
Year		**2004**	**2005**	**2006**	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**
Soil Type	**Treatment**												
Gs1	VR	-	-	-	1.864	3.060	5.071	1.393	5.647	4.329	1.530	**5.335**	**2.979**
	SR	-	-	-	1.775	3.032	4.766	1.433	5.810	5.449	1.517	**5.204**	**2.732**
Gs2	VR	-	-	-	**2.037**	**3.258**	**5.412**	-	-	-	1.236	4.909	**3.029**
	SR	-	-	-	**1.608**	**2.983**	**4.774**	-	-	-	1.404	5.203	**2.724**
Gs3	VR	1.630	2.296	-	-	-	-	-	-	-	-	-	-
	SR	1.583	2.797	-	-	-	-	-	-	-	-	-	-
Gs4	VR	-	-	-	-	-	-	1.354	5.547	4.141	1.555	5.443	**2.991**
	SR	-	-	-	-	-	-	1.588	6.040	5.915	1.389	5.510	**2.815**
Gs5	VR	-	-	-	-	-	-	-	-	-	-	-	-
	SR	-	-	-	-	-	-	-	-	-	-	-	-

TABLE G1: MEAN YIELD OF FIELDS (CONTINUES)

Field		L2			K3A			K5			K7A		
Year		2004	2005	2006	2004	2005	2006	2004	2005	2006	2004	2005	2006
Soil Type	Treatment												
Gs6	VR	**1.717**	2.687	-	-	-	-	-	-	-	-	-	-
	SR	**1.546**	2.735	-	-	-	-	-	-	-	-	-	-
Gs7	VR	1.484	2.593	-	-	-	-	-	-	-	-	-	-
	SR	1.546	2.826	-	-	-	-	-	-	-	-	-	-
Gm	VR	-	-	-	1.782	3.118	4.915	-	-	-	-	-	-
	SR	-	-	-	1.546	2.955	4.967	-	-	-	-	-	-
Sw1	VR	-	-	-	-	-	-	-	-	-	-	-	-
	SR	-	-	-	-	-	-	-	-	-	-	-	-
Sw2	VR	-	-	-	-	-	-	-	-	-	-	-	-
	SR	-	-	-	-	-	-	-	-	-	-	-	-

TABLE G1: MEAN YIELD OF FIELDS (CONTINUES)

Field		L2			K3A			K5			K7A		
Year		**2004**	**2005**	**2006**	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**
Soil Type	**Treatment**												
Cf	VR	-	-	-	-	-	-	-	-	-	1.615	5.323	2.931
	SR	-	-	-	-	-	-	-	-	-	1.713	5.073	2.736
Cg	VR	1.460	2.667	-	-	-	-	-	-	-	-	-	-
	SR	1.380	2.491	-	-	-	-	-	-	-	-	-	-
Et	VR	1.685	2.902	-	-	-	-	1.267	5.762	3.028	-	-	-
	SR	1.596	2.829	-	-	-	-	1.316	5.510	3.590	-	-	-
Oa	VR	**1.745**	**3.311**	-	-	-	-	-	-	-	-	-	-
	SR	**1.642**	**3.027**	-	-	-	-	-	-	-	-	-	-

Annexure H

TABLE H1: SOIL TYPES AND SYMBOLS

Soil type	Symbol
Gs1	S1
Gs2	S2
Gs3	S3
Gs4	S4
Gs5	S5
Gs6	S6
Gs7	S7
Gm	S8
Sw1	S9
Sw2	S10
Cf	S11
Cg	S12
Et	S13
Oa	S14

Annexure I

TABLE I1: WINTER GRAIN RESPONSE TO P VARIATION ON DIFFERENT SOIL TYPES WITH DIFFERENT MODELS: L2 (2004)

Regression output																								
	OLS				SER				REML															
									Gaussian				Spherical				Exponential							
	Cf	**Std Err.**	**t-Statistics**	**Pr**	**Cf**	**Std Err.**	**z-Value**	**Pr**	**Cf**	**Std Err.**	**t-Value**	**Pr > |t|**	**Cf**	**Std Err.**	**t-Value**	**Pr > |t|**	**Cf**	**Std Err.**	**t-Value**	**Pr > |t|**				
Constant	1582.591	16.1877	97.7650	0.00000	1594.922	95.0882	16.7731	0.00000	1606.47	69.5479	23.10	-	1570.98	97.1020	16.18	-	1611.69	86.8842	18.55	-				
TRT	46.8870	22.8024	2.05623	0.03988	-101.0105	67.4668	-1.4972	0.13434	-131.05	73.2921	-1.79	0.0739	-99.7969	82.0126	-1.22	0.2238	-135.37	76.7064	-1.76	0.0778				
S6	-36.1457	25.2404	-1.4321	0.15228	12.2188	51.7630	0.2361	0.81339	15.5174	55.5244	0.28	0.7799	-17.0685	64.3721	-0.27	0.7909	-44.8038	57.0168	-0.79	0.4321				
S7	-37.1182	25.3438	-1.4646	0.14318	-10.4180	39.9364	-0.2609	0.79420	-2.4459	43.5769	-0.06	0.9552	-14.1341	49.5061	-0.29	0.7753	-28.9889	44.4201	-0.65	0.5141				
S12	-202.7968	60.5689	-3.3482	0.00083	-265.9948	70.6174	-3.7667	0.00017	-223.20	74.2178	-3.01	0.0027	-271.04	89.8425	-3.02	0.0026	-255.60	81.8102	-3.12	0.0018				
S13	13.5207	30.7140	0.4402	0.65978	-26.6751	59.9340	-0.4451	0.65627	26.0877	65.4137	0.40	0.6901	-14.5565	75.2637	-0.19	0.8467	-12.6543	67.3691	-0.19	0.8510				
S14	59.0380	22.7847	2.5911	0.00963	-38.9485	57.4792	-0.6776	0.49802	16.9817	61.8549	0.27	0.7837	-25.5085	71.4158	-0.36	0.7210	-10.4551	63.0723	-0.17	0.8684				
TRTS6	123.7998	47.2786	2.6185	0.00889	31.3482	89.6403	0.3497	0.72656	6.0705	97.2552	0.06	0.9502	71.0820	106.56	0.67	0.5048	108.96	99.4663	1.10	0.2735				
TRTS7	-108.3709	35.3079	-3.0693	0.00217	67.9723	60.8182	1.1176	0.26373	110.48	64.9964	1.70	0.0893	88.9119	74.5056	1.19	0.2329	115.74	67.3861	1.72	0.0860				
TRTS12	33.4151	92.0248	0.3631	0.71656	232.0962	113.9201	2.0374	0.04161	262.13	121.88	2.15	0.0316	300.21	143.88	2.09	0.0371	335.08	129.92	2.58	0.0100				
TRTS13	41.4744	39.0601	1.0618	0.28843	79.0042	80.5734	0.9805	0.32683	104.30	88.1462	1.18	0.2369	108.90	100.85	1.08	0.2803	127.88	91.2262	1.40	0.1611				
TRTS14	56.1402	48.4696	1.1583	0.24690	108.7056	90.6486	1.1992	0.23045	167.02	100.20	1.67	0.0957	141.84	111.95	1.27	0.2053	194.17	103.22	1.88	0.0601				
LAMBDA	-	-	-	-	0.9359	0.0215	43.4947	0.00000	-	-	-	-	-	-	-	-		-	-	-				

