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# Soil Variability Effects on the Yield of Winter Wheat under Variable-Rate Nitrogen Applications

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## i. ABSTRACT

Seven UK fields located across Oxfordshire, Southampton and W. Berkshire, five cropped in winter wheat in 2014 and two in 2013 were investigated to assess the effect of soil variability on mean yield and yield variance under flat-rate and variable-rate nitrogen applications. The high level aim being to provide information to help guide growers on how best to apply nitrogen fertiliser to increase yield and enhance yield uniformity. Data layers were collated for shallow Electrical-Conductivity (EC), Leaf Area Index, nitrogen application and yield. Yields were neither significantly higher under flat-rate nor variable-rate treatment ($p = 0.8356$). Variation in shallow EC was neither significantly more different in the variable-rate treatments or the flat-rate treatments ($p = 0.7862$). Variability in EC held a positive relationship with yield variability under both flat-rate ($R^2 = 0.2102$) ($p = 0.0213$) and variable-rate treatment ($R^2 = 0.1507$) ($p = 0.0176$). This suggests that variable-rate treatment provided no significant benefit in reducing yield variability.

Keywords:

Precision Farming, GPS, Fertiliser, UK Agriculture, Remote Sensing.

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| | |
|---|---|
| ADAS | Agricultural Development and Advisory Service |
| DEFRA | Department for Environment, Food and Rural Affairs |
| EC | Electrical Conductivity |
| GAI | Green Area Index |
| GIS | Geographic Information System |
| GPS | Global Positioning System |
| GS | Growth Stage |
| HGCA | Home Grown Cereals Authority |
| LAI | Leaf Area Index |
| MAD | Mean Average Deviation |
| NDVI | Normalised Difference Vegetation Index |
| NUE | Nitrogen Uptake Efficiency |
| OM | Organic Matter |
| WUE | Water Use Efficiency |

# 1. Introduction

Agriculture in the UK has become a refined and demanding industry. Growers are under constant pressure to deliver high yielding crops in a sustainable manner with minimal impact on the environment. As well as producing high yielding crops, farmers in the UK have strict targets to meet concerning the quality of harvested material. As modern farming strives to achieve more from less, there is great agronomic and financial justification for refining the way farmers manage their inputs.

Winter wheat is the most commonly grown arable crop in the UK. In 2015, 1.87 Mha of winter wheat was planted, producing 16.2 Mt and accounting for 50% of the UK's cereal crop area (DEFRA, 2015). Modern varieties grown in the UK offer the potential for high yields, ranging between 8-12 t/ha (HGCA, 2012).

In its most simplistic terms, final winter wheat yield, like most arable crops, is dependent on photoperiod (Tippett,, 1926), temperature (Porter and Gawith, 1999), moisture availability (Fisher, 1924), variety, nutrient availability (Davis *et al.,* 1996) and pest/disease intervention. Some of these factors such as variety and nutrient availability can be influenced by the grower (Delogu *et al.,* 1997). Growers can apply fertiliser to maximise yield and quality. N is a key component in the growth of the wheat plant (Novoa and Loomis, 1981) and as a result has a direct effect on yield (Austin *et al.,* 1977). Growers apply N at key growth stages of the crop in an effort to maximise grain number and size (Bing-nian and Sheng-xiu, 2006). The amount of N fertiliser required, depends on the variety grown, end market, anticipated yield, time of application, expected rate of uptake and is restricted by environmental legislation (MAFF, 2010).

Applied N fertiliser needs to find its way into the soil solution to be available to the crop. An established rooting system then allows for the N to be absorbed by the plant (Barraclough *et al.,* 1991). N that is not captured by the crop can be lost through leaching and volatilisation which can pose negative effect to the environment (DEFRA, 2012). Successful uptake by the crop is dependent on an adequately established rooting zone and is influenced by the physical characteristics of the soil (Barraclough *et al.,* 1991).

The cost of N is dependent on global markets. More efficient application of N fertiliser and uptake by the crop leads to more efficient use of inputs on farm, potentially contributing to overall farm profit. This is amplified by an increase to yield. As a result, accurate applications of N fertiliser are paramount to UK growers to enhance yields whilst minimising wasted inputs (Austin *et al.,* 1977). Selecting products that are more efficiently consumed by the crop and applying these products at times that result in efficient uptake are an integral consideration of any wheat grower's nutrient program.

In the UK, it is typical for soil type and related water retaining characteristics to vary on farm and in-field (Avery *et al.,* 1980). Differences in soil structure and pore space have an influence on soil moisture availability (Hall *et al.,* 1977). Electrical Conductivity (EC) shows the water holding capabilities of a soil. This can typically show the difference between lighter and heavier soils. By taking frequent EC measurements in all areas of a field, a georeferenced image can be produced which shows changes in soil type. This, when coupled with an onsite investigation, can help produce a detailed soil map for a field. EC is a sliding scale. Unique EC values do not exist for certain soils, instead the range shows the extent of in-field variation and where soil type changes. Reduced soil moisture availability can restrict N uptake while excessive soil moisture can lead to N loss (Avery, 1973). Although N fertiliser can typically be applied at a uniform rate to a wheat crop, it is understood that the efficient uptake of N varies within field (Baxter and Oliver, 2005). This can lead to non-uniform yield within field; posing difficulties to disease management, harvesting, as well as obvious financial loss due to low yielding areas (Bakker *et al.,* 2005).

UK growers have the capability to variably apply their N depending on the state of the crop through the use of GPS application equipment (Welsh *et al.,* 2003b). This relies on measuring the crop within the field and assigning georeferenced areas an NDVI value (Asrar *et al.,* 1984). Normalised Difference Vegetation Index illustrates the ratio of bare soil to cop. A higher NDVI value represents thicker crop, a lower NDVI value thinner crop. Values in the range 0-1.5 can be recorded in February and figures up to 8.0 obtainable in early July. Through on ground calibration, NDVI values can be translated to LAI (Leaf Area Index) which illustrates crop biomass. The amount of N applied can be adjusted to address variation in crop biomass. Usually, more N can be applied to areas of lower biomass to help promote rapid crop growth in an attempt to catch up with the more forward areas in the field. Conversely, the amount of N applied to areas of higher biomass, illustrating more advanced areas of the crop, can be restricted in an attempt to bring all biomass in-field to the same level. Variable application of N fertiliser, directed by biomass, allows inputs to be adjusted but does not consider the influence that soil variation has regarding efficient uptake of N by the crop after point of application. It could be suggested that variable applications of N are irrelevant if in-field soil variation is the controlling factor in the successful uptake of N fertiliser by the crop.

Literature shows that soil characteristics affect the way that N is taken into the soil solution and consumed by the crop (Avery, 1973, Barraclough *et al.,* 1991 and Hall *et al.,* 1977), also that N availability has a direct effect on the yield of winter wheat (Novoa and Loomis, 1981). In-field variation of soil is common in the UK (Avery *et al.,* 1980) and the technology to map such variation exists (Waine *et al.,* 2000 and Earl *et al.,* 2003).

The creation of seasonal N programs as advised by MAFF (2010) and the canopy management approach established by the HGCA (2012) offer a field-by-field approach and indeed do factor in soil type but do not fully consider in-field variation. Work conducted by the HGCA (2012) in refining the canopy management approach noted differences in the performance of the models on different soil types and recommended adjustment between fields depending on soil type but not adjustment between zones within a field.

Although GPS directed services offered by UK industry address in-field variation (Griffin, 2007), they are based purely on crop biomass and do not consider in-field soil variation. Soil types are treated as spatially non variable within a field. Therefore the differences in soil characteristics within field and their effects on crop performance under variable-rate N applications need to be understood.

## 1.1 Aims and Objectives

This project aims to evaluate the extent to which soil variability affects the response of winter wheat to N under variable-rate application. In order to meet this aim, the objectives are;

- To determine the difference in yield between areas of flat-rate and variable-rate N application.
- To critically evaluate the relationships between soil characteristics and yield.
- To critically evaluate the variation in yield and soil type under flat-rate and variable-rate N application, using electrical conductivity (EC) as an indicator of soil characteristics.

# 2 Literature Review

## 2.1 Winter Wheat in the UK

Numerous varieties of winter wheat exist in the UK and are selected for their characteristics suiting the end market. Main market options are for; UK bread-making, UK cake and biscuit making, UK distilling and for international export. Hard wheats, with high protein and starch content are grown for bread production. Soft wheats (low protein and starch) are used for biscuit production. Poorer quality wheats are used for animal feed. A small amount of wheat is gown each year for seed production. 77.4% of domestic wheat grain is used for human and industrial consumption (HGCA, 2013). Ideal grain characteristics focus on endosperm texture, protein content and the Hagberg falling number. In 2014, the UK winter wheat area was 1,929,000 ha, with 16.6 Mt produced, of which 10% was exported, and the remaining used in national livestock production and UK food production (HGCA, 2014).

Winter wheat yields in the UK have seen a steady increase over the last 50 years with 10 t/ha currently achievable for most farmers in England (HGCA, 2014). First wheat will usually yield a tonne higher per hectare than second wheat. Different varieties of wheat have been developed to produce high yields of quality grain from plants that are resistant to disease and climatic stress. Cultivar development is mainly responsible for increases in yield over time (HGCA, 2013). It is also relevant to note that changes to farming practice, fertilisation and pest/disease management has also played a part (Austin, 1999). Yields vary depending on cultivar (Smith, 1976) with 8.5 -10.5 t/ha being the average across the UK (DEFRA, 2012).

The yield and selling price of a wheat crop is important for the grower as it has a significant effect on farm income. Growers can justify expenditure on fertilisers and crop protection products if the choices will result in an increase in yield. As a result, agronomic decision making typically focuses on three key stages which can have a significant effect on yield (Tottman, 1987). This includes an initial application to aid root establishment (Barraclough and Leigh, 1984 and Barraclough *et al.,* 1991), an application to promote tillering and an application to promote protein development during grain fill (Thorne *et al*., 1988; Willington and Biscoe, 1985).

## 2.2 Nitrogen

Nitrogen (N) is the most important nutrient regarding yield and grain quality of wheat (Novoa and Loomis*,* 1981). It is also the most mobile nutrient with uptake efficiency highly dependent on available N in the rooting zone of the crop and the soils susceptibility to leaching through the profile (Barraclough *et al.,* 1991). N can be served to the crop in two key forms; as inorganic N or 'bagged fertilisers' and as organic N that goes through the process of mineralisation becoming available during the crop's growing period . Timing the application of N is key to high yield and adequate protein levels (Mahler *et al.,* 1994). N needs to be available at all growth stages but is particularly important at rooting; tillering and grain fill (Spiertz and Vos, 1985). A wheat crop will typically take up to 30% of final N demand by the start of stem extension and 90% by flowering. Extra N can be applied later in the season (end of May/July) to achieve optimum protein levels, (HGCA, 2009).

Nitrogen applied to the crop will typically enter the soil solution and then the crop via the roots. Uptake efficiency of N ranges from 10 – 80% with 60% uptake efficiency accepted by industry as a general average (MAFF, 2010). Uptake efficiency depends on three key elements. Firstly an adequate rooting system needs to be in place to capture N in the soil solution. Secondly, temperature controls the process of mineralisation (Baxter and Oliver*,* 2005). Low temperatures will see slower mineralisation and in turn less N released in to the available pool. Thirdly, soil moisture must be present to contribute to the soil solution so that N can be delivered to the rooting zone and taken up by the plant (Baier and Robertson, 1968). If a soil lacks moisture, this process is inhibited with N remaining in the soil but becoming immobile (Delogu *et al.,* 1997). Moisture levels in the soil must be kept constant throughout the growing season to aid nitrogen use efficiency (NUE). High precipitation rates can contribute to the soil solution to a point where water and N are forced down through and out of the soil profile (Parkinson *et al.,* 1988). This can lead to N not being taken up by the crop making the application of N fertiliser a wasteful exercise. Concerning N leaching, certain soils retain moisture and therefore N more effectively than other soils (Richards, 1965).

## 2.3 Soil

Soils in the UK are varied in terms of their physical characteristics due to underlying geology, climate and previous geological processes. Five factors lead to differences in soil type: parent material, climate, relief, biotic factors and time (Burnham *et al.,* 1980). These processes affect the ratio of sand, silt and clay in a soil as well as soil depth, drainage characteristics and Organic Matter (OM) content.

Soil type has a significant effect on wheat yields (Bakker, *et al*., 2005). Deep and fertile soils when combined with ideal climatic conditions provide the highest yields (Avery, 1962). Depth of the soil profile is important because it allows the crop's root structure to develop fully and therefore have an increased ability to draw in nutrients and water (Barraclough *et al.,* 1991). It is also important to note the effect that soil structure can have on crop development. Compacted soils, typically clays, can inhibit root movement, meaning that roots struggle to find water and nutrients. However, if roots have the option of being mobile in a clay soil they will benefit from the soil's ability to retain moisture and nutrients (Barraclough and Weir, 1988). Soils comprised predominantly of sand may favour root mobility but due to increased drainage and leaching may have less moisture and fewer nutrients for the crop to utilise (Barraclough and Leigh*,* 1984). Soils need to have a balance between adequate pore space, suitable moisture levels and adequate nutrient composition (Barraclough *et al.,* 1991). Some soils in England have ideal characteristics for the production of winter wheat helping to explain the spatial distribution of UK industry (Avery, 1962 and Bakker *et al*., 2005).

Soil characteristics and their ability to maintain water with varying levels of efficiency have been evaluated (Rowell, 1994). The maximum amount of water that a soil can hold is its saturated water content which is dependent on soil porosity. This is typically 40-60% of the soil volume. This is reduced to 10-55% when macropores are drained and the stage of field capacity has been reached. Permanent wilting point falls into the range of 5-35%. The ability to retain water is dependent on forces acting between water molecules and hydrophilic particle surfaces. These forces can include electrical attraction, hydrogen bonds and van der Waals forces. These processes are heavily influenced by particle size, particle distribution and OM content. Commonly, sandy soils will drain more quickly and have a lesser ability to maintain water while clay soils will typically retain water more effectively (Jarvis and Leeds-Harrison, 1987). Different soils within a particular field will have varied compositions regarding soil particle size and distribution, in turn leading to different drainage characteristics (Hall et al., 1997).