TABLE I2: WINTER GRAIN RESPONSE TO P VARIATION ON DIFFERENT SOIL TYPES WITH DIFFERENT MODELS: L2 (2005)

Regression output																								
	OLS				SER				REML															
									Gaussian				Spherical				Exponential							
	Cf	Std Err.	t-Statistics	Pr	Cf	Std Err.	z-Value	Pr	Cf	Std Err.	t-Value	Pr > |t|	Cf	Std Err.	t-Value	Pr > |t|	Cf	Std Err.	t-Value	Pr > |t|				
Constant	2796.887	29.3725	95.2212	0.00000	2511.451	679.9206	3.6937	0.00022	2760.62	113.36	24.35	-	2762.43	131.07	21.08	-	2761.59	140.65	19.63	-				
TRT	-500.468	40.9634	-12.217	0.00000	-398.715	78.0105	-5.1110	0.0000003	-198.93	118.76	-1.68	0.0941	-228.16	133.15	-1.71	0.0868	-227.61	125.69	-1.81	0.0703				
S6	-62.1428	45.6687	-1.3607	0.17374	-23.7685	65.8975	-0.3607	0.71833	46.7982	96.1403	0.49	0.6265	10.6390	110.77	0.10	0.9235	-10.272	101.48	-0.10	0.9194				
S7	28.5940	44.7985	0.6383	0.52338	-102.176	51.5509	-1.9820	0.04747	81.2838	76.8446	1.06	0.2903	41.6905	86.9965	0.48	0.6318	50.7087	80.5123	0.63	0.5289				
S12	-305.887	105.4331	-2.9012	0.00375	-513.071	108.2441	-4.7399	0.0000021	-236.24	128.01	-1.85	0.0651	-239.84	152.98	-1.57	0.1171	-215.03	143.38	-1.50	0.1338				
S13	32.1737	55.5366	0.5793	0.56244	-134.253	80.6279	-1.6651	0.95895	-78.668	115.10	-0.68	0.4944	-53.835	131.50	-0.41	0.6823	-62.620	121.21	-0.52	0.6055				
S14	229.879	41.2441	5.5736	0.00000	-125.136	72.3699	-1.7291	0.08379	-13.207	105.99	-0.12	0.9008	6.8077	121.08	0.06	0.9552	23.4107	110.86	0.21	0.8328				
TRTS6	453.1566	89.5968	5.0577	0.0000005	346.4466	111.7429	3.1004	0.00193	87.3083	175.23	0.50	0.6184	123.05	196.61	0.63	0.5315	169.41	183.43	0.92	0.3558				
TRTS7	267.6517	62.4968	4.2826	0.0000193	255.7546	74.9005	3.4146	0.00064	92.0890	111.93	0.82	0.4107	94.1787	128.64	0.73	0.4642	49.9869	118.51	0.42	0.6732				
TRTS12	676.0587	155.0776	4.3595	0.0000136	427.4147	161.7181	2.6430	0.00822	32.1686	207.73	0.15	0.876	71.9105	244.56	0.29	0.768	39.1166	228.34	0.17	0.864				
TRTS13	573.4334	70.4693	8.1374	0.00000	249.4995	105.1289	2.3733	0.01763		152.52	1.03		97.372	175.44	0.56		56.762	160.96	0.35					
TRTS14		87.4244	8.9713	0.00000			3.6013	0.00032		174.38	1.03			194.22	0.85			182.94	0.76					
LAMBD							94.680				-				-				-					

A	784.3078 -	-	-	-	405.2518 0.9845	112.5295 0.0104	8	0.00000	157.74 180.25 -	-		9 0.3011 0.3014 -	0 165.12 -	-		8 0.5789 0.3953 -	7 139.87 -	-		0 0.7244 0.4446 -

TABLE I3: WINTER GRAIN RESPONSE TO P VARIATION ON DIFFERENT SOIL TYPES WITH DIFFERENT MODELS: K3A (2004)

Regression output																				
	OLS				SER				REML											
									Gaussian				Spherical				Exponential			
	Cf	Std Err.	t-Statistics	Pr	Cf	Std Err.	z-Value	Pr	Cf	Std Err.	t-Value	Pr > |t|	Cf	Std Err.	t-Value	Pr > |t|	Cf	Std Err.	t-Value	Pr > |t|
Constant	1775.031	32.9289	53.905	0.00000	656.5154	961.2603	0.6830	0.49462	1101.75	221.00	4.99	-	1453.23	163.71	8.88	-	1203.18	315.07	3.82	-
TRT	88.4339	45.7602	1.9326	0.05346	185.1151	48.4878	3.8178	0.00013	222.00	56.7541	3.91	<.0001	143.01	95.1004	1.50	0.1328	162.01	77.0389	2.10	0.0356
S2	-167.0817	41.7621	-4.0008	0.00007	-119.1514	41.6297	-2.8622	0.00421	-39.4254	45.2421	-0.87	0.3836	40.8241	77.9797	0.52	0.6007	37.7853	64.2804	0.59	0.5567
S8	-229.5377	47.0947	-4.8740	0.0000012	-155.3556	48.8301	-3.1816	0.00147	7.5458	58.1556	0.13	0.8968	54.3059	89.0987	0.61	0.5423	48.3678	73.3615	0.66	0.5098
TRTS2	340.4157	60.2143	5.6534	0.00000	213.8903	55.6586	3.8429	0.00012	101.27	55.3602	1.83	0.0675	51.8859	95.4362	0.54	0.5867	55.1055	78.6914	0.70	0.4839
TRTS8	148.3417	63.8199	2.3244	0.20226	175.0012	64.0831	2.7308	0.00632	93.6970	69.7235	1.34	0.1792	69.5550	111.88	0.62	0.5342	82.5568	92.2017	0.90	0.3707
LAMBDA	-	-	-		0.9885	0.0077	127.5286	0.00000	-	-	-	-	-	-	-	-	-	-	-	-

TABLE I4: WINTER GRAIN RESPONSE TO P VARIATION ON DIFFERENT SOIL TYPES WITH DIFFERENT MODELS: K3A (2005)