## 2.4 In-Field Variability

Moisture levels can vary across a field and will normally have a significant correlation with soil type (Waine *et al.,* 2000). During times of drought stress, parts of the field with lower moisture levels will see reduced yields (Taylor *et al.,* 2003). The relationship between soil moisture and yield typically relates to two key processes. Firstly the initial phase of root development following drilling whereby the roots require adequate moisture to establish (Porter, 1993; Pringle *et al*., 2003) and secondly the steady supply of moisture through the growing season to facilitate the successful uptake of nutrients at key growth stages (Shepherd *et al.,* 2001 and Zwart *et al.,* 2010). Successful uptake of nutrients can be determined by the spatial distribution of N as well as the physical soil characteristics that allow the N to be taken into the roots (Delin et al., 2005). Supply of N can vary in-field due to a number of reasons. Areas of a field with free draining soils may see more leaching of N (Casa and Castrignano, 2008) or areas of compaction may inhibit N uptake (Barraclough *et al.,* 1991). A soil may be uniform across the field in terms of its composition but compaction or waterlogging may affect NUE after N is applied as well as affecting the mineralisation process (Baxter *et al.,* 2003; Barraclough and Weir, 1988).

Organic matter supports microbial activity and binds aggregates, improving water and nutrient holding capacity (DEFRA, 2012). OM can vary in-field, affecting N mineralisation and availability. Some soils may have substantially more naturally occurring OM. Peaty soils will have a higher presence of OM compared to sandy soils (Huang *et al.,* 2007 and Chai *et al.,* 2008). OM can vary due to crop residue input and the spreading of organic manures. Crop residue such as the material left in-field after harvest, returns OM back to the soil. It is then this OM that through the process of mineralisation returns N back to the soil. Therefore, parts of a field that had a more developed crop will see more biomass turned back into the soil than parts of the field where there was less biomass at the time of harvest (Chai *et al.,* 2008).

Implications of baling or incorporating the straw post-harvest also affect soil OM. If the straw is baled, N is removed. If it is chopped and incorporated, N will be returned to contribute to the mineral N pool. Applications of organic manures will grant OM and N to the field. Due to their nature and general farming practice, spreading of such materials is not as accurate as prilled fertilisers. As a result, OM distribution following organic manure applications can vary in-field (Baxter *et al.,* 2003b and Baxter and Oliver, 2005). OM content will also affect N distribution in-field with high OM levels more likely to provide a constant source of N into the soil solution, dependant on temperature and adequate aeration of the soil (Nolan *et al.,* 1995).

Electrical Conductivity (EC) scanning can be used to illustrate the water holding capacity of a soil at a particular location in a field and in turn describe the abundance of porosity (Waine *et al.,* 2000) serving as a base layer to spatially distinguish changes in soil type. High EC shows soils which are less permeable and in turn are less free draining due to a higher abundance of tightly placed, typically smaller, clay particles. Low EC illustrates higher permeability due to larger coarser sand particles which can be related to free draining soils (Godwin and Miller*,* 2003). Soils represented by high EC may restrict germination and rooting development, ultimately leading to a lower yielding crop. In contrast, low EC soils can favour establishment, promoting rapid development in the early stages of the crops growing period crop (Barraclough and Leigh*,* 1984, Barraclough and Weir 1988 and Barraclough *et al.,* 1991). Georeferenced EC values allow soil zones to be identified within a field which can then be classified through further on site investigation.

## 2.5 Current Industry Practice for Applying Nitrogen Fertiliser

Arable farmers growing winter wheat in the UK are largely dependent on the fertiliser manual (RB209) (DEFRA, 2012). An N fertiliser plan needs to establish how much N is available to the crop (a combined influence of previous crop, residual material and soil type) and how much the crop will require through the growing season. RB209 currently offers two key strategies for calculating how much N is available to and required by the crop. Both estimate the amount of N available or the Soil Nitrogen Supply (SNS) and then propose a balance to be applied through the growing season. SNS is affected by rainfall (due to N's ability to be leached) soil type and OM content.

The first approach to calculating SNS is the field assessment method. Location in the UK is determined and the level of expected/typical rainfall assigned – low, medium or high. The most common soil type of the field is identified (options of; light sand soils, shallow soils, medium soils, deep clayey soils, deep silty soils, organic soils and peat soils) and the previous crop in-field noted. An SNS index ranging from 0-6 is then determined. Deep silts and deep clays typically retain residual N more effectively than shallow or sandy soils influencing the prescribed rate of N proposed by the SNS figure (HGCA, 2009).

The field assessment method offers a basic approach but may be inaccurate if the SNS is likely to be large or uncertain (Sylvester-Bradley *et al.,* 2008). It assumes that previous crops have been managed well and that previous fertiliser recommendations have been accurate enough to ensure optimum uptake with minimal leaching through the profile. The second method is based on measured amount of N in the profile through soil sampling to 90 cm. The measurement method requires three key steps to be undertaken. Firstly the Soil Mineral Nitrogen (SMN) of the soil needs to be determined. Then, an estimate of how much N is in the crop needs to be made. An allowance for net mineraliseable N is then made and finally the SNS index calculated. To estimate the amount of N in the crop, the number of shoots per m$^2$ can be counted and the likely amount of N present in the crop determined. An adjustment is then made for N that will be mineralised from OM and crop debris after soil sampling. An OM figure below 10% (common in most mineral soils) will see no adjustment. High OM soils or fields receiving frequent manure applications may need to be accounted for. As a general rule, an OM reading of 10% can potentially release 60-90 kg/ha more potentially available N. As a result, SNS = SMN (0-90cm or maximum rooting depth in shallow soils over rock) + Crop N (at time of sampling for SMN) + estimate of available N from mineralisation of OM. The exact SNS figure in kg/ha N falls into a range of SNS indices ranging from 0-6.

Limitations of the two management strategies have been addressed in literature (Sylvester-Bradley *et al.,* 2008), Ten N-response trials were carried out for wheat in 2005, 2006 and 2007 on trial sites on a number of soils located in the East of England. Trial plots were chosen for their generally uniform soil characteristics. Results were used to update the following edition of the RB209. It was discovered that to maximise average profit from feed grain production, current recommendations (at the time RB209, 7th edition, 2000) had to be increased by 18 kg/ha N for modern wheat varieties. It was also stated that the field assessment method to predict SNS did not perform satisfactorily hence an industry trend for people to adopt the in-field measurement approach and monitor the crop through the growing season.

RB209 (MAFF, 2010) uses the previously calculated SNS index which combined with soil type produces an overall N requirement in kg for the growing season for a wheat crop. This method considers the dominant soil type for the field but with no consideration for in-field variation. The total amount of N recommended is then broken down into “splits” that relate to key requirements in the wheat plants growth cycle. The aim being to enhance the effectiveness of key physiological stages that influence yield. The number of splits is dependent on the overall season’s requirements but may lead to three key applications being made. For example, an overall total requirement exceeding 120 kg/ha N could consist of an early application (Feb/March) of 40 kg/ha, a main application (early April, early May) of 120 kg/ha just before stem extension and a late application (end of May) of 40 kg/ha to boost grain protein. For milling varieties, a final foliar application (late July) of 40 kg/ha could be applied to enhance protein levels. An overall requirement less than 120 kg/ha would be applied as a single dressing before the onset of early stem extension.

Devising an N fertiliser plan before the growing season is useful for budgeting and logistical purposes, but does not factor in the numerous variables that can exist through the growing season and have an effect on the performance of the crop. Measuring the biomass or Green Area Index (GAI) through the growing season can allow for adjustments to be made in the N fertilisation plan, saving costs and amplifying yields. The HGCA provides benchmarks relating growth stage to expected Green Area Index as shown in Table 1.

Table 1. Wheat Growth Stage and expected Green Area Index Value (HGCA, 1998).

| **Growth Stage** | **Green Area Index (GAI)** |
|---|---|
| 23 – 3 tillers | 0.7 |
| 30 – ear at 1cm | 1.6 |
| 31 – first node | 2.0 |
| 39 – flag leaf emerged | 6.1 |
| 59 – ears emerged | 6.3 |
| 61 – flowering | 6.3 |
| 71 – watery ripe | 5.7 |
| 87 – hard dough | 1.3 |

Between 1993 and 1995, the HGCA conducted a number of trials to assess the differences between the canopy management model (as used by DEFRA today) and conventional wisdom as put forward by MAFF in 1994. The aim was to improve N management and help refine the accuracy of fertiliser practice. The two strategies were trialled in 90 tests over the three years. Trial plots were at least 24mx6m with wheat drilled at a rate determined by local experience to expect 275 plants/m$^2$ in the spring. Soil types within the trial plots were treated as uniform. All applications under both the canopy management model and the MAFF approach were applied flat-rate by hand. Satellite sites were also scrutinised in different years; 1993 ADAS Rosemand, 1994 Harper Adams, 1995 SAC Edinburgh. These sites along with the main sites of the project showed savings in N costs and an increase in yield under the canopy management model. However, results from additional satellite sites were less favourable to the canopy management model. In 1994 and 1995 at Cirencester and ADAS Terrington and in 1995 at Rosemand and ADAS High Mowsthorpe, yields were lower under the canopy management model compared to the conventional MAFF management strategy. The project speculated that yields may have been lower, possibly due to highly calcareous soils and suggested that recovery of N is significantly poorer on shallow soils over their deeper counterparts. Concluding thoughts of the work suggested that it may be sensible to adjust the canopy management rules depending on soil type and proneness to drought.

## 2.6 Precision Fertiliser Application

Precision farming has witnessed rapid development over the past 20 years. Early work focused on recording spatial differences in yield which highlighted the need to consider variable treatments (Davis *et al.,* 1996 and Stafford *et al*., 1996). Technological advances such as the combination of Global Positioning Systems (GPS) with variable-rate spreader technology has facilitated the end goal of precise and accurate fertiliser placement. Large savings stand to be made through variable placement. Godwin *et al*., (2002) showed a gross margin benefit in yield of £22/ha when variably applying N fertilisers compared to doing so at a uniform rate. They estimated that the cost of equipment required ranged from £5-18/ha based on a 250ha farm. With advances in the capabilities of equipment for other purposes, this is widely seen as a sound financial investment by many UK growers.

Variable N plans require a spatially referenced map, based on data that has an influence on end yield and can be manipulated by the application of N (Mulla *et al.,* 1992). Rationale on how to variably apply the fertiliser divides into two groups with some variably applying N due to changes in soil characteristics (Ferguson *et al*., 1996) and others due to changes in historic yield data collected from the combine (Moore, 1998).

N applications have historically been based on the collation of multiple years of yield data whereby areas of a field that consistently deliver high yield are granted more N fertiliser than areas of the field that consistently produce poorer yields (Pringle *et al.,* 2003 and Pringle and Lark, 2006). This method allows underperforming areas of the field to be identified. Areas that consistently fail to yield that of the field average receive a higher rate of N to promote crop development or conversely no N, as it could be decided that another factor other than N is having an influence on crop performance.

While yield maps focus on biomass, they do so at the final stage of the crop's existence. Biomass distribution at this time of the year can be due to numerous factors through the growing season such as nutrient distribution (other than N), moisture distribution, waterlogging, compaction or other soil structure related issues. Disease and pest prevalence is also ignored. This forced the industry to consider stages of the crop during the growing season and was also combined with the concept of applying N in splits to reduce environmental impact and capitalise on key growth stages that have a strong influence on yield.

Originally, aerial photography was utilised for this purpose. Photographic imagery allowed growers to take an image during the growing season that showed underperforming as well as more advanced parts of the crop. N could then be applied variably by eye or the image could be uploaded into a GIS program and an application plan created. This involved a set of base GPS data collected in-field that could then have application zones of varying rate laid on top. This required two layers of data; the aerial image and a field boundary logged by GPS on foot.

Aerial photography has remained popular in the Unites States where air traffic is sparsely distributed. This is different in the UK with numerous airstrips, flight paths and RAF bases making it difficult to gain free permission to fly in UK airspace. Legislation and resulting restriction made this option commercially unviable. Light remote aircraft and unmanned aerial vehicles (UAVs) have since been utilised to replicate imagery taken by larger aircraft but slow rates of data capture combined with the human interaction required to launch and fly such equipment has made this option commercially unviable. Satellite data does not suffer from these problems.

Modern satellites can capture large high quality images daily, which are then sent remotely to servers to process and pass on to industry.

Initially, high resolution photographic images were interpreted by the grower and agronomist to mark key zones within a field. This consumed time, money and did not consistently provide an accurate portrayal of the status of the crop. It was realised that biomass is the ultimate indicator of crop development concerning the uptake of N and can be defined by spectral reflectance (Asrar *et al.,* 1984). By applying N to the backward, thinner areas, crop development is promoted in an effort to obtain uniform biomass across the field (Blackmer *et al.,* 1996).

Normalised Difference Vegetation Index (NDVI) was proposed as a way of graphically illustrating in-field variation (Goward *et al.,* 1991). This index utilises light reflectance signatures with changes between soil and crop easily identifiable. A thinner crop will show more soil which will affect the ratio of soil to crop. A denser crop will tilt the ratio the other way. NDVI is the raw data used in much research (Goward *et al.,* 1991, Blackmer *et al.,* 1996, Jago *et al.,* 1999 and Combal *et al.,* 2003) but has also been converted to a biomass index known as Leaf Area Index (LAI). In-field calibration allows NDVI to be converted to LAI. The use of 1m$^2$ quadrat measurements and the manual cutting and weighing of crop, in a specific square area after its NDVI reading is recorded allows an LAI figure to be determined (Wood *et al*., 2003a). By carrying out this process numerous times and considering the key growth stages of wheat, LAI can be obtained from NDVI and can also give an accurate judgement as to typical Growth Stages (GS) in a crop of wheat.