Regression output																								
	OLS				SER				REML															
									Gaussian				Spherical				Exponential							
	Cf	Std Err.	t-Statistics	Pr	Cf	Std Err.	z-Value	Pr	Cf	Std Err.	t-Value	Pr > |t|	Cf	Std Err.	t-Value	Pr > |t|	Cf	Std Err.	t-Value	Pr > |t|				
Constant	3032.062	41.7855	72.5626	0.00000	3002.356	416.6773	7.2055	0.00000	3018.73	173.58	17.39	-	3000.49	176.89	16.96	-	2984.68	227.31	13.13	-				
TRT	28.3525	56.5257	0.5016	0.61601	-14.3217	67.3851	-0.2125	0.83169	-23.3803	102.40	-0.23	0.8194	-142.37	135.60	-1.05	0.2939	-145.86	123.59	-1.18	0.2381				
S2	-49.3958	52.6184	-0.9388	0.34799	-82.1806	53.6661	-1.5313	0.12569	-63.8326	82.4470	-0.77	0.4389	-110.05	104.76	-1.05	0.2936	-136.18	93.8101	-1.45	0.1468				
S8	-77.5098	59.0934	-1.3116	0.18983	64.5021	63.0129	1.0236	0.30601	162.53	96.6074	1.68	0.0927	110.14	123.29	0.89	0.3718	69.6132	109.18	0.64	0.5238				
TRTS2	247.2876	74.0447	3.3397	0.00086	238.4092	73.1986	3.2570	0.00113	227.58	98.3208	2.31	0.0208	289.76	128.32	2.26	0.0241	315.54	116.13	2.72	0.0067				
TRTS8	134.8798	78.3728	1.7210	0.08545	253.4759	84.1148	3.0135	0.00258	319.74	117.02	2.73	0.0064	395.86	152.06	2.60	0.0093	420.52	136.02	3.09	0.0020				
LAMBDA	-	-	-	-	0.9652	0.0217	44.5712	0.00000	-	-	-	-	-	-	-	-	-	-	-	-				

TABLE I5: WINTER GRAIN RESPONSE TO P VARIATION ON DIFFERENT SOIL TYPES WITH DIFFERENT MODELS: K3A (2006)

Regression output																								
	OLS				SER				REML															
									Gaussian				Spherical				Exponential							
	Cf	**Std Err.**	**t-Statistics**	**Pr**	**Cf**	**Std Err.**	**z-Value**	**Pr**	**Cf**	**Std Err.**	**t-Value**	**Pr > |t|**	**Cf**	**Std Err.**	**t-Value**	**Pr > |t|**	**Cf**	**Std Err.**	**t-Value**	**Pr > |t|**				
Constant	4766.429	65.0863	73.2325	0.00000	3843.553	873.564	4.3999	0.0000108	4014.42	452.12	8.88	-	4518.90	332.45	13.59	-	4421.85	423.43	10.44	-				
TRT	304.7531	91.5731	3.3280	0.00089	188.4164	98.4635	1.9136	0.05568	97.0019	112.21	0.86	0.3875	295.65	190.19	1.55	0.1203	308.71	178.08	1.73	0.0832				
S2	7.1395	84.2874	0.0847	0.93232	-67.1887	88.8218	-0.7564	0.44948	-78.5076	85.8286	-0.91	0.3605	122.67	152.21	0.81	0.4204	180.50	143.10	1.26	0.2074				
S8	200.7566	95.4139	2.1041	0.03553	64.6998	98.0570	0.6598	0.50937	322.37	115.38	2.79	0.0053	217.30	177.65	1.22	0.2214	244.62	163.61	1.50	0.1351				
TRTS2	334.1119	121.9414	2.7399	0.00621	202.1098	121.001	1.6703	0.09486	40.4009	111.77	0.36	0.7178	-60.5589	190.18	-0.32	0.7502	-78.3122	178.25	-0.44	0.6605				
TRTS8	-356.525	129.1266	-2.7611	0.00583	-130.605	133.0806	-0.9814	0.32640	-393.19	139.18	-2.83	0.0048	-269.66	222.86	-1.21	0.2265	-272.04	206.94	-1.31	0.1888				
LAMBDA	-	-	-	-	0.01848	0.01848	52.5985	0.00000	-	-	-	-	-	-	-	-	-	-	-	-				

TABLE I6: WINTER GRAIN RESPONSE TO P VARIATION ON DIFFERENT SOIL TYPES WITH DIFFERENT MODELS: K5 (2004)

Regression output																				
	OLS				**SER**				**REML**											
									Gaussian				**Spherical**				**Exponential**			
	Cf	**Std Err.**	**t-Statistics**	**Pr**	**Cf**	**Std Err.**	**z-Value**	**Pr**	**Cf**	**Std Err.**	**t-Value**	**Pr > |t|**	**Cf**	**Std Err.**	**t-Value**	**Pr > |t|**	**Cf**	**Std Err.**	**t-Value**	**Pr > |t|**
Constant	1433.362	10.1529	141.1782	0.00000	1172.731	211.0781	5.5559	0.00000	1321.12	57.7647	22.87	-	1333.33	60.8810	21.90	-	1317.09	70.0245	18.81	-
TRT	-40.7099	13.9074	-2.9272	0.00345	77.0680	29.8022	2.5860	0.00971	30.0028	46.0324	0.65	0.5146	25.4782	54.9464	0.46	0.6429	-3.2484	50.3863	-0.06	0.9486
S4	155.0847	100.9176	1.5367	0.12448	145.6594	96.0150	1.5170	0.12925	84.5260	86.7226	0.97	0.3298	94.2647	108.11	0.87	0.3833	91.0460	87.0805	1.05	0.2959
S13	-117.8548	29.2475	-4.0296	0.0000576	-248.842	42.9623	-5.7921	0.00000	-193.57	59.6554	-3.24	0.0012	-202.07	72.2013	-2.80	0.0052	-221.03	59.8691	-3.69	0.0002
TRTS4	-193.2879	104.0606	-1.8575	0.06336	-242.979	98.8494	-2.4581	0.01397	-133.09	88.6363	-1.50	0.1333	-136.20	112.21	-1.21	0.2250	-127.72	91.0138	-1.40	0.1606
TRTS13	-8.0310	49.7314	-0.1615	0.87187	195.2403	61.7856	3.1600	0.00158	220.26	90.4472	2.44	0.0150	211.91	108.92	1.95	0.0518	243.97	90.1388	2.71	0.0068
LAMBDA	-	-	-	-	0.9717	0.0171	56.7714	0.00000	-	-	-	-	-	-	-	-	-	-	-	-

TABLE I7: WINTER GRAIN RESPONSE TO P VARIATION ON DIFFERENT SOIL TYPES WITH DIFFERENT MODELS: K5 (2005)

Regression output																								
	OLS				**SER**				**REML**															
									Gaussian				**Spherical**				**Exponential**							
	Cf	**Std Err.**	**t-Statistics**	**Pr**	**Cf**	**Std Err.**	**z-Value**	**Pr**	**Cf**	**Std Err.**	**t-Value**	**Pr > |t|**	**Cf**	**Std Err.**	**t-Value**	**Pr > |t|**	**Cf**	**Std Err.**	**t-Value**	**Pr > |t|**				
Constant	5810.449	28.1644	206.3045	0.00000	3107.193	1686.035	1.8429	0.06534	5416.34	175.09	30.93	-	5542.73	167.02	33.19	-	5376.05	237.81	22.61	-				
TRT	-163.8438	38.8397	-4.2185	0.0000255	81.0491	58.8219	1.3779	0.16824	263.84	124.68	2.12	0.0344	80.6799	151.64	0.53	0.5947	135.14	145.07	0.93	0.3517				
S4	229.7179	296.8792	0.7738	0.43916	27.4644	279.7808	0.0982	0.92180	143.00	252.47	0.57	0.5712	-8.6146	315.70	-0.03	0.9782	22.9602	279.74	0.08	0.9346				
S13	-300.1866	80.8156	-3.7145	0.00021	-401.5652	84.6984	-4.7411	0.0000021	-475.37	149.17	-3.19	0.0015	-475.16	180.44	-2.63	0.0085	-489.33	158.22	-3.09	0.0020				
TRTS4	-329.6638	304.7685	-1.0817	0.27949	-42.265	287.3869	-0.1471	0.88308	-349.17	254.77	-1.37	0.1706	-184.49	324.99	-0.57	0.5703	-215.84	288.38	-0.75	0.4543				
TRTS13	415.0333	146.7621	2.8280	0.00472	617.045	146.0574	4.2247	0.0000239	462.84	240.90	1.92	0.0548	375.84	290.53	1.29	0.1959	395.40	256.41	1.54	0.1232				
LAMBDA	-	-	-	-	0.9901	0.0069	144.3525	0.00000	-	-	-	-	-	-	-	-	-	-	-	-				

TABLE I8: WINTER GRAIN RESPONSE TO P VARIATION ON DIFFERENT SOIL TYPES WITH DIFFERENT MODELS: K5 (2006)

	Regression output																			
	OLS				SER				REML											
									Gaussian				Spherical				Exponential			
	Cf	**Std Err.**	**t-Statistics**	**Pr**	**Cf**	**Std Err.**	**z-Value**	**Pr**	**Cf**	**Std Err.**	**t-Value**	**Pr > |t|**	**Cf**	**Std Err.**	**t-Value**	**Pr > |t|**	**Cf**	**Std Err.**	**t-Value**	**Pr > |t|**
Constant	5448.973	56.8647	95.8234	0.00000	1176.141	2884.182	0.4078	0.68343	4938.68	554.61	8.90	-	4405.22	398.60	11.05	-	3027.42	1022.77	2.96	-
TRT	-1119.98	78.0868	-14.3428	0.00000	39.4513	207.6265	0.1900	0.84930	-173.31	141.35	-1.23	0.2203	-472.23	250.08	-1.89	0.0591	-271.01	167.15	-1.62	0.1051
S4	466.3271	511.1505	0.9123	0.36172	-242.654	396.3498	-0.6122	0.54039	-558.65	231.57	-2.41	0.0159	-39.584	287.60	-0.14	0.8905	137.35	175.11	0.78	0.4329
S13	-1859.25	186.2848	-9.9807	0.00000	-1275.44	233.6758	-5.4582	0.00000	-1011.94	168.45	-6.01	<.0001	-963.26	207.78	4.64	<.0001	-954.42	125.08	-7.63	<.0001
TRTS4	-654.464	529.6928	-1.2356	0.21677	-352.256	404.7465	-0.8703	0.38413	-9.1284	237.53	-0.04	0.9693	25.4132	306.34	0.08	0.9339	-123.43	187.13	-0.66	0.5096
TRTS13	558.4433	327.5772	1.7048	0.8839	1162.354	346.7484	3.3522	0.00080	845.84	253.87	3.33	0.0009	1360.58	328.96	4.14	<.0001	1349.07	198.68	6.79	<.0001
LAMBDA	-	-	-	-	0.9908	0.0048	208.243	0.00000	-	-	-	-	-	-	-	-	-	-	-	-

TABLE I9: WINTER GRAIN RESPONSE TO P VARIATION ON DIFFERENT SOIL TYPES WITH DIFFERENT MODELS: K7A (2004)

Regression output																				
	OLS				SER				REML											
									Gaussian				Spherical				Exponential			
	Cf	Std Err.	t-Statistics	Pr	Cf	Std Err.	z-Value	Pr	Cf	Std Err.	t-Value	Pr > |t|	Cf	Std Err.	t-Value	Pr > |t|	Cf	Std Err.	t-Value	Pr > |t|
Constant	1516.929	14.3015	106.0678	0.00000	-1791.917	858.7013	-2.0868	0.03690	1064.00	180.92	5.88	-	1210.82	136.23	8.89	-	1053.61	264.25	3.99	-
TRT	13.3865	21.221	0.6308	0.52823	13.7803	39.4740	0.3491	0.72702	60.2285	43.9834	1.37	0.1711	129.12	82.3744	1.57	0.1172	111.26	66.1497	1.68	0.0928
S2	-112.4881	26.4669	-4.2502	0.0000224	5.6716	25.7324	0.2204	0.82555	4.1350	28.2572	0.15	0.8837	-49.715	45.7369	-1.09	0.2772	-31.6819	37.1385	-0.85	0.3937
S4	-127.786	40.7452	-3.1362	0.00174	-94.2285	43.9093	-2.1460	0.03187	-68.117	57.1072	-1.19	0.2331	-56.9582	82.1583	-0.69	0.4882	-63.5070	66.9300	-0.95	0.3428
S11	195.7695	28.8219	6.7924	0.00000	270.7779	29.3824	9.2156	0.0000	213.68	34.5025	6.19	<.0001	146.82	55.6569	2.64	0.0084	150.60	45.4895	3.31	0.0009
TRTS2	-181.8488	63.0522	-2.8841	0.00397	-154.2028	61.8040	-2.4950	0.01259	-10.723	69.5561	-0.15	0.8775	-51.8126	98.9845	-0.52	0.6007	-71.1395	80.1622	-0.89	0.3750
TRTS4	152.0991	47.8658	3.1776	0.00151	82.5413	50.0262	1.6500	0.09895	116.81	63.8961	1.83	0.0677	83.4732	93.8884	0.89	0.3741	85.9719	76.2657	1.13	0.2598
TRTS11	-110.7556	61.7273	-1.7942	0.07293	-231.534	55.3170	-4.1856	0.00003	-153.64	52.6366	-2.92	0.0036	-98.2111	82.3595	-1.19	0.2332	-108.21	67.1254	-1.61	0.1071
LAMBDA	-	-	-	-	0.9920	0.0056	177.8905	0.00000	-	-	-	-	-	-	-	-		-	-	-

TABLE I10: WINTER GRAIN RESPONSE TO P VARIATION ON DIFFERENT SOIL TYPES WITH DIFFERENT MODELS: K7A (2005)