Physically measuring the crop costs time and labour. Automated technology can provide a solution for this. Tucker (1979) showed that Infra-red radiances can be used to monitor photosynthetically active biomass of plant canopies. The sensitivity of the equipment used could determine the difference between bare soil and green leaf area or green leaf biomass. This applied to all vegetation, which although useful to the remote sensing community was too general and not crop specific for agriculture. At the time, cost of obtaining such imagery was financially unfeasible to industry. The use of remote sensing to monitor vegetation saw the associated technology being refined and improved. Blackmer *et al.* (1996) were able to detect N deficiency using reflected shortwave radiation. This work identified the specific reflected electromagnetic wavelengths that were most sensitive to detecting N deficiencies in a wheat canopy. A portable spectroradiomater was used to measure reflected radiation (400-1100nm in 1992 and 350-1050nm in 1993) at key growth stages. The project progressed in 1993 with the creation of a relatively cheap photometric cell which made this approach to crop monitoring more accurate and financially suitable. This work provided the basis for following research to refine the most accurate way to measure reflectance in the crop. In 2001, the use of remote data began to appear more commercially viable to industry. This technology saw rapid refinement in following years up to present date. Siegmund and Menz (2005) in particular, used LANDSAT 7 to show differences between canopy and soil with great accuracy. HGCA (2001) assessed advanced radar for measuring GAI biomass and shoot numbers in wheat. The work compared SPARTAN which used spectral reflectance and SAR (Synthetic Aperture Radar). Key findings were; that radar could operate 24 hours a day and is not restricted by cloud cover, radar could be used to monitor in season vegetation but more research would be required to provide an accurate and robust system, hyper spectral reflectance is more accurate up to a GAI of 3.0 and that SAR was deemed unsuitable to be practically mounted on a tractor.

Data collected via satellite can be restrained by the influence of shadowing and cloud cover. Tractor and equipment manufacturers have responded with equipment that can be operated in-field by the grower to produce an on-the-go fertiliser plan. YARA’s N-sensor determines N demand by measuring the crop’s light reflectance which shows high and low biomass. The sensor covers an area of approximately 50 $m^2$ with the software used to analyse the acquired data based on typical light reflectance readings for vegetation. The sensor measures light reflectance at specific bands related to chlorophyll content and biomass, calculating N uptake of the crop. The first model was introduced in 1999 for use on cereals. By taking measurements of the crop and combining with agronomic knowledge, N rates could be adjusted in different areas of the field. Through the running of 250 trials between 1997 and 2010 the system was refined with the creation of the YARA N-Sensor ALS (Active Light Source), providing a contrast beam of light with the use of xeon lamps rather than depending on natural daylight. From associated trial work, YARA claim a cereal yield increase of 3.5%, N savings of up to 14%, reduction of carbon footprint (through N use efficiency) of 10-30%, an even canopy leading to increased combine performance and an 0.2-0.5% increase in grain protein (YARA, 2015). The ability to use the YARA system during reduced light conditions and with the presence of cloud cover has provided a commercial advantage but the inability to assess the farm as a whole and the use of just the field average model (dependant on one pre driven-pass) highlights limitations of the system.

Tractor mounted sensors are dependent on accurate calibration and a representative pass of the field to establish the average LAI of that crop. Boom mounted sensors could offer the ability to collect multiple data sets relating to LAI if utilised during other farming operations such as the spraying of crop protection products. HGCA (2013) reviewed this concept in further detail. Different seed rates (70 – 400 seeds /m$^2$) were drilled over experimental plots over three seasons to give different canopy characteristics. The plots were based at two sites; a heavy land site near Biggleswade (Bedfordshire) and a light land site near Andover (Hampshire). A manually operated light attenuation instrument was then compared to a boom mounted spreader. From the trial, the accuracy of the boom mounted sensor was recognised.

## 2.7 Combining Crop Monitoring Technology and Agronomic Advice for Variable-Rate Treatment

In 2001, suitable technology existed for in season monitoring of wheat but the gap between collation of data and fertiliser recommendations was still significant (Welsh *et al.,* 2003b and Wood *et al.,* 2003b). Certain machinery manufacturers were beginning to offer GPS compatible equipment that would allow the use of geo-referenced data for variable-rate fertiliser applications. Over the following years, GPS compatible fertiliser spreaders became commonplace in the UK. Griffin (2007) evaluated a commercial service 'SOYLsense' offered to UK growers that utilises satellite imagery to devise an N application plan. It was suggested that N fertiliser could be applied variably, through the use of GPS enabled fertiliser spreaders and sprayers. 90 commercial farms were assessed and the financial findings discussed. The service allowed growers to produce an N fertiliser plan through an online management tool. Satellite images were collected, uploaded to a website and the grower given the option of the following three models depending on timing of application, stage in the growing season and end crop requirement:

1. The Field Average Model is used for the first application. Areas with lower LAI receive a higher application and those with a higher LAI receive a reduced application. This model assesses each field separately. The average NDVI of a field is calculated and matched to the average rate of kg/ha N that the grower wishes to apply based on best practice. Application rates are then adjusted to the range of NDVI values within the field whereby the lowest NDVI value will receive 20% more than the average kg/ha N and the highest NDVI value will receive 20% less than the average kg/ha N. NDVI values in between the average, minimum and maximum are assigned proportional rates in kg/ha. 20% variation either side of the average is typical but can be adjusted if required. Of the 90 commercial farms assessed by Griffin (2007), a significant proportion opted to stick to this range due to the presence of sulphur in the first dose on wheat following the notion that too much variation around the proposed average rate would see too much variation in applied sulphur delivered to the crop. The model encourages growth in poor areas, stops over-tillering and shadowing in forward areas and evens out the crop at a time which can have significant effect on final canopy uniformity.

2. The Canopy Management Model is used for the second application. This model allows the grower to group fields of the same variety and drilling date together with the aim of bringing all fields to the same LAI value. The user specifies a ‘target’ growth stage and typical best practice rate of kg/ha N for the second application. LAI values are calculated for the field by combining satellite measured NDVI values and on ground regional calibrations. Average LAI value for the group of fields combined receives the average kg/ha N proposed by the grower. Areas of lower LAI receive additional N (to the best practice average entered) to build to the target LAI value based on HGCA guidance of 30 kg/ha N applied results in growth of one unit of LAI for winter cereals (e.g. LAI of 1.0 to 2.0) (HGCA, 2004). Areas of forward LAI are run down based on a deduction of 30 kg/ha for one unit of LAI from the prescribed

average kg/ha N. The Canopy Management Model is used after tillering and at the beginning of stem elongation. Use of the Canopy Management Model will encourage canopy growth in areas of low LAI (in comparison to field average LAI) and ensure tiller survival based on the notion of 3 tillers per 3 heads to ensure optimum yield.

3. The Field Average Reverse Model is used for the final application and assesses each field individually with the aim of applying more N to the more forward areas of the field. The model is utilised by growers farming milling varieties aiming for high protein levels. Similar to the field average model used in the first split, the grower provides an average kg/ha N based on best practice which is paired to the average recorded NDVI value for the field. Application rates are then adjusted to the range of NDVI values within the field whereby the lowest NDVI value will receive 20% less than the average kg/ha N and the highest NDVI value will receive 20% more than the average kg/ha N. 20% variation either side of the average is typical but can be adjusted in the higher range to limit rates to prevent the dilution of protein. For growers farming feed wheat's, many will rerun the canopy management model for their third application.

Benefits of the variable N system 'SOYLsense' can be demonstrated by in-field trials testing the result of variable treatment vs. flat-rate treatment on yield. Trials on wheat for multiple years (SOYL, 2015) have shown benefits in final average yield and grain protein as below.

Table 2. Yield (t/ha) and grain protein levels (g) under flat-rate and variable treatment (SOYL, 2015).

| | **Flat-rate** | | **Variable-rate** | |
|---|---|---|---|---|
| **Field** | **Average Protein Content (g)** | **Average Yield (t/ha)** | **Average Protein Content (g)** | **Average Yield (t/ha)** |
| Field 1 2014 | 9.4 | 10.67 | 9.8 | 10.91 |
| Field 2 2014 | 10.98 | 9.08 | 12.24 | 10.13 |
| Field 1 2013 | Not recorded | 11.38 | Not recorded | 11.89 |
| Field 2 2013 | Not recorded | 12.04 | Not recorded | 12.05 |

Yield benefits through the use of 'SOYLsense' reported in 2015 are shown in Table 2. All four fields received a seasonal total of 220kg/ha divided into three splits. Average rate at each split varied with the average proposed in the flat-rate treatment assigned to the average rate in the variable-rate plan. Variable-rate plans saw rates adjusted 20% each side of the average rate. Application rates were increased in areas of low biomass and decreased in areas of high biomass. Trials in 2013 demonstrated a yield increase of 1.5% (vs. flat-rate treatment) and a monetary benefit (based on grain prices for 2013 harvest) of £19.50/t. Yield increases in 2014 were highlighted as 4.5% and 3.8% with monetary benefits of £75.48/t and £68.08/t. (SOYL, 2015). These findings confirm yield increase through the use of variable-rate treatment based on satellite imagery as shown in unrelated work by Welsh *et al.,* (2003) and Wood *et al., (*2003b).

Applying N variably according to NDVI (Welsh *et al.,* 2003 and Wood *et al.,* 2003b) and by LAI through the use of satellite imagery (Griffin, 2007) offers the ability to address in-field variation of biomass through the variable application of N fertiliser. However, separate work shows that soil variability is linked to OM variability (Chai *et al.,* 2008 and Huang *et al.,* 2007) and that nutrient availability is often varied in-field (Casa and Castrignano, 2008). Current approaches to variable N application do not consider in-field variation of soil moisture and OM through their relationships with in-field variability of soil characteristics. In-field variation of soil characteristics can be measured through the use of EMI (Waine et al., 2000, Earl *et al.,* 2003, Godwin and Miller, 2003 and Wood *et al.,* 2003a) offering an additional layer of georeferenced data that could potentially be utilised in the creation of spatial treatment plans for the variable application of N fertilisers.

By utilising soil EC data and yield maps the influence of variable nitrogen applications could be assessed to determine if they help to overcome the influence that variable soil types have on yield variability. By looking at fields that have had trials to demonstrate the benefit of flat-rate N treatment against variable-rate N treatment, select geospatial techniques could be utilised to assess the effectiveness of variable-rate treatment.

# 3 Methodology

## 3.1 Site Selection

Seven fields in three sites within southern England were selected that had previously been surveyed for shallow EC, soil type,  LAI, N application and yield for one growing season. All data was collected by SOYL, a UK company offering data collection and precision farming advice to UK growers. All seven fields had trials to assess SOYLs variable N service ‘SOYLsense’. All N application trials were carried out in 2014 with the exception of Singford and Weston Bottom which had trials carried out in 2013. Fields were divided into flat-rate (control) and variable-rate strips with the number of strips dependant on field size. Width of the strips was not consistent between fields but guided by the size of the field to include at least two sets of tramlines. All three growers had previous experience of using precision farming techniques. The final fields were selected due to the presence of higher than normal in-field variation of EC. The selected fields were deemed to be ‘varied’ by their owners hence their use in the ‘SOYLsense’ trials conducted by SOYL.

Table 3. Field location, size and predominant soil texture of trial sites.

| Field Name | Area (ha) | County | Easting/Northing | Predominant Soil Texture | Date of EC Scan |
|---|---|---|---|---|---|
| Bugmore | 33.20 | Hampshire | 459155/136883 | Heavy Silty Clay | 26/09/2013 |
| ChalkChurn | 28.79 | W. Berkshire | 440688/171054 | Sandy Clay Loam | 01/03/2012 |
| Hamstyles | 47.57 | Oxfordshire | 465741/193676 | Clay Loam | 02/11/2010 |
| High Street Lane | 44.61 | W. Berkshire | 441164/170867 | Sandy Clay Loam | 20/11/2014 |
| Home Farm | 10.14 | W. Berkshire | 440689/172478 | Medium Clay Loam | 01/03/2012 |
| Singford | 20.74 | W. Berkshire | 440604/173582 | Medium Clay Loam (Chalky) | 01/03/2012 |
| Weston Bottom | 21.89 | W. Berkshire | 440398/173691 | Sandy Loam | 01/03/2012 |

Bugmore possessed soils ranging from medium silty clay loam to heavy silty clay loam. All soils at Bugmore were over chalk with a typically slight to moderate stone content recorded in the topsoil. A patch of heavier silty clays was noted in the middle of the field.

At ChalkChurn, soil types were varied ranging from sandy soils (sandy clay, medium sandy clay loams, and heavy sandy/silty clay loams) to heavier soils (heavy silty clay loams and medium heavy silty clay loams). Sandy clays to 30-35cm had loamy soils beneath.

Hamstyles provided a mixture of soils with medium heavy soil found over grey chalk to light loamy soils.

High Street Lane possessed sandy clay with loamy clays (below 30-35cm).

Home Farm possessed only three different soil types over the 10.14 Ha. These consisted of a medium clay loam (very stony), medium heavy sandy clay loam and medium silty clay loam.

Soils at Singford ranged from medium clay loams (some noted as chalky) to heavy silty clay loams.

Weston Bottom provided significant in-field variation of soil type. Soil types ranged from sandy loam to medium silty clay loams to medium clay loams, all sub divided due to variations in topsoil stone content and presence of calcareous material provided by chalky parent material.

## 3.2 EC Scanning and Soil Zoning

All fields had been scanned by SOYL using a quad bike trailed EC scanner (Figure 1). Readings were recorded at depths of 40cm and driven at a width of 24m along the tramlines. Point conductivity data was contoured using the inverse distance kriging method. Through in-field assessment and hand texturing analysis, fields had been zoned and classified according to soil description based on BSSS (2010).

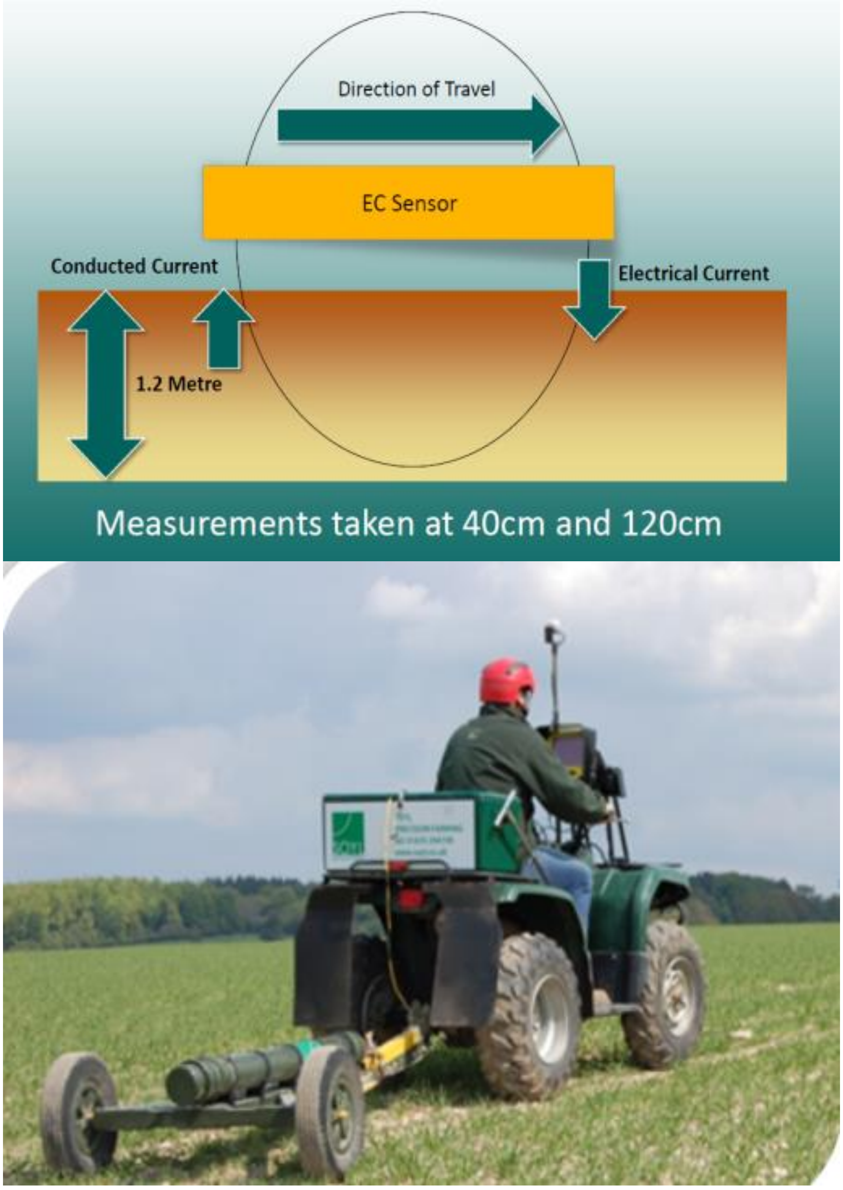

Figure 1. Upper diagram shows how ground scanner interacts with soil and illustrates the two depths to which soils were scanned. Ground scanner is towed behind a quad bike equipped with GPS (SOYL, 2012).

## 3.3 Soil Sampling for Macronutrients

All fields had been soil sampled by SOYL utilising a 1 ha grid system. For each grid point, a composite sample was taken composed of 16 sub-samples. Placement of the sub-samples was based on two concentric circles, around the central point of the grid square (spaced 2m and 4m outwards). Depth of sampling was 15cm. Composite sample location was logged using in-field GPS equipment. Soils were dried and analysed for phosphorus (Olsen's P method), potassium and magnesium (ammonium nitrate extract method) and pH. Data returned was then plotted, interpolated and converted to RB209s soil index system.

## 3.4 Collation of crop and N data

### 3.4.1 LAI

NDVI data was collected by SOYL between October and May (2012, 13 & 14) by satellites UK-DMC-2 and Deimos-1. Both satellites carried an on-board multi-spectral imager with a resolution of 22 m and 600 km of swath operating in green, red and near infrared spectra. Daily acquisitions were carried out at mid-day over the area of interest in an attempt to offer an image unrestricted by cloud cover. Successful data capture of a region of interest resulted in an image being converted to an LAI reading with the aid of on-ground calibration using a Sun Scan meter. NDVI for selected points was registered against the LAI measured in-field. A line of best fit was then assigned to the data to give the figure used for the imagery.

### 3.4.2 N Applications

Fertiliser application plans were produced by SOYL using SOYLs 'SOYLsense'[1]. Plans utilised the most recent LAI image produced using the latest captured NDVI image at the time. N application plans were based on an average rate of best practice determined by the grower and on farm agronomist. Plans were devised based on SOYLs 'SOYLsense' management guidelines (see literature review 1.7).

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[1] http://www.cerelia.geosys-eu.com, 2015

### 3.4.3 Yield

To determine the difference in yield between flat-rate and variable-rate areas, yield maps for the year of study had to be collected. All three sites utilised CLAAS Lexion Combines which possessed an in-cab CEBIS head unit with the ability to map and georeference yield within field. Yield was recorded using a Quantimeter yield monitoring system[2]. Location of point readings was established by a GPS system mounted in the roof of the cab. Calibration and cleaning of the Quantimeter lens was carried out every day during harvest by the growers. All data was read back into CLAAS Agromap[3] by the grower.

## 3.5 Geoprocessing of Data

### 3.5.1 Collation of Shape Files

A common file format had to be decided for all input sources into ArcMap in preparation for analysis. ESRI WGS84 shape files were chosen as a common industry standard. All yield data was exported as raw point data from growers yield mapping backups. Data for shallow EC and soil zone was all processed by SOYL using Farmworks[4]. Data relating to LAI and N application was stored in the online SOYLsense website. LAI dates for each of the fields were selected and the related shape file exported. For the N plans, previously issued application programs were retrieved and the relevant data exported as shape files.

### 3.5.2 Geoprocessing in ArcMap

ArcMap V10.2[5] was used for the spatial mapping and analysis. For each field, data layers were imported for Shallow EC, LAI, N application and yield.

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[2] http://www.claasofamerica.com/product/combines/lexion-780-670/electronics-operation/quantimeter-proficam

[3] http://www.claas.co.uk/products/easy/agrocom-software

[4] http://www.farmworks.com/index.php

[5] https://desktop.arcgis.com/en/desktop/

### 3.5.3 Converting the Cell Size of LAI and N Application Data

LAI data produced from the online platform was based on a 5m grid system. N application data however was resized at the time of the production of the N application plans, as it was not uncommon for many cells within the same area of the field to possess the same application value in kg/ha due to uniform LAI. As a result, cells of similar N application had been grouped together to form larger polygons of the same application rate, in turn altering the grid size of the data layer. For analysis all data cells for LAI and N application were converted back to a 5x5m grid. All LAI and N application layers were converted from polygon to raster using the ‘polygon to raster conversion’ tool. During this process the output cell size was amended to 5x5 metres. Cell assignment type was set as Cell_Center. Value field and priority field set to value rather than field ID. Projection was established as WGS1984.

### 3.5.4 Converting and Cleaning Yield Data

Yield data layers were exported as generic shape files but did not possess a projection. Coordinates had to be added to the .dbf component. Firstly, shape files were saved to WGS1984 projection, x, y columns added to the attribute table and coordinates produced using the ‘calculate geometry’ tool.

Due to the abundance of rogue data points recorded by the combines, the values for yield for each field had to be cleaned. Firstly the attribute table was converted to .csv for editing. The standard deviation (SD) and mean were then calculated to guide the removal of rogue yield points in each field’s data set. Data was sorted in numerical order. Yield values outside of the range mean ± 2 SD were deemed as anomalies and therefore deleted from the data set. Features were created from .csv using ‘Create Feature Class from xy Table’. XY fields were selected and projection was established as WGS1984. The resulting subset layer was then imported as a point data file ready for interpolation. Due to the presence of a large amount of data points, Inverse Distance Weighted Kriging was used to interpolate the yield point data based on the notion that although kriging is theoretically superior when it comes to interpolating yield data with high accuracy, the influence of interpolation method on yield maps is substantially lower than the influence of the yield monitoring system and the effect of filtering (Noack *et al*., 2005). As a result, the inverse distance to a power approach proved most suitable. The data layer was then exported as .TIFF file for further analysis.

### 3.5.5 Interpolation of Soil EC

Although data for deep EC (to 120cm) was available, shallow EC data (to 40cm) was more relevant to the function of the crop and to the variable output of yield as the interaction between crop and applied N fertiliser is more prominent in the top 40cm of the soil profile with no interaction occurring below 60cm (Gregory, 1979). EC data was imported as point data and interpolated using inverse distance weighted kriging. The result of this process was a polygon file which was then converted to raster.

### 3.5.6 Resampling the Data

Following interpolation and resizing, each field possessed data in the following formats. Multiple LAI and N application layers as raster files, shallow soil EC as a raster file and a yield file as .TIFF. All layers were imported for resampling. To resample, the ‘Fishnet’ function was used. The extent of the fishnet was determined by an LAI boundary for that field. Cell size of the net was set at 5x5 metres to match the centre of the LAI and N application layers. This created a grid of resampling points which were then clipped to the boundary of the field (using the ‘Clip Analysis’ tool) to ensure that no null data points were returned.

The ‘intersect’ function was then used to resample the data based on the point placement of the fishnet. The clipped fishnet label was used as the template with the LAI, N application and shallow EC then ranked below. This allowed unique values to be extracted based on the 5x5 metre fishnet grid. The result was then exported as a standard shape file which in the .dbf component contained the ID of the fishnet point and corresponding data values for the required variables. As yield data was exported as a .TIFF, this layer had to be added to the resampling file using the ‘Extract to Points’ tool (points input was the intersect output and the input raster was the yield ‘TIFF).

This produced a large number of points for each field but failed to address the influence of headland and boundary placement on LAI and yield. As all fields were a mixture of flat-rate control strips and variable treatment, the single data set did not differentiate between the two styles of N treatment as required by the project. To assess the effects of variable and flat-rate treatment, data points for each had to be separated. As a result data was sub-sampled further to produce smaller sets of data that were not affected by headland and boundary interference and which could be categorised into flat-rate and variable-rate treatments. This was achieved by utilising a yield map to guide the placement of the plots, avoiding extreme yield readings noticed on the headland. Plot placement was selected to fall within the trial zones and to capture areas of the field that were particularly uniform or particularly varied in terms of soil shallow EC.  Sub-sample plot size was based on capturing 200 unique points per plot. Due to the elongated shape of the trial strips, individual plots measured approximately 85x100 m. Due to the physical placement of the plots and the intention of avoiding headland and boundary interference, sub-sample plot size averaged 200 unique points with some slightly more and some slightly less. Due to their smaller sizes and placement of the trial strips, Home Field and Singford produced plots that contained an average of 100 unique values. Weston Bottom plots had an average of 70 unique points. Once the sub-sample plot size had been determined, values from the fishnet were then extracted to a .dbf for further analysis.

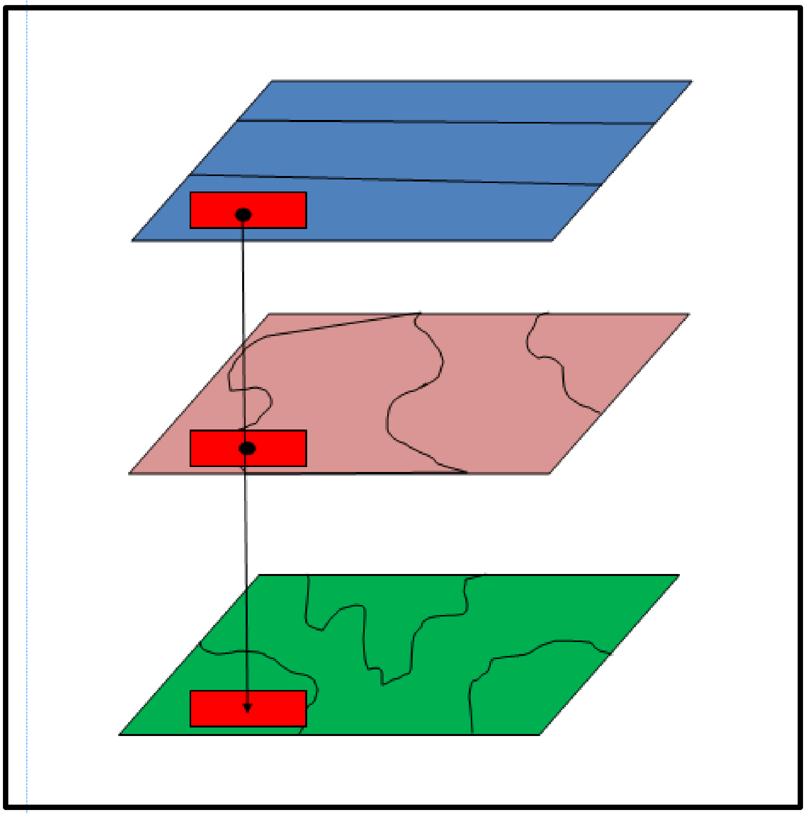

Figure 2. Extraction of data points through sub sampling. Data extracted at fixed location in field for variable-rate/flat-rate (blue), shallow EC (brown) and yield (green). As a result each fixed point that was extracted had a value for type of treatment, shallow EC and yield). This allowed relationships between shallow EC and yield to be compared under either flat-rate or variable-rate treatment.