Regression output																				
	OLS				SER				REML											
									Gaussian				Spherical				Exponential			
	Cf	Std Err.	t-Sta-tistics	Pr	Cf	Std Err.	z-Value	Pr	Cf	Std Err.	t-Value	Pr > |t|	Cf	Std Err.	t-Value	Pr > |t|	Cf	Std Err.	t-Value	Pr > |t|
Constant	5203.912	30.9420	168.1827	0.00000	5152.543	90.3604	57.0221	0.00000	5068.52	182.59	27.76	-	5025.49	215.33	23.34	-	5011.81	263.25	19.04	-
TRT	131.3301	47.0601	2.7907	0.00531	194.7491	122.7415	1.5867	0.11259	234.24	146.78	1.60	0.1107	280.87	170.01	1.65	0.0987	297.78	171.07	1.74	0.0819
S2	-0.9072	58.4256	-0.0155	0.98784	85.3656	1038351	0.8221	0.41100	61.0089	97.8531	0.62	0.5330	102.45	111.59	0.92	0.3587	152.01	109.21	1.39	0.1641
S4	305.5611	88.8101	3.4406	0.00059	129.6552	180.5674	0.7180	0.47273	-102.34	174.92	-0.59	0.5586	12.8689	197.37	0.07	0.9480	54.4920	190.62	0.29	0.7750
S11	-130.8687	67.2949	-1.9447	0.05196	18.8806	127.8753	0.1476	0.88262	122.66	122.43	1.00	0.3165	136.70	141.49	0.97	0.3341	121.96	137.99	0.88	0.3769
TRTS2	-425.1947	121.9965	-3.4853	0.00050	-332.6745	212.6538	-1.5644	0.11772	-140.35	192.79	-0.73	0.4667	-248.79	219.30	-1.13	0.2567	-362.47	214.21	-1.69	0.0908
TRTS4	-197.3727	105.5044	-1.8708	0.06153	-65.2786	207.7592	-0.3142	0.75337	96.8176	200.09	0.48	0.6285	31.7960	226.13	0.14	0.8882	-10.4936	218.59	-0.05	0.9617
TRTS11	118.9009	131.1475	0.9066	0.36473	3.7790	197.923	0.0191	0.98477	-108.21	172.96	-0.63	0.5316	-143.69	202.86	-0.71	0.4788	-127.81	201.67	-0.63	0.5263
LAMBDA	-	-	-	-	0.7577	0.0388	19.5392	0.00000	-	-	-	-	-	-	-	-	-	-	-	-

TABLE I11: WINTER GRAIN RESPONSE TO P VARIATION ON DIFFERENT SOIL TYPES WITH DIFFERENT MODELS: K7A (2006)

Regression output																								
	OLS				**SER**				**REML**															
									Gaussian				**Spherical**				**Exponential**							
	Cf	**Std Err.**	**t-Statistics**	**Pr**	**Cf**	**Std Err.**	**z-Value**	**Pr**	**Cf**	**Std Err.**	**t-Value**	**Pr > |t|**	**Cf**	**Std Err.**	**t-Value**	**Pr > |t|**	**Cf**	**Std Err.**	**t-Value**	**Pr > |t|**				
Constant	2731.659	19.8878	137.3535	0.00000	2788.446	66.7606	41.7678	0.00000	2841.41	118.46	23.99	-	2852.22	109.83	25.97	-	2836.79	168.44	16.84	-				
TRT	247.2937	29.8494	8.2847	0.00000	107.7537	88.8376	1.2129	0.22516	-44.3699	89.9996	-0.49	0.6221	-43.4630	111.81	-0.39	0.6975	12.9390	103.30	0.13	0.9003				
S2	-8.0783	37.0939	-0.2178	0.82762	-33.1601	67.7593	-0.4894	0.62457	-84.9482	57.9617	-1.47	0.1429	-43.1446	73.2763	-0.59	0.5561	-25.7342	60.7221	-0.42	0.6718				
S4	83.7238	52.5030	1.5947	0.11095	-27.9193	114.035	-0.2448	0.80659	-50.9486	102.47	-0.50	0.6191	-48.3742	126.67	-0.38	0.7026	-25.8617	106.12	-0.24	0.8075				
S11	4.0524	41.7225	0.0971	0.92252	-69.1621	81.1276	-0.8525	0.39393	-70.3408	69.5533	-1.01	0.3120	-91.4459	88.6752	-1.03	0.3026	-91.5334	72.8972	-1.26	0.2094				
TRTS2	57.6521	77.0114	0.7486	0.45417	189.0432	137.4986	1.3749	0.16917	256.87	111.96	2.29	0.0219	187.37	142.37	1.32	0.1883	183.26	119.73	1.53	0.1260				
TRTS4	-72.0423	63.4498	-1.1354	0.25634	136.585	131.6809	1.0372	0.29962	205.01	117.52	1.74	0.0812	152.92	145.13	1.05	0.2922	109.39	121.45	0.90	0.3679				
TRTS11	-51.6531	80.7532	-0.6396	0.52251	153.2732	124.0024	1.2361	0.21644	241.75	98.7450	2.45	0.0144	251.85	130.39	1.93	0.0536	220.03	108.44	2.03	0.0426				
LAMBDA	-	-	-	-	0.8126	0.0288	28.2004	0.00000	-	-	-	-	-	-	-	-	-	-	-	-				

Annexure J

Annexure J1: Profit calculation

The following example shows how profit was calculated on K3A during 2004.

If P_RATE = 75 then do; kgFertiliser=68; kgP=13,6; end; (SR rate)

If P_RATE = 40 then do; kgFertiliser=0; kgP=0; end; (VRT rate)

If P_RATE = 60 then do; kgFertiliser=47; kgP=9,4; end; (VRT rate)

If P_RATE = 80 then do; kgFertiliser=68; kgP=13,6; end; (VRT rate)

Profit_ha	=	Income_ha – Expenditure_ha
Income_ha	=	GrainPrice*(Yield/1000);
Expenditure_ha	=	ProductionC + RPrecision + RFertiliser + InterestC(a) + InterestC(b);
ProductionC	=	Production costs
RPrecision	=	Precision cost;
RFertiliser	=	kgFertiliser*FertiliserPrice; (P)
InterestC(a)	=	Interest cost for precision equipment
InterestC(b)	=	Interest cost for fertiliser

GrainPrice = ZAR1 033,05/t

ProductionC = ZAR194,67/ha (See Table J1 to Table J3)

RPrecision = ZAR80,16/ha (See Table J4)

FertiliserPrice = ZAR2,51/kg

InterestC(a) = ZAR27,80/ha (See Table J5)

InterestC(b) = -ZAR1,51 (See Table J6a to J6d)

TABLE J1: PRODUCTION COSTS (ProductionC) – ALL FOUR FIELDS – 2004

L2 (Wheat)	Bumper	Dimethoat e	Folicur	Coptrel	MCPA Aurora	Photrel	Metamidifos	Bortrac	Galant	**TOTAL VARIABLE CHEMICA L COSTS**	KAN	**TOTAL INPUTS**
	mℓ/ha	mℓ/ha	mℓ/ha	mℓ/ha	g/ha	kg/ha	mℓ/ha	liter/ha	mℓ/ha		kg/ha	
	400	500	750	125	0	0	0	0	0		20	
	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing			
	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/kg	ZAR/kg	ZAR/liter	ZAR/liter	ZAR/liter		ZAR/ton	
	107,00	24,00	104,79	72,00	22,00	43,00	24,00	35,00			189,.69	
	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	**ZAR/ha**	ZAR/ha	**ZAR/ha**
	42,80	12,00	78,59	9,00	0,00	0,00	0,00	0,00	0,00	**142,39**	37,83	**180,23**
K3A (Wheat)	Bumper	Dimethoat e	Folicur	Coptrel	MCPA Aurora	Photrel	Metamidifos	Bortrac	Galant		KAN	**TOTAL INPUTS**
	mℓ/ha	mℓ/ha	mℓ/ha	mℓ/ha	g/ha	kg/ha	mℓ/ha	liter/ha	mℓ/ha		kg/ha	
	400	1000	750	125	25	0	0	0	0		21	
	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing			
	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/kg	ZAR/kg	ZAR/liter	ZAR/liter	ZAR/liter		ZAR/ton	
	107,00	24,00	104,79	72,00	22,00	43,00	24,00	35,00			1 891,69	
	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	**ZAR/ha**	ZAR/ha	**ZAR/ha**
	42,80	24,00	78,59	9,00	0,55	0,00	0,00	0,00	0,00	**154,94**	39,73	**194,67**