## 3.6 Statistical Analysis

Statistical analysis was conducted using Statistica[6]. Descriptive statistics were generated for all individual sub-sample plots. Yield data was grouped together for the variable and the flat-rate treatment plots for each field to determine the difference in yield between areas of flat-rate and variable-rate treatment. Data was analysed using a standard t-test to compare the means and the Brown-Forsythe test to compare the variance. Shallow EC was plotted against yield for each sub-sample plot. Data for each sub-sample plot was then tested for normality. As it was not

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[6] http://www.statsoft.com/Products/STATISTICA/Product-Index

normally distributed it was decided that calculating the Mean Average Deviation (MAD) would be a more statistically sound method (than using the standard deviation) of analysing the distribution of the data as the presence of outliers in the data are less relevant. MAD values were calculated for all sub-sample plots and then for all flat-rate and all variable-rate sub-sample plots for each field. This allowed the difference in the variance of yield and EC under flat-rate and variable-rate treatment to be determined. MAD values for both treatments for each field were then plotted on a scatter graph to highlight potential relationships between variation in yield and variation in EC.

# 4 Results

## 4.1 Location of Sub-sample Plots

Figures 3 to 9 show the location of the sub-sample plots overlaid on top of the soil zones (shown in grey) for each field. Plots that capture areas of variable- rate treatment are shown in red, plots capturing areas of flat-rate treatment are shown in blue. Although fields were selected for their in-field variability, some fields had more soil zones than others. For example, Bugmore and High Street lane had a large number of soil zones and related soil types (detailed soil type descriptions can be found in appendix, see Figure 11, 28, 44, 61, 78, 95 and 114). Home Farm and Singford had less variation, but this may be explained by the smaller size of these fields.

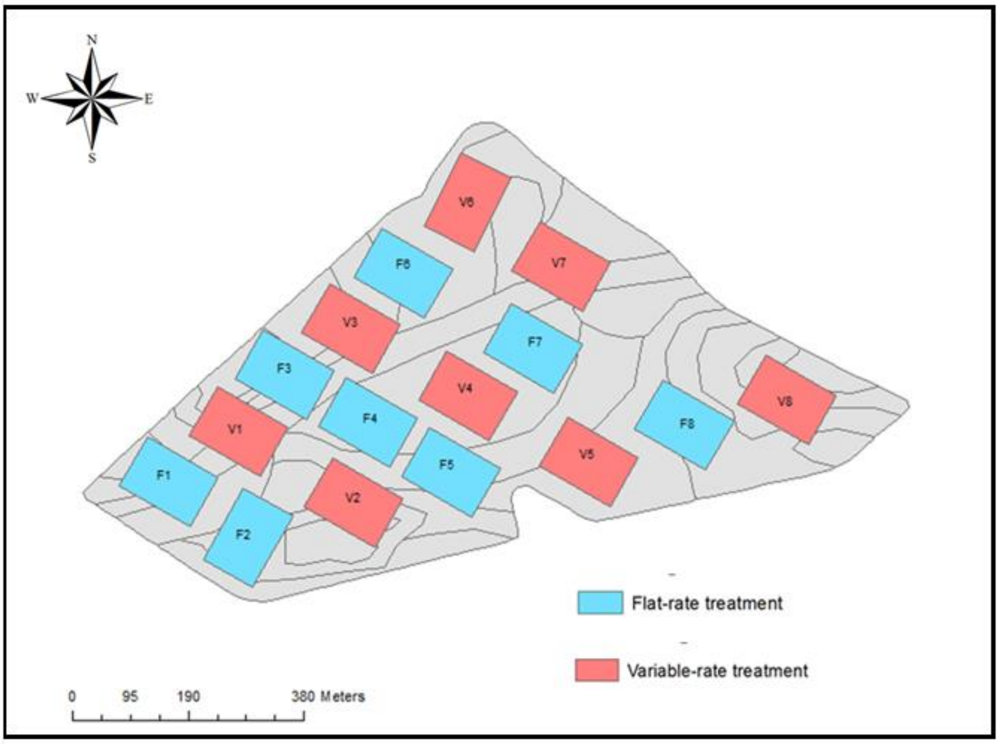

Figure 3. Placement of sub-sample plots in Bugmore (33.20 ha).

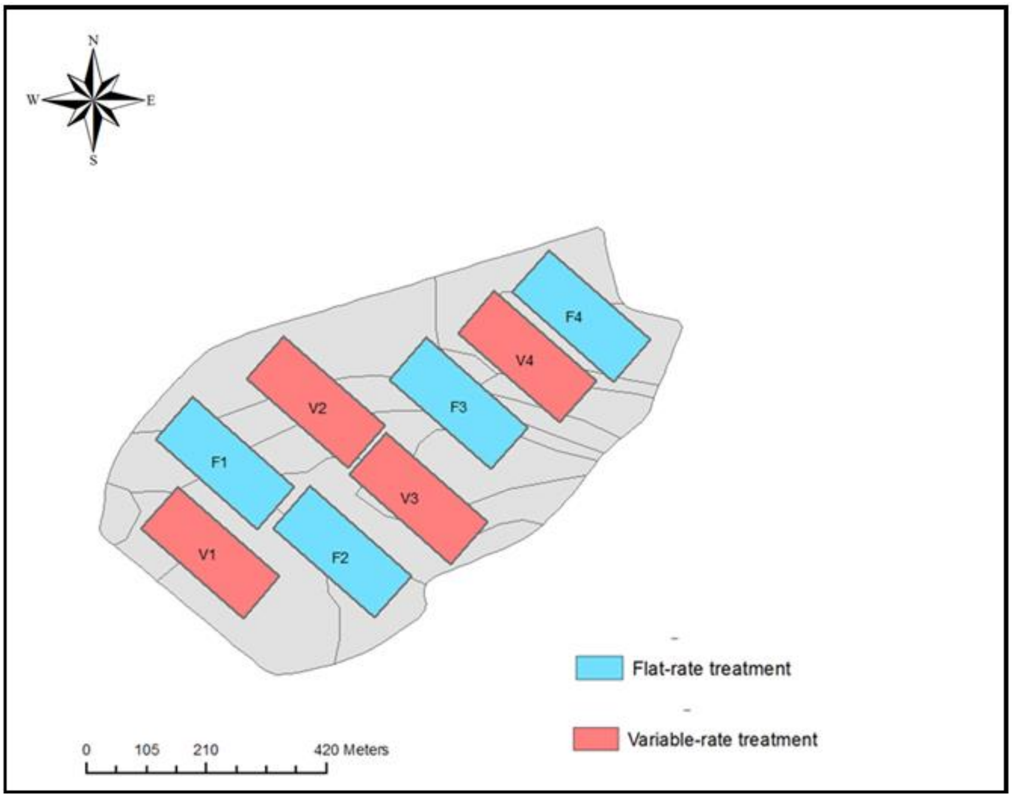

Figure 4. Placement of sub-sample plots in Chalk Churn (28.79 ha).

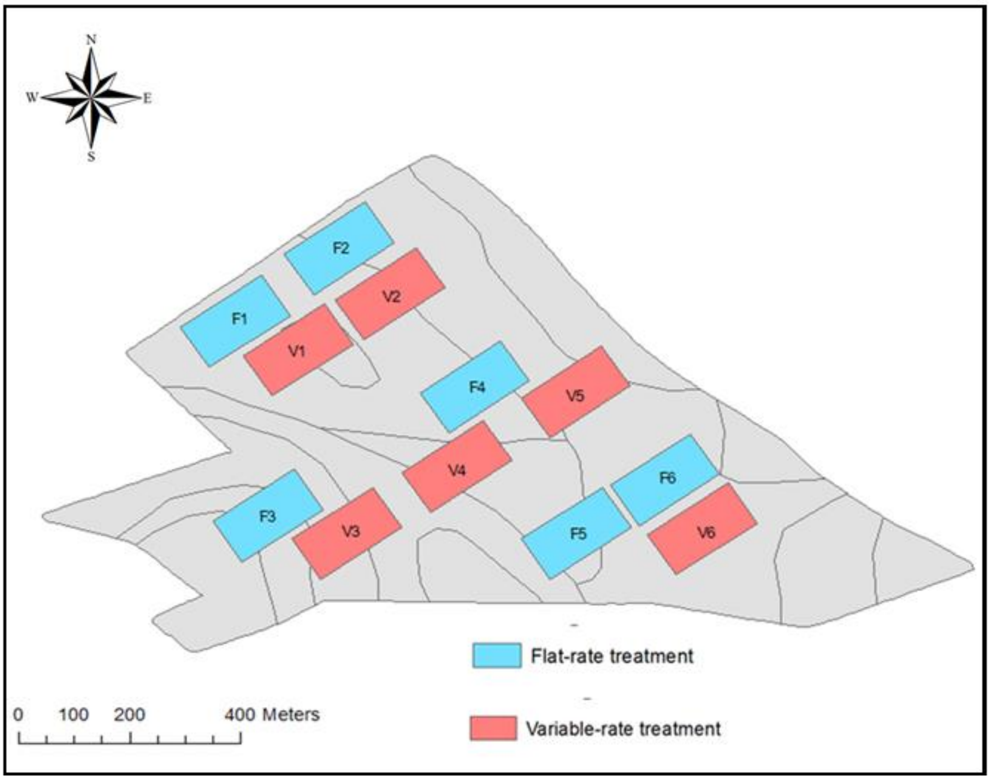

Figure 5. Placement of sub-sample plots in Hamstyles (47.57 ha).

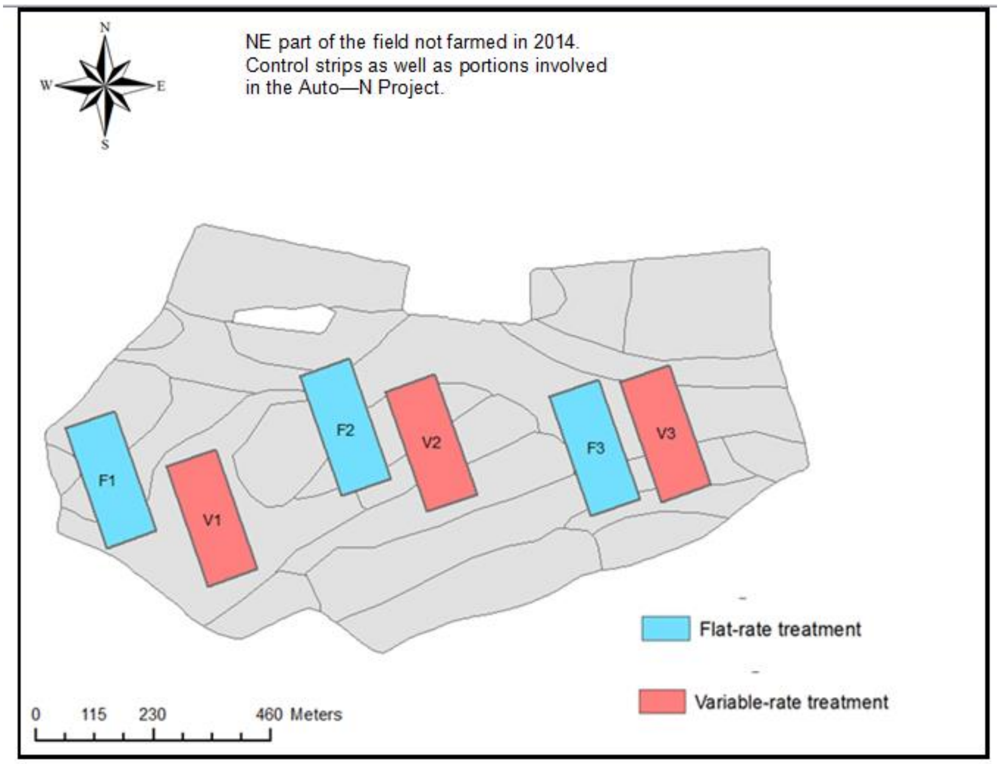

Figure 6. Placement of sub-sample plots in High Street Lane (44.61 ha).

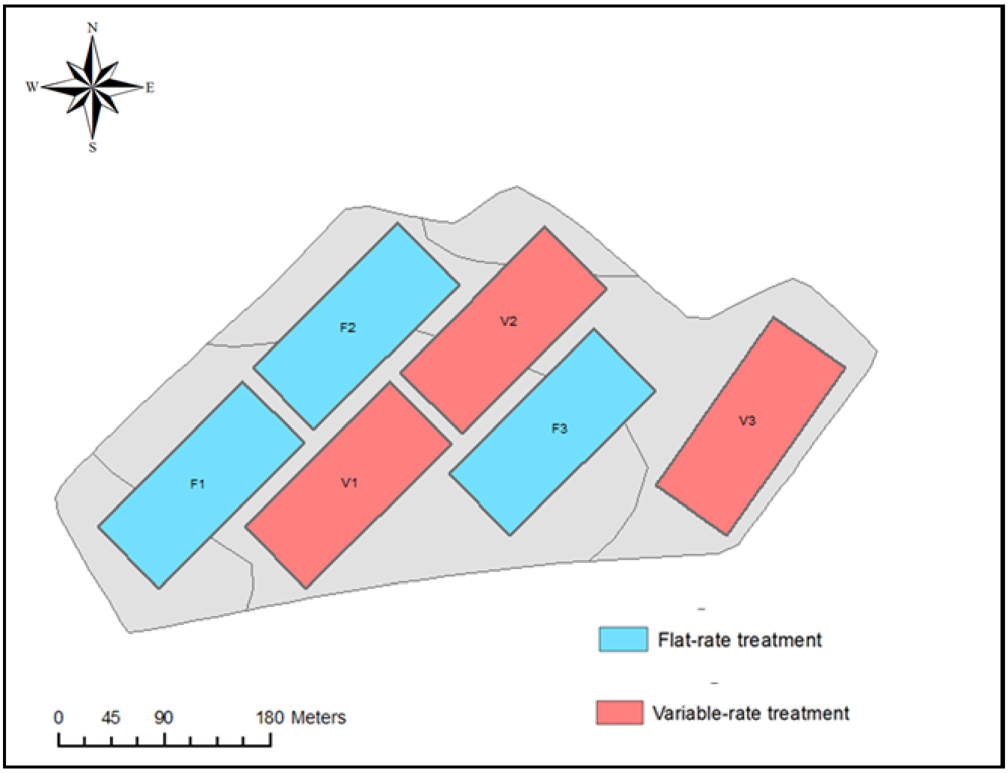

Figure 7. Placement of sub-sample plots in Home Farm (10.14 ha).