*Variable chemical and KAN production costs

TABLE J1 (continues): PRODUCTION COSTS (ProductionC) – ALL FOUR FIELDS – 2004

K5 (Canola)	Bumper	Dimethoate	Folicur	Coptrel	MCPA Aurora	Photrel	Metamidifos	Bortrac	Galant	TOTAL VARIABLE CHEMICAL COSTS	KAN	TOTAL INPUTS
	mℓ/ha	mℓ/ha	mℓ/ha	mℓ/ha	g/ha	kg/ha	mℓ/ha	liter/ha	mℓ/ha		kg/ha	
	0	0	0	275	0	1	1 500	1	0		21	
	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing			
	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/kg	ZAR/kg	ZAR/liter	ZAR/liter	ZAR/liter		ZAR/ton	
	107,00	24,00	104,79	72,00	22,00	43,00	24,00	35,00			1891,69	
	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	**ZAR/ha**	ZAR/ha	**ZAR/ha**
	0,00	0,00	0,00	19,80	0,00	43,00	36,00	35,00	0,00	**133,80**	39,73	**173,53**

K7A (Canola)	Bumper	Dimethoate	Folicur	Coptrel	MCPA Aurora	Photrel	Metamidifos	Bortrac	Galant		KAN	TOTAL INPUTS
	mℓ/ha	mℓ/ha	mℓ/ha	mℓ/ha	g/ha	kg/ha	mℓ/ha	liter/ha	mℓ/ha		kg/ha	
	0	0	0	275	0	1	1500	1	400		21	
	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing			
	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/kg	ZAR/kg	ZAR/liter	ZAR/liter	ZAR/liter		ZAR/ton	
	107,00	24,00	104,79	72,00	22,00	43,00	24,00	35,00	173,70		1891,69	
	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	**ZAR/ha**	ZAR/ha	**ZAR/ha**
	0,00	0,00	0,00	19,80	0,00	43,00	36,00	35,00	69,48	**203,28**	39,73	**243,01**

*Variable chemical and KAN production costs

TABLE J2: PRODUCTION COSTS (ProductionC) – ALL FOUR FIELDS – 2005

L2 (Canola)	Galant	Dimethoate	Bortrac	Photril	SupM	Metamidifos	Co-pilot	Coptril	Bumper	Folicur	Fulfaat	**TOTAL VARIABLE CHEMICAL COSTS**	KAN	**TOTAL INPUTS**
	mℓ/ha	mℓ/ha	liter/ha	liter/ha	mℓ/ha	mℓ/ha	liter/ha	mℓ/ha	mℓ/ha	mℓ/ha	liter/ha		kg/ha	
	500	1 000	1	1	300	500	0	0	0	0	0		20	
	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing			
	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter		ZAR/ton	
	193,00	24,00	33,00	35,10	60,00	24,00	160,00	70,00	98,00	82,80	20,00		2101,88	
	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	**ZAR/ha**	ZAR/ha	**ZAR/ha**
	96,50	24,00	33,00	35,10	18,00	12,00	0,00	0,00	0,00	0,00	0,00	**218,60**	42,04	**260,64**

K3A (Canola)	Galant	Dimethoate	Bortrac	Photril	SupM	Metamidifos	Co-pilot	Coptril	Bumper	Folicur	Fulfaat		KAN	**TOTAL INPUTS**
	mℓ/ha	mℓ/ha	liter/ha	liter/ha	mℓ/ha	mℓ/ha	mℓ/ha	mℓ/ha	mℓ/ha	mℓ/ha	liter/ha		kg/ha	
	0	1000	1	1	300	500	500	0	0	0	0		20	
	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing			
	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter		ZAR/ton	
	193,00	24,00	33,00	35,10	60,00	24,00	160,00	70,00	98,00	82,80	20,00		2101,88	
	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	**ZAR/ha**	ZAR/ha	**ZAR/ha**
	0,00	24,00	33,00	35,10	18,00	12,00	80,00	0,00	0,00	0,00	0,00	**202,10**	42,04	**244,14**

*Variable chemical and KAN production costs

TABLE J2 (continues): PRODUCTION COSTS (ProductionC) – ALL FOUR FIELDS – 2005

K5 (Wheat)	Galant	Dimethoate	Bortrac	Photril	SupM	Metamidifos	Co-pilot	Coptril	Bumper	Folicur	Fulfaat	**TOTAL VARIABLE CHEMICAL COSTS**	KAN	**TOTAL INPUTS**
	mℓ/ha	mℓ/ha	liter/ha	liter/ha	mℓ/ha	mℓ/ha	mℓ/ha	mℓ/ha	mℓ/ha	mℓ/ha	liter/ha		kg/ha	
	0	1 500	1	0	0	0	0	1 200	1 000	400	2		18	
	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing			
	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter		ZAR/ton	
	193,00	24,00	33,00	35,10	60,00	24,00	160,00	70,00	98,00	82,80	20,00		2101,88	
	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	**ZAR/ha**	ZAR/ha	**ZAR/ha**
	0,00	36,00	33,00	0,00	0,00	0,00	0,00	84,00	98,00	33,12	40,00	**324,12**	37,83	**361,95**

K7A (Wheat)	Galant	Dimethoate	Bortrac	Photril	SupM	Metamidifos	Co-pilot	Coptril	Bumper	Folicur	Fulfaat		KAN	**TOTAL INPUTS**
	mℓ/ha	mℓ/ha	liter/ha	liter/ha	mℓ/ha	mℓ/ha	mℓ/ha	mℓ/ha	mℓ/ha	mℓ/ha	liter/ha		kg/ha	
	0	1000	1	0	0	0	0	200	1000	400	2		17	
	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing	Packing			
	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter		ZAR/ton	
	193,00	24,00	33,00	35,10	60,00	24,00	160,00	70,00	98,00	82,80	20,00		2101,88	
	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	**ZAR/ha**	ZAR/ha	**ZAR/ha**
	0,00	24,00	33,00	0,00	0,00	0,00	0,00	14,00	98,00	33,12	40,00	**242,12**	35,73	**277,85**

*Variable chemical and KAN production costs

TABLE J3: PRODUCTION COSTS (ProductionC) – ALL FOUR FIELDS – 2006

L2 (Wheat)	MCPA/Aurora	Dimethoate	Metamidifos	Bumper	Tri-Grass	Capitan	**TOTAL VARIABLE CHEMICAL COSTS**	1:0:0 (40)	**TOTAL INPUTS**
	mℓ/ha	mℓ/ha	mℓ/ha	mℓ/ha	liter/ha	mℓ/ha		kg/ha	
	500	500	750	400	0	0		6	
	Packing	Packing	Packing	Packing	Packing	Packing			
	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter		ZAR/ton	
	22,00	24,00	25,00	103,00	111,00	234,70		2460,00	
	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	**ZAR/ha**	ZAR/ha	**ZAR/ha**
	11,00	12,00	18,75	41,20	0,00	0,00	**82,95**	14,76	**97,71**