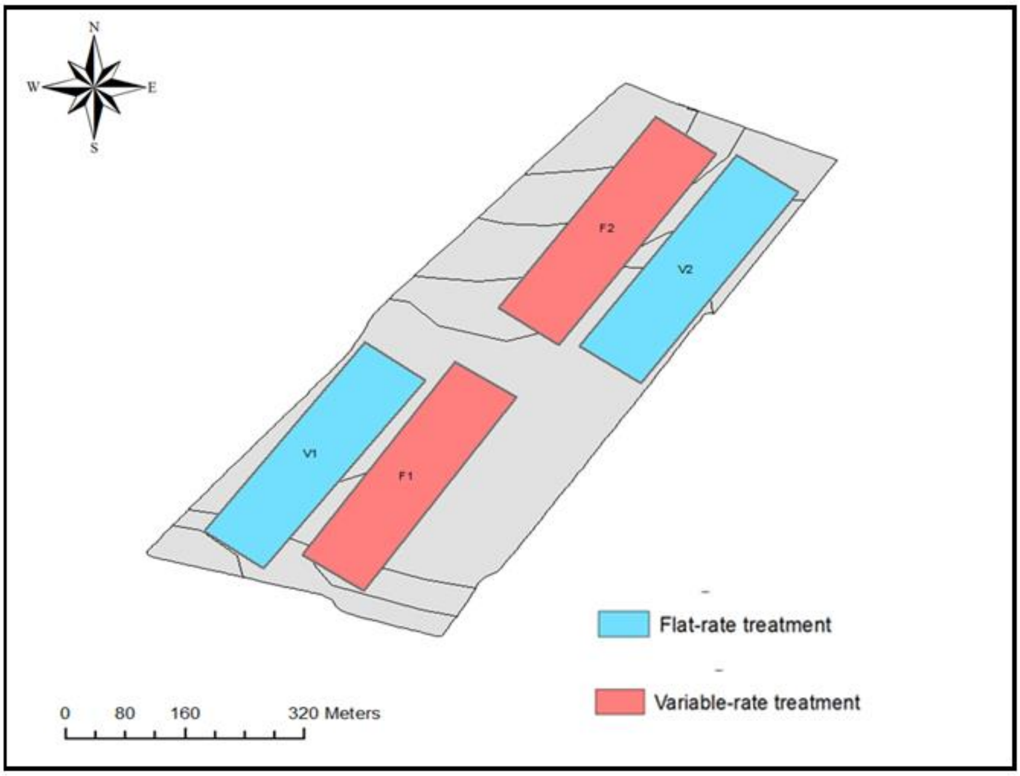

Figure 8. Placement of sub-sample plots in Singford (20.74 ha).

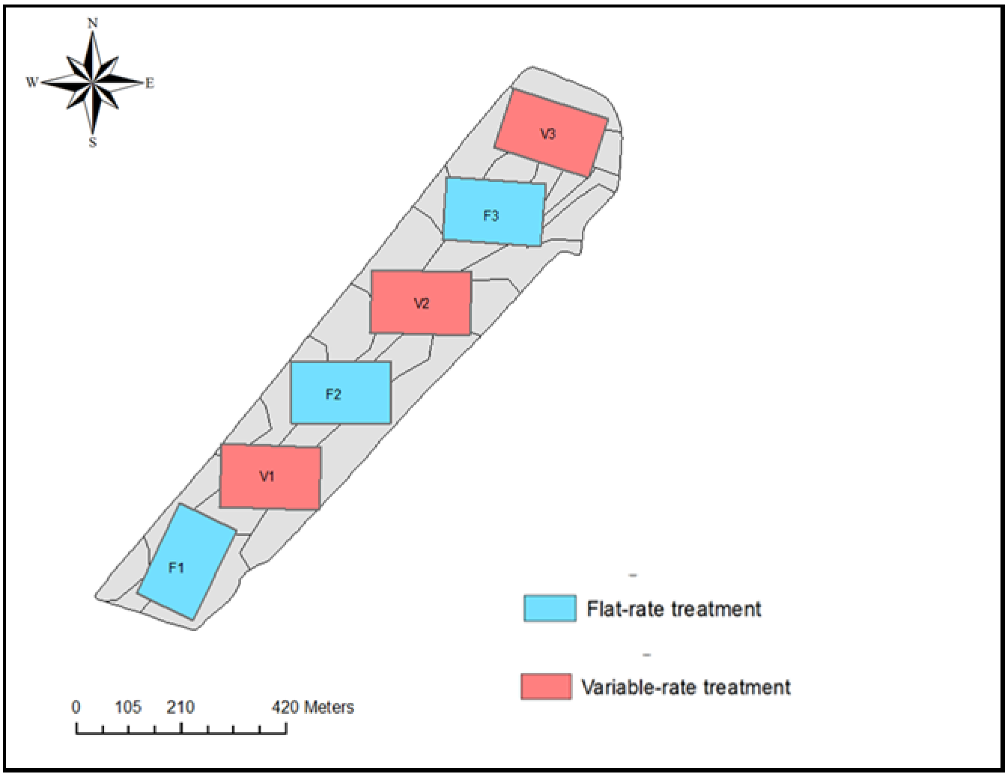

Figure 9. Placement of sub-sample plots in Weston Bottom (21.89 ha).

## 4.2 Rainfall

Table 4. Monthly rainfall data (mm) for harvest years 2013 and 2014 (Oct-Sept) at Oxford (Met Office, 2016). Monthly average between 2000-16 = 48.33mm.

| **2013 Harvest** | **mm** | **2014 Harvest** | **mm** |
|---|---|---|---|
| Oct-12 | 24.2 | Oct-13 | 86.5 |
| Nov-12 | 83.3 | Nov-13 | 55.2 |
| Dec-12 | 3.3 | Dec-13 | 97.7 |
| Jan-13 | 58.5 | Jan-14 | 46.9 |
| Feb-13 | 47.4 | Feb-14 | 90.1 |
| Mar-13 | 76.6 | Mar-14 | 39.2 |
| Apr-13 | 24.8 | Apr-14 | 50.2 |
| May-13 | 66.2 | May-14 | 90.3 |
| Jun-13 | 17.3 | Jun-14 | 36.9 |
| Jul-13 | 45.7 | Jul-14 | 45.5 |
| Aug-13 | 19.3 | Aug-14 | 85.6 |
| Sep-13 | 40.6 | Sep-14 | 4.1 |
| **2013 Total:** | 507.2 | **2014 Total:** | 728.2 |
| **Seasonal Monthly Av.** | 42.27 | **Seasonal Monthly Av.** | 60.68 |

Data was obtained from the Met Office website to provide an average overview between 2013 and 2014 (see Table 4). Oxford was chosen for its proximity to all three sites. More site specific data for rainfall was not obtainable. 2014 growing season was wetter than 2013 growing season (seasonal monthly average 60.68mm vs. 42.27mm). Average monthly rainfall between 2000 and 2016 was 48.3mm. . Oct 2013 had notably high rainfall (86.5mm) for the establishment of the 2014 crop (Oct 2012 = 24.2mm). March to July 2013 received a total of 230.6mm vs. March to July 2014 a total of 262.1mm. During the growing season, April and June 2013 were particularly low rainfall months at 24.8mm and 17.3mm respectively. It is important to note that rainfall data was not site specific, only measurements from Oxford were available from the Met Office.

## 4.3 Nitrogen Application Rate

Table 5. Average rate of N (Kg/ha) and total applied for each field.

| | 1st Application | 2nd Application | 3rd Application | Total |
|---|---|---|---|---|
| **Field** | **Av Kg/ha N** | **Av Kg/ha N** | **Av Kg/ha N** | **Av Kg/ha N** |
| Bugmore | 46 | 150 | 43 | 239 |
| ChalkChurn | 70 | 46 | 69 | 185 |
| Hamstyles | 55 | 90 | 40 | 185 |
| High Street Lane | 61 | 107 | 53 | 221 |
| Home Farm | 92 | 92 | 50 | 234 |
| Singford | 87 | 87 | 46 | 220 |
| Weston Bottom | 87 | 87 | 46 | 220 |

Table 5 shows the average rate of N applied in kg/ha for each field. This will have been the exact amount applied to the flat-rate control strips and the average rate applied to each of the variable rate strips. Overall, Bugmore had the highest amount of total N applied at 239kg/ha, ChalkChurn and Hamstyles had the lowest at 185kg/ha.

## 4.4 Wheat Yields

Firstly yield data was tested for normality in Statistica. Due to a normal distribution, the use of ANOVA was deemed adequate. Table 6 shows the average yield for each field. Singford had the highest average yield and Hamstyles the lowest. The highest yields were noted in 2013 for both Singford and Weston Bottom.

Table 6. Average Yield (t/ha) for each field and Mean Yield (t/ha) for all Flat-rate and Variable-rate treatment plots combined for each field. ns = Not significant ($p > 0.05$). For number of sub-sample plots; F = Flat, V = variable. Note that it was not possible to statistically determine an accurate level of significance for Singford due to low number of sub-sample plots.

| **Field Name** | **Harvest Date** | **Field Average Yield from the Combine (t/ha)** | **Number of sub-sample plots** | **Flat-rate Average Yield (t/ha)** | **Variable-rate Average Yield (t/ha)** | **Significance (p value)** |
|---|---|---|---|---|---|---|
| Bugmore | 23/08/2014 | 10.70 | 8 F, 8 V | 11.4 | 11.1 | 0.183 ns |
| Chalk Churn | 29/07/2014 | 10.88 | 4 F, 4 V | 11.2 | 11.1 | 0.230 ns |
| Hamstyles | 28/07/2014 | 9.55 | 6 F, 6 V | 8.9 | 9.4 | 0.056 ns |
| High Street Lane | 28/07/2014 | 10.69 | 3 F, 3 V | 11.2 | 11.1 | 0.500 ns |
| Home Farm | 28/07/2014 | 11.46 | 3 F, 3 V | 12.0 | 11.1 | 0.355 ns |
| Singford | 13/08/2013 | 12.27 | 2 F, 2 V | 12.1 | 13.3 | Not recorded |
| Weston Bottom | 13/08/2013 | 11.90 | 3 F, 3 V | 12.4 | 12.4 | 0.531 ns |

Average yield was then calculated separately for the flat-rate and the variable-rate combined areas for each field (see Table 6. and full statistics in Table 10. of appendices). The lowest average yields for both flat-rate and variable-rate treatments were recorded in Hamstyles. Yield for variable treatment plots did not significantly exceed their flat-rate counterparts. Hamstyles provided a yield difference of 0.5 t/ha ($p = 0.056$), and Singford a difference of 1.2 t/ha (a p value could not be calculated for Singford as only two sub-sample plots existed for each treatment). Note that Hamstyles produced a p value of 0.056 nearly making the difference significant. Average yield was not significantly higher in the flat-rate treatment plots. (Bugmore ($p = 0.183$), Chalk Churn ($p = 0.230$), High Street Lane ($p = 0.500$) and Home Farm ($p = 0.355$)). Highest overall yield was recorded in the combined variable-rate treatment plots for Singford. Weston Bottom produced the same average yield value for both variable and flat-rate treatment plots. Yields were on average higher, but not significantly, under variable-rate treatment (11.36 t/ha) as opposed to flat-rate treatment (11.31 t/ha).

## 4.5 Variation of Yield and EC

Standard deviation of yield was plotted against mean yield to see if the yield variability was affected by the mean yield (see Figure 10). Singford produced the highest average yield out of all 7 fields. Some of the higher yielding plots in Singford did have less yield variation. Bugmore and ChalkChurn demonstrated a slight relationship whereby plots that yielded higher had less yield variation. Lower yielding subsample plots in Hamstyles seemed to demonstrate a large range of yield variation.

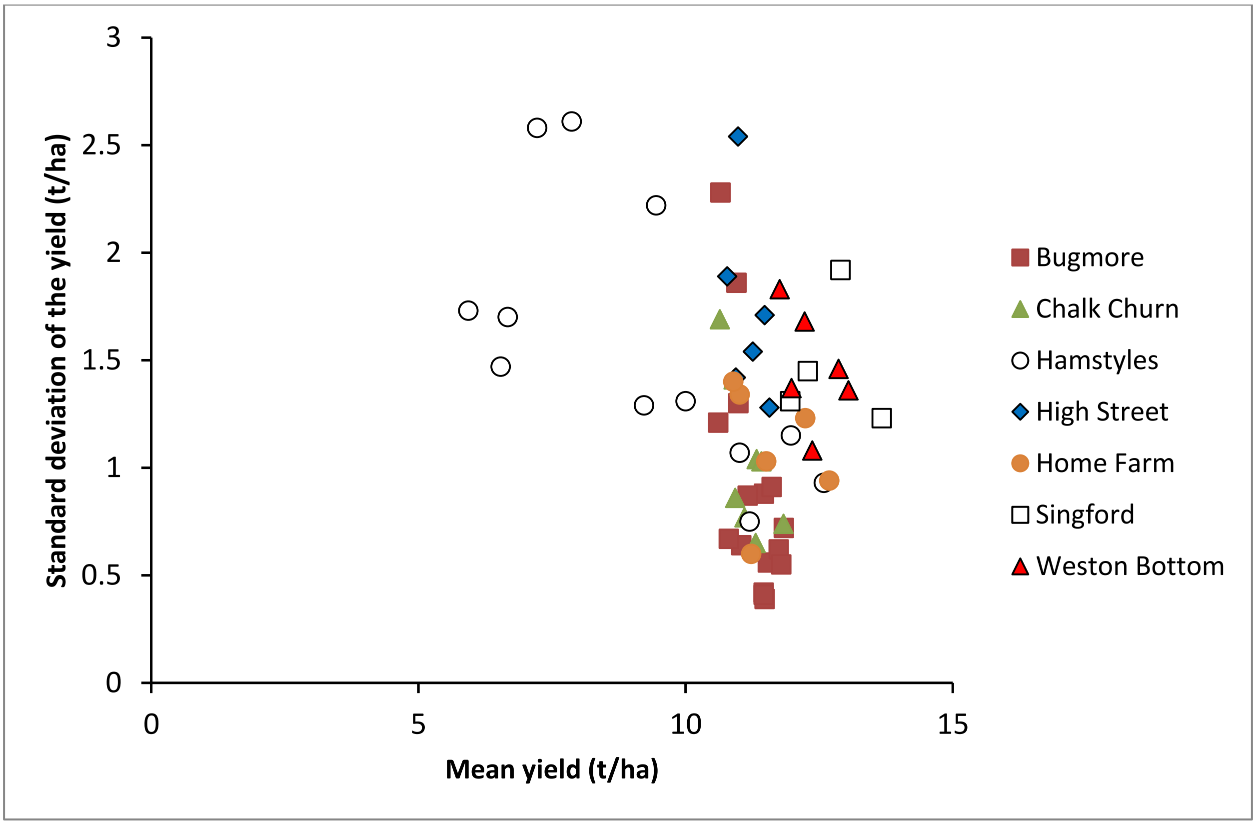

Figure 10. Standard Deviation of yield (t/ha) vs. Mean Yield (t/ha).

Standard deviation of EC was plotted against mean EC (see Figure 11). Bugmore in particular provided plots close to an EC value of 5 µS/m which were not very varied when compared with the other fields. The same applied to Weston Bottom with an EC value of -5 µS/m and Home Farm a value of -4 µS/m.

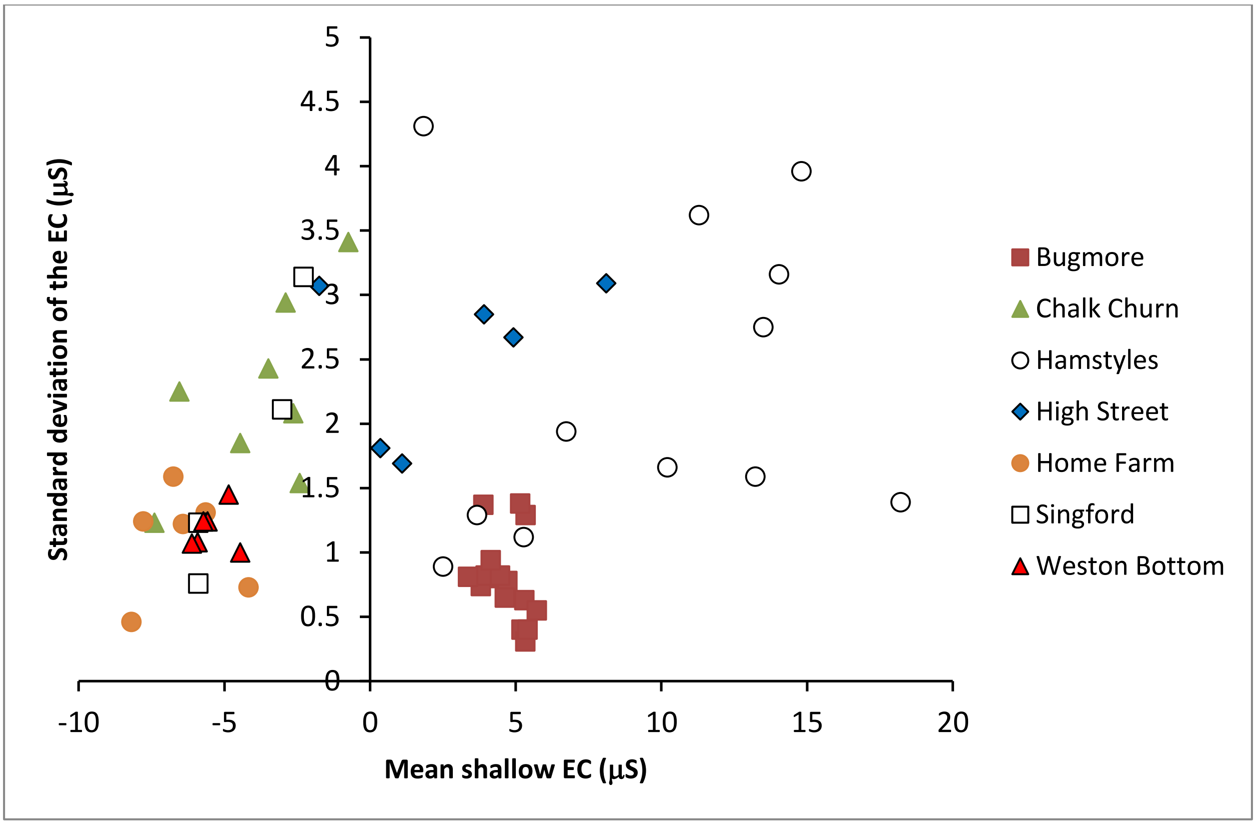

Figure 11. Standard Deviation of EC (µS/m) vs. Mean (µS/m).

The average of the SDs of each sub-sample plot was calculated for combined flat-rate and combined variable-rate plots for each field for yield and shallow EC. P values were calculated to determine the significance of difference in variation of yield between flat-rate and variable-rate treatment. The same was also calculated for soil EC. Results are shown in Table 7.

Table 7. Average SD of yield for flat-rate and variable-rate sub-sample plots for each field.

| | **Av SD of Yield (t/ha)** | | **Av SD Dev Shallow EC (μS/m)** | |
|---|---|---|---|---|
| **Field** | **Flat** | **Variable** | **Flat** | **Variable** |
| Bugmore | 1.03 | 1.02 | 0.59 | 0.73 |
| Chalk Churn | 1.02 | 1.15 | 1.16 | 1.23 |
| Hamstyles | 1.39 | 1.28 | 1.31 | 1.31 |
| High Street Lane | 1.44 | 1.23 | 1.65 | 1.83 |
| Home Farm | 2.14 | 1.30 | 2.67 | 2.65 |
| Singford | 1.38 | 1.03 | 2.75 | 2.89 |
| Weston Bottom | 1.76 | 1.13 | 2.96 | 3.89 |
| **Overall Av:** | **1.45** | **1.16** | **1.87** | **2.08** |
| **Significance** | | | | |
| **FR Yield Av vs VR Yield Av** | **p = 0.8356** | **ns** | | |
| **FR EC Av vs VR EC Av** | **p = 0.7862** | **ns** | | |
| **FR Yield Av vs FR EC Av** | **p = 0.0213** | ***** | | |
| **VR Yield Av vs VR EC Av** | **p = 0.0176** | ***** | | |

Average SD of yield was higher under flat-rate treatment for 6 out of 7 fields. Greatest variation for yield was recorded in the combined flat-rate plots of Home Farm. The combined variable plots for Bugmore provided the least variation for yield. For shallow EC, greatest variation was noted in the combined variable-rate plots of Weston Bottom. Least variation for shallow EC was recorded in the combined flat-rate plots of Bugmore. Concerning variation of yield, there was no significant difference between the flat-rate treatment strips and the variable-rate treatment strips (p = 0.8356). For shallow EC, there was no significant difference between the variable-rate treatment sub sample plots and the flat-rate treatment sub sample plots. (p = 0.7862).

## 4.6 Relationships between Shallow EC and Yield

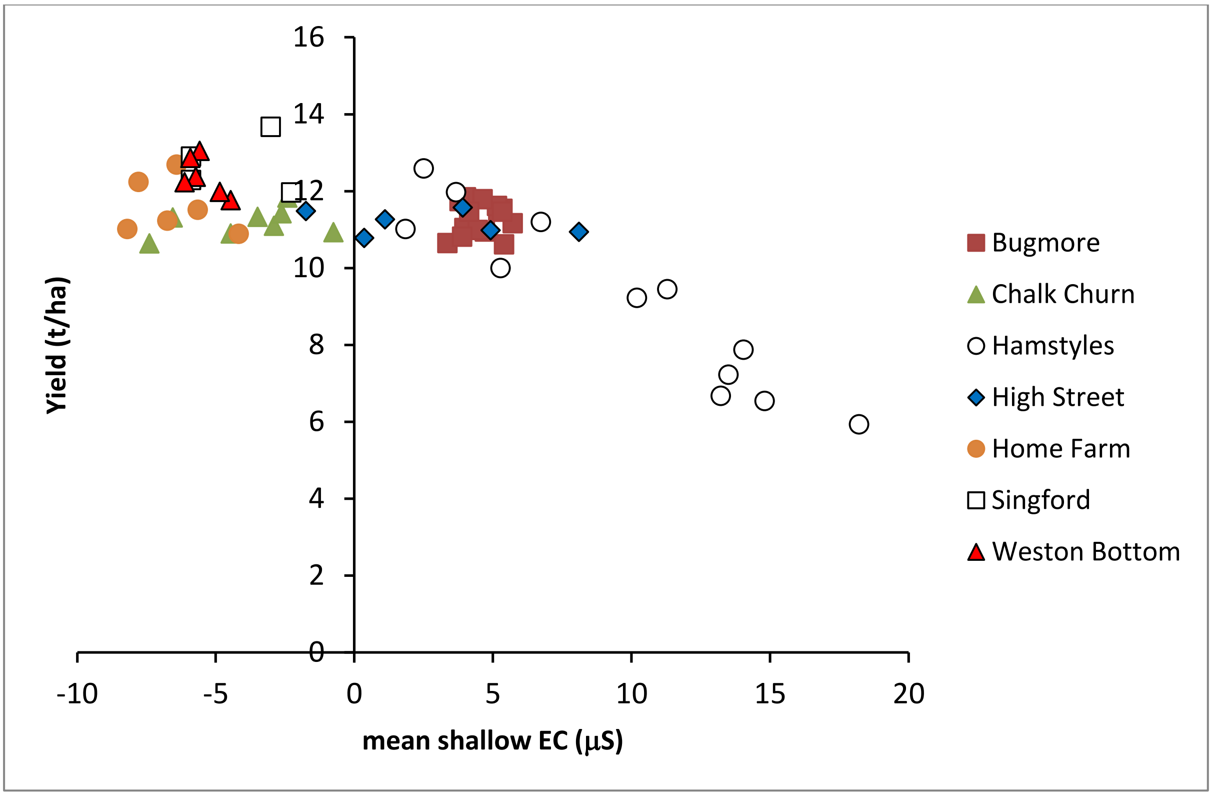

Figure 12. Average Yield t/ha vs. Mean Shallow EC (µS/m) for all fields.

Average yield was plotted against mean shallow EC values as shown in Figure 12. Certain EC values did not lead to either exceptionally high or low yield. Higher shallow EC values for Hamstyles did lead to lower yields in some of the subsample plots. Shallow soil EC was plotted against yield for each individual sub-sample plot. Scatter plots produced showed no distinct relationships between shallow soil EC and yield (see Figure 132-138 in appendices). For flat-rate treatment, 16 plots showed a positive relationship against 13 showing a negative relationship between yield and shallow EC. For the variable-rate sub-sample plots, 13 of the plots showed a positive relationship against 16 showing a negative relationship between shallow EC and yield. MAD values for yield and EC were calculated (Table 9 in appendices) and plotted on scatter plots for each of the 7 fields (see Figure 139-145 in appendices). A summary of the scatter plots are shown in Table 8.

Table 8. Summary of relationships between Shallow EC and Yield under Flat-rate and Variable-rate treatment. For scatter plots refer to Figure 139-145 in appendices.

| | **Flat-rate** | | | **Variable-rate** | | |
|---|---|---|---|---|---|---|
| **Field Name** | **Relationship** | **$R^2$** | **Significance (p value)** | **Relationship** | **$R^2$** | **Significance (p value)** |
| Bugmore | + | 0.001 | 0.776 ns | + | 0.000 | 0.831 ns |
| Chalk Churn | - | 0.214 | 0.057 ns | - | 0.087 | 0.013 * |
| Hamstyles | + | 0.032 | 0.253 ns | + | 0.517 | 0.255 ns |
| High Street Lane | + | 0.373 | 0.201 ns | - | 0.600 | 0.116 ns |
| Home Farm | - | 0.698 | 0.056 ns | - | 0.858 | 0.649 ns |
| Singford | + | 1.000 | 0.609 ns | - | 1.000 | 0.790 ns |
| Weston Bottom | - | 0.546 | 0.909 ns | - | 0.994 | 0.896 ns |

Only ChalkChurn demonstrated a significant negative relationship between shallow EC and yield under variable-rate treatment ($p = 0.013$). All other relationships were not significant. ChalkChurn provided a p value of 0.057 for a negative relationship under flat-rate treatment and Home Farm a p value of 0.056 for a negative relationship under flat-rate treatment.