K3A (Wheat)	MCPA/Aurora	Dimethoate	Metamidifos	Bumper	Tri-Grass	Capitan		1:0:0 (40)	**TOTAL INPUTS**
	mℓ/ha	mℓ/ha	mℓ/ha	mℓ/ha	liter/ha	mℓ/ha		kg/ha	
	500	500	750	400	0	0		6	
	Packing	Packing	Packing	Packing	Packing	Packing			
	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter		ZAR/ton	
	22,00	24,00	25,00	103,00	111,00	234,70		2460,00	
	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	**ZAR/ha**	ZAR/ha	**ZAR/ha**
	11,00	12,00	18,75	41,20	0,00	0,00	**82,95**	14,76	**97,71**

*Variable chemical and 1:0:0 (40) production costs

TABLE J3 (continues): PRODUCTION COSTS (ProductionC) – ALL FOUR FIELDS – 2006

K5 (Barley)	MCPA/Aurora	Dimethoate	Metamidifos	Bumper	Tri-Grass	Capitan	**TOTAL VARIABLE CHEMICAL COSTS**	1:0:0 (40)	**TOTAL INPUTS**
	mℓ/ha	mℓ/ha	mℓ/ha	mℓ/ha	liter/ha	mℓ/ha		kg/ha	
	500	500	300	500	1,1	300		0	
	Packing	Packing	Packing	Packing	Packing	Packing			
	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter		ZAR/ton	
	22,00	24,00	25,00	103,00	111,00	234,70		2460,00	
	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	**ZAR/ha**	ZAR/ha	**ZAR/ha**
	11,00	12,00	7,50	51,50	122,10	70,41	**274,51**	0,00	**274,51**

K7A (Barley)	MCPA/Aurora	Dimethoate	Metamidifos	Bumper	Tri-Grass	Capitan		1:0:0 (40)	**TOTAL INPUTS**
	mℓ/ha	mℓ/ha	mℓ/ha	mℓ/ha	liter/ha	mℓ/ha		kg/ha	
	500	0	0	800	1,1	300		0	
	Packing	Packing	Packing	Packing	Packing	Packing			
	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter	ZAR/liter		ZAR/ton	
	22,00	24,00	25,00	103,00	111,00	234,70		2460,00	
	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	ZAR/ha	**ZAR/ha**	ZAR/ha	**ZAR/ha**
	11,00	0,00	0,00	82,40	122,10	70,41	**285,91**	0,00	**285,91**

*Variable chemical and 1:0:0 (40) production costs

TABLE J4: PRECISION COSTS (RPrecision)

	2004 (ZAR)	2005 (ZAR)	2006 (ZAR)
Hiring of digger	3 517,47	-	-
Soil samples (laboratory costs)	24 007,50	-	-
Soil samples (field work) ZAR30/sample x 165 samples	4 950,00	-	-
TOTAL FOR 109,63 HA (A)	**32 474,97**	**-**	**-**
TOTAL PER YEAR (10 years)* 109,63 HA (A ÷ 10) = B	**3 247,50**	**3 247,50**	**3 247,50**
SUB TOTAL PER HA (B ÷ 109,63) = C	**29.62**	**29.62**	**29.62**
GPS	3 500,00		
DGPS	30 000,00		
SS Toolbox	35 000,00	-	-
Yield monitor	250 000,00	-	-
Computer	10 000,00	-	-
TOTAL FOR 1 300 HA (D)	**328 500,00**	**-**	**-**
TOTAL PER YEAR (5 years) 1 300 HA (D ÷ 5) = E**	**65 700,00**	**65 700,00**	**65 700,00**
SUB TOTAL PER HA (E ÷ 1 300) = F	**50,54**	**50,54**	**50,54**
TOTAL PER HA (C + F)	**80,16**	**80,16**	**80,16**

***The costs associated with soil sampling are depreciated over 10 years according to current farming practices (5 years cash crops and 5 years grazing). Only columns for the three production years are shown.**

****Although the costs are depreciated over five years, only the columns of the three production years are shown.**

TABLE J5: INTEREST COSTS [InterestC(a)*]

Description	Amount (ZAR)
GPS	3 500,00
DGPS	30 000,00
SS Toolbox	35 000,00
Yield monitor	250 000,00
Computer	10 000,00
TOTAL	**328 500,00**
Interest rate (Prime) for 12 months = 11 %	
Interest for 12 month period	(328 500 x 11 / 100) = ZAR36 135,00
Interest per hectare per year (1 300 ha)	**ZAR36 135 ÷ 1 300 = ZAR27,80/ha/year**

***Interest cost calculation on additional equipment needed for precision agriculture**

TABLE J6a: INTEREST COSTS [InterestC(b)]* – Field L2 (24,33 hectares)

Kg fertiliser applied per ha (A)	Hectare (B)		Total kg fertiliser applied (A x B) = C		Fertiliser price (ZAR/kg) (D)	Total cost (ZAR) (C x D) = E		Cost per ha (ZAR/ha) E ÷ B		Cost difference (ZAR/ha)***	Interest (ZAR/ha)
	VRT	**SR**	**VRT**	**SR**		**VRT**	**SR**	**VRT**	**SR**	**VRT minus SR**	
2004					**2.51**						
35	12,35		370.50			929.96					
40	0,004		0.16			0.40					
50	0,58	9.79	29.00	489.50		72.79	1228.65				
60	1,61		96.60			242.47					
TOTAL	**14,54**	**9,79**	**496,26**	**489,50**		**1245,62**	**1228,65**	**85,67**	**125,50**	**-39,83**	**-1,39**
2005					**2,69**						
40	5,84		233,60			628,38					
50	4,28	9,77	214,00	488,50		575,66	1 314,07				
60	4,44		266,40			716,62					
TOTAL	**14,56**	**9,77**	**714,00**	**488,50**		**1 920,66**	**1 314,07**	**131,91**	**134,50**	**-2,59**	**-0,09**
2006**					**2,48**						
0 ÷2 = 0	1,40		0,00			0,00					
44 ÷2 = 22	9,79	9,70	215,38	213,40		534,14	529,23				
54 ÷2 = 27	2,76		74,52			184,81					
77 ÷ 2 = 38,50	0,52		20,02			49,65					
104 ÷ 2 = 52	0,08		4,16			10,32					
TOTAL	**14,55**	**9,70**	**314,08**	**213,40**		**778,92**	**529,23**	**53,53**	**54,56**	**-1,03**	**-0,04**

***Interest cost calculation on difference between VRT and SR fertiliser applications**

**** Kg fertiliser applied is a correction for current year as well as 5 year lucerne grazing. Only half of the nutrients applied is applicable to the current crop (kg fertiliser ÷ 2)**

*****Negative balance (VRT cost/ha lower than the SR cost/ha) 7 % interest per year for 6 months**
Positive balance (VRT cost/ha higher than the SR cost/ha) 11 % interest per year for 6 months

TABLE J6b: INTEREST COSTS [InterestC(b)]* – Field K3A (25,80 hectares)

Kg fertiliser applied per ha (A)	Hectare (B)		Total kg fertiliser applied (A x B) = C		Fertiliser price (ZAR/kg) (D)	Total cost (ZAR) (C x D) = E		Cost per ha (ZAR/ha) E ÷ B		Cost difference (ZAR/ha)***	Interest (ZAR/ha)
	VRT	**SR**	**VRT**	**SR**		**VRT**	**SR**	**VRT**	**SR**	**VRT minus SR**	
2004					**2.51**						
0	1,1		0,00			0,00					
47	5,2		244,40			613,44					
68	4,42	15,08	300,56	1 025,44		754,41	2 573,85				
TOTAL	**10,72**	**15,08**	**544,96**	**1 025,44**		**1 367,85**	**2 573,85**	**127,60**	**170,68**	**-43,08**	**-1,51**
2005					**2,69**						
21	0,1		2,10			5,65					
35	3,1		108,50			291,87					
42	2,76		115,92			311,82					
45	2,92		131,40			353,47					
48	2,00	14,92	96,00	716,16		258,24	1 926,47				
TOTAL	**10,88**	**14,92**	**453,92**	**716,16**		**1 221,05**	**1 926,47**	**112,23**	**129,12**	**-16,89**	**-0,59**
2006**					**2,48**						
19 ÷ 2 = 9,50	1,80		17,10			42,41					
45 ÷ 2 = 22,50	1,70	14,90	38,25	335,25		94,86	831,42				
70 ÷ 2 = 35	1,90		66,50			164,92					
131 ÷ 2 = 65,50	5,50		360,25			893,42					
TOTAL	**10,90**	**14,90**	**482,10**	**335,25**		**1 195,61**	**831,42**	**109,69**	**55,80**	**53,89**	**2,96**

***Interest cost calculation on difference between VRT and SR fertiliser applications**

**** Kg fertiliser applied is a correction for current year as well as 5 year lucerne grazing. Only half of the nutrients applied is applicable to the current crop (kg fertiliser ÷ 2)**

*****Negative balance (VRT cost/ha lower than the SR cost/ha) 7 % interest per year for 6 months**
Positive balance (VRT cost/ha higher than the SR cost/ha) 11 % interest per year for 6 months

TABLE J6c: INTEREST COSTS [InterestC(b)]* – Field K5 (38,98 hectares)

Kg fertiliser applied per ha (A)	Hectare (B)		Total kg fertiliser applied (A x B) = C		Fertiliser price (ZAR/kg) (D)	Total cost (ZAR) (C x D) = E		Cost per ha (ZAR/ha) E ÷ B		Cost difference (ZAR/ha)***	Interest (ZAR/ha)
	VRT	**SR**	**VRT**	**SR**		**VRT**	**SR**	**VRT**	**SR**	**VRT minus SR**	
2004					**2,51**						
100	0,02		2,00			5,02					
125	2,03		253,75			636,91					
150	12,69	23,14	1 903,50	3 471,00		4 777,79	8 712,21				
175	1,10		192,50			483,18					
TOTAL	**15,84**	**23,14**	**2 351,75**	**3 471,00**		**5 902,90**	**8 712,21**	**372,66**	**376,50**	**-3,84**	**-0,13**
2005					**2,69**						
15	0,7		10,50			28,25					
34	5,2		176,80			475,59					
41	4,4		180,40			485,28					
45	3,3		148,50			399,47					
48	2,24	23,14	107,52	1 110,72		289,23	2 987,84				
TOTAL	**15,84**	**21,64**	**623,72**	**1 110,72**		**1 677,82**	**2 987,84**	**105,92**	**138,07**	**-32,15**	**-1,13**
2006**					**2,48**						
9 ÷ 2 = 4,50	0,80		36,00			89,28					
41 ÷ 2 = 20,50	0,76	23,70	15,58	485,85		38,64	1 204,91				
90 ÷ 2 = 45	2,20		99,00			245,52					
166 ÷ 2 = 83	3,24		268,92			666,92					
245 ÷ 2 = 122,50	8,28		1 014,30			2 515,46					
TOTAL	**15,28**	**23,70**	**1 433,80**			**3 555,82**		**232,71**	**50,84**	**181,87**	**10,00**

***Interest cost calculation on difference between VRT and SR fertiliser applications**

**** Kg fertiliser applied is a correction for current year as well as 5 year lucerne grazing. Only half of the nutrients applied is applicable to the current crop (kg fertiliser ÷ 2)**

*****Negative balance (VRT cost/ha lower than the SR cost/ha) 7 % interest per year for 6 months**
Positive balance (VRT cost/ha higher than the SR cost/ha) 11 % interest per year for 6 months

TABLE J6d: INTEREST COSTS [InterestC(b)]* – Field K7A (20,52 hectares)

Kg fertiliser applied per ha (A)	Hectare (B)		Total kg fertiliser applied (A x B) = C		Fertiliser price (ZAR/kg) (D)	Total cost (ZAR) (C x D) = E		Cost per ha (ZAR/ha) E ÷ B		Cost difference (ZAR/ha)***	Interest (ZAR/ha)
	VRT	**SR**	**VRT**	**SR**		**VRT**	**SR**	**VRT**	**SR**	**VRT minus SR**	
2004					**2,51**						
41	0,72		29,52			74,10					
66	1,30		85,80			215,36					
89	0,84	9,86	74,76	877,54		187,65	2 202,63				
116	1,20		139,20			349,39					
142	6,60		937,20			2 352,37					
TOTAL	**10,66**	**9,86**	**1 266,48**	**877,54**		**3 178,87**	**2 202,63**	**298,21**	**223,39**	**74,82**	**4,12**
2005					**2,69**						
26	0,2		5,20			13,99					
32	3,8		121,60			327,10					
42	2,0		84,00			225,96					
45	2,0		90,00			242,10					
48	2,54	9,98	121,92	479,04		327,97	1 288,62				
TOTAL	**10,54**	**9,98**	**422,72**	**479,04**		**1 137,12**	**1 288,62**	**107,89**	**129,12**	**-21,23**	**-0,74**
2006**					**2,48**						
0	0,40		0,00			0,00					
41 ÷ 2 = 20,50	5,52	10,00	113,16	205,00		280,64	508,40				
117 ÷ = 58,50	3,2		187,20			464,26					
271 ÷ 2 = 135,50	1,0		135,50			336,04					
529 ÷ 2 =264,50	0,4		105,80			262,38					
TOTAL	**10,52**	**10,00**	**541,66**	**205,00**		**1 343,32**	**508,40**	**127,69**	**50,84**	**76,85**	**4,23**

***Interest cost calculation on difference between VRT and SR fertiliser applications**

**** Kg fertiliser applied is a correction for current year as well as 5 year lucerne grazing. Only half of the nutrients applied is applicable to the current crop (kg fertiliser ÷ 2)**

*****Negative balance (VRT cost/ha lower than the SR cost/ha) 7 % interest per year for 6 months**
Positive balance (VRT cost/ha higher than the SR cost/ha) 11 % interest per year for 6 months