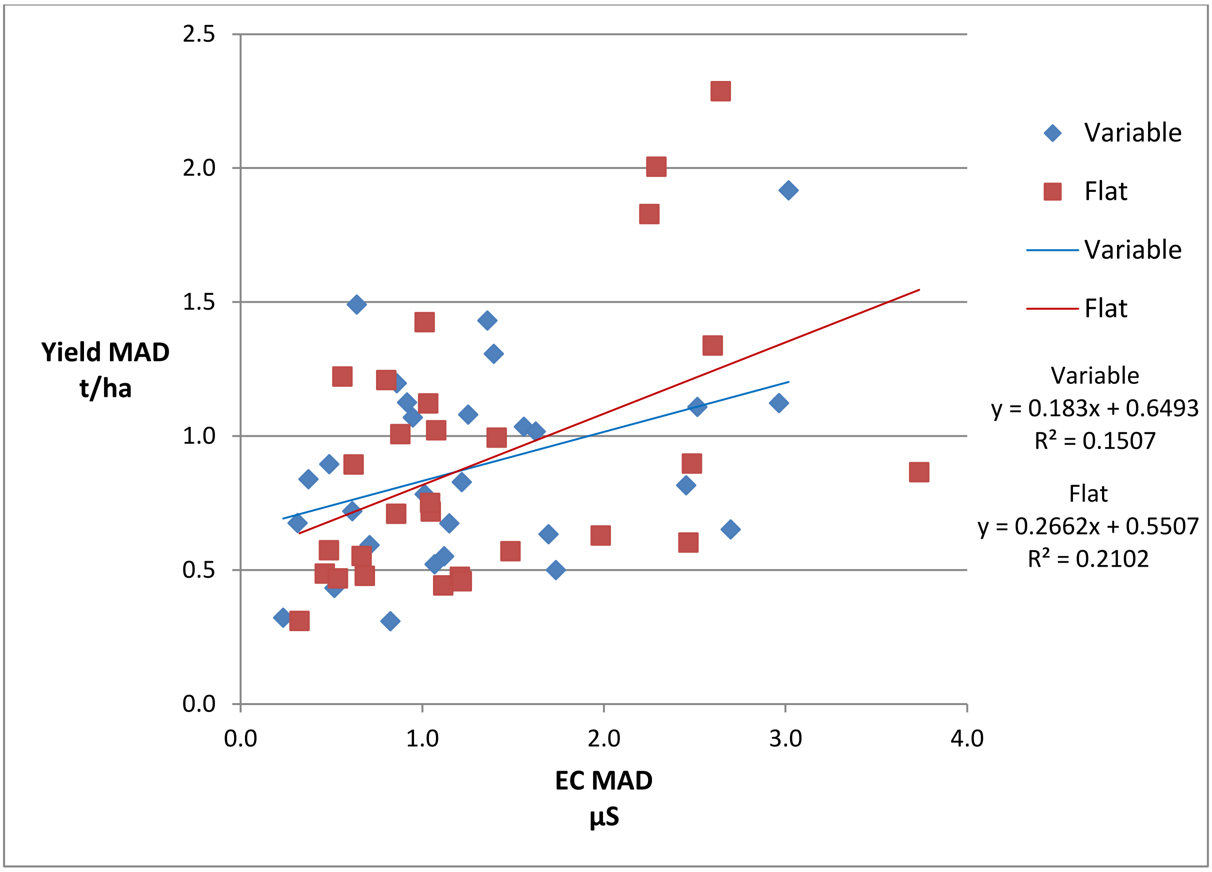

Figure 13. Yield MAD (t/ha) vs. EC MAD (µS) for all Flat-rate and all Variable-rate Treatment sub-sample Plots.

Plotting all sub-sample points showed that the relationship between yield variability and EC variability was significant in the flat-rate treatment ($p = 0.0213$) and the variable-rate treatment ($p = 0.0176$).

# 5 Discussion

## 5.1 Yield

The first research objective was to determine if there was a difference in yield between areas of flat-rate and variable-rate treatment. Recorded average yields were different under flat-rate and variable-rate treatment (see Table 6). However, none of these results were significant (no p values <=0.05 recorded). Average yield was higher under variable treatment overall but just for two fields which challenges approaches put forward by Griffin (2007), Godwin *et al.,* (2002), Welsh *et al.,* (2003) and Wood *et al.,* (2003b). Some of the sub sample plots yielded higher under variable –rate treatment and some yielded higher under flat-rate treatment. This provides limited credibility to claims by Godwin *et al.,* (2002) who claimed a gross margin benefit of £22/ha through variable placement of N fertiliser using similar techniques to those used in this study.

Characteristics of the yield maps can help to explain the findings. Hamstyles had visible patches of low and high yielding areas (Figure 51) In particular; two low yielding areas can be noticed in the Northwest of the field. These may have been caused by a number of variables that were not fully investigated in this study, for example OM content or soil moisture levels at the time of establishment. The upper portion of this low yielding area was covered by a flat-rate treatment strip (refer to Figures 60-62). This will have likely contributed to the lower yields recorded in the flat-rate areas. Regarding relationships between average yield and mean shallow EC, results shown in Figure 12 provided limited findings. Hamstyles did produce some low yielding areas that were related to higher EC values but this was the only example out of the 7 fields. Evidence of this can be recognised in Figure 12. Timing of the EC scan relating to soil moisture levels and field conditions will have influenced the EC values provided.

The yield map for Singford (Figure 102) seems to demonstrate a benefit of the variable-rate treatment strips (refer to Figure 115). Interestingly Singford only saw one variable application (only two N applications were made, the first applied at a flat-rate due to the presence of sulphur in the dressing). It is also important to note that due to the low number of sub-sample plots (two for variable, and two for flat-rate treatment) a p value could not be calculated so the significance of the differences between the two treatments could not be fairly evaluated.

Bugmore provided high yielding areas in the northwest of the field (Figure 18) but these had no visual relationship with the placement of the control strips (Figures 27-29). The yield map for High Street Lane (Figure 68) demonstrates two high-yielding bands but these relate to natural features rather than treatment with yields higher in these areas due to the presence of valleys. This confirms work by Bakker (2005) and also helps to confirm fundamental concepts put forward by Barraclough *et al.,* (1991) and Pringle *et al.,* (2003) highlighting the importance of deep fertile seedbeds to facilitate root development determining not only the successful establishment of the crop but ultimately (when combined with the protection that a valley offers) leading to high yields. Interestingly the location of these two valleys and their associated high yielding areas covers both flat-rate and variable-rate strips (refer to Figures 77-79) so their presence will have unlikely affected the average yield values. A high yielding area in Home Farm (Figure 85) will have enhanced the high yield demonstrated in the flat-rate area in the Northwest portion of the field (Figure 94). Only Weston Bottom provided the same average yield (12.4 t/ha) for both flat-rate and variable-rate treatment areas. The highest recorded average yield for all areas was recorded in the variable-rate treatment areas for Singford (13.3 t/ha). The lowest recorded average yield was in the flat-rate treatment areas for Hamstyles (8.9 t/ha). Hamstyles was a poor yielding field regardless of treatment, again with no significant difference in yield being noted between flat-rate and variable-rate treatment ($p = 0.056$). However, the p value recorded was close to being significant.

The higher yields in Singford and Weston Bottom, regardless of treatment, could be related to the fact that these two fields were the only two fields in the study based on 2013 harvest data. All other fields were cropped in winter wheat in 2014. This could suggest that 2013 was a more favourable growing season concerning yield, however, both Singford and Weston Bottom were from the same farm, potentially highlighting the effect of crop management by the grower or localised climatic conditions. Total N fertiliser applied in each field may have had some effect on final yield. Low yields in Hamstyles may have been caused by the low amount of N applied at just 185kg/ha. Bugmore and Home Farm both had an average of

239kg/ha and 234kg/ha N applied, yet yielded 10.7t/ha and 11.46t/ha respectively. ChalkChurn had a low total of 185kg/ha N applied for the growing season yet was able to still yield an average of 10.88t/ha across the field. It is important to remember that total N figures relate to bagged product applied through the growing season and do not consider N input from the previous crop or from mineralisation. Drilling conditions for the 2014 crop (October 2013) were wetter than for the 2013 crop (October 2012) at 86.5mm vs. 24.2mm respectively (refer to Table 4) which may have influenced soil conditions and establishment but seems to not have had a negative effect on the yields of Singford and Weston Bottom. In addition, March 2014 received just 39.2mm of rainfall (compared to 76.6 mm in March 2013). However, it is important to note that the rainfall data was not site specific with reginal averages only available. Interestingly, both fields typically had different soil type's in-field, with Singford comprised of more medium clay loams and Weston Bottom containing more sandy soils. As a result, average yields (regardless of treatment) of 12.27 t/ha in Singford and 11.90 t/ha in Weston Bottom could be related to the predominant soil types within each field. December 2013 saw particularly heavy rainfall (97.7mm) for the 2014 harvest crop (compared to 3.3mm in December 2012). This may have affected nitrogen content in the soil at the start of the spring period with some N potentially lost to leaching. However, inspection of the crop in the early spring by the grower will have likely influenced the average rate of N to be applied, thus a higher rate of N will have been recommended to compensate for over winter leaching.

## 5.2 Yield variability

Scatter plots for shallow soil EC vs. yield allowed relationships between soil characteristics and yield to be evaluated. Early work by Davis *et al.,* (1996) and Stafford *et al.,* (1996) suggested that relationships can exist between soil characteristics and yield. The only relationship in this study was demonstrated by Hamstyles (see Figure 12.) where areas of higher EC did result in lower yields. Twenty-nine of the individual field plots showed a positive relationship between EC and yield compared to 29 plots showing a negative relationship. Note that for the two fields cropped in 2013 (Singford and Weston Bottom) 6 of the plots showed a positive relationship between EC and yield vs. 4 plots showing a negative relationship. Studying the maps for soil type, shallow EC, deep EC and yield (see breakdown for each field in appendices) shows no clear relationships. Levels for P, K, Mg and pH were not at a value where they could significantly inhibit crop growth (No values <1+ for PK or pH <6.0 were recorded). There were only two exceptions to this finding. Low Mg levels (Index 0-1) were recorded in Weston Bottom which actually provided the second highest whole field average yield of the seven fields (11.9 t/ha). Low pH spots were recognised in ChalkChurn (pH 5.0-6.0) however, these results were from sampling carried out in 2010. It is highly likely that the grower applied lime to these areas to address this before 2014.

Regarding EC and soil type, a poor yielding area in the North of Hamstyles (yielding less than 7 t/ha) does relate to an area of higher EC when compared to the rest of the field. A heavy soil (slightly stony medium/heavy silty clay loam over silty clay subsoil) in the Northern portion of the field may have limited crop establishment and root development. However, early LAI images taken from 12/02/14 to 05/05/14 (see Figures 53-57) show more forward LAI through the growing season. Two high yielding strips (over 14 t/ha) are noticeable in the yield map for High Street Lane (see Figure 68). This illustrates the bottom of a slight valley which will have favoured crop development. Interestingly, an early LAI image taken 30/10/13 (Figure 69) does not show this, suggesting that in-field variation of altitude did not have an effect on establishment. However, LAI imagery through the growing season from 12/02/14, to 01/07/14 (Figures 70-76) does show more forward LAI in these areas highlighting the benefit of being situated in a valley. Low LAI resulting in low yield (less than 6 t/ha) can be recognised in Southern parts of the field by the field boundary which may have held a relationship with High EC, however, placement close to the boundary could suggest a range of other factors such as pest damage/grazing or inaccurate monitoring by the combine leading to low values recorded in the yield maps. Sub-sample plot placement should have minimised inaccurate data values from the combine. Singford showed an area in the northwest portion of the field that correlated with high EC, illustrating a clay loam (see Figure 100) which led to low LAI through the season and ultimately a hotspot of low yield (less than 8.5 t/ha) in the yield map (see Figure 102). Relationships between EC, LAI readings through the season and yield are limited at best, suggesting that applying N to soil maps alone as investigated by Ferguson *et al.,* (1996) is not a robust approach to take.

Calculation of MAD values for yield showed no significant differences between flat-rate and variable-rate treatments ($p = 0.8356$). Yield was more variable in the recorded sub-sample plots for flat-rate treatment for 6 out of the 7 fields, Chalk Churn, Hamstyles and High Street Lane (MAD = 0.707, 1.36 and 1.387 respectively). However, only the Hamstyles flat-rate areas had more variable EC (MAD = 2.008). EC was neither significantly more variable ($p = 0.7862$) in the variable treatment plots or the flat-rate treatment plots. However, more variation was noted for Bugmore (0.666 vs. 0.604), ChalkChurn (1.922 vs. 1.672), High Street Lane (2.121 vs. 2.086) and Weston Bottom (1.027 vs. 0.974). LAI imagery through the growing season illustrates a reduction in LAI variation, particularly in Bugmore, Chalk Churn and on Home Farm (Final image on 01/07/14 provided LAI ranges as 5.66-7.54, 4.62-7.04 and 5.87-615 respectively). It is important to note that in-field variation for Bugmore and ChalkChurn was exaggerated by particularly low LAI on the headland at the northern part of the boundary for both Bugmore and Chalk Churn (refer to Figures 19-26 and 36-42 respectively). Interestingly this study only focused on one year of yield data. Pringle *et al.,* 2003 and Pringle and Lark, 2006) for example looked at multiple years of yield data suggesting possible scope for future related work.

Plotting Yield MAD (t/ha) against. EC MAD (µS/m) provided mixed findings. On a field by field basis, only ChalkChurn demonstrated a significant negative relationship between shallow EC and yield under variable-rate treatment ($p = 0.013$). None of the other relationships were statistically significant. However, combining all sub-sample plots for all fields to provide a dataset for flat-rate treatment and a dataset for variable-rate treatment showed that variability in EC leads to variability in yield under both flat-rate ($R^2 = 0.2102$) ($p = 0.0213$) and Variable rate treatment ($R^2 = 0.1507$) ($p = 0.0176$).

Dramatically eliminating the effect of variability in EC under variable N treatment based on LAI imagery alone appears challenging. Studying LAI imagery through the season for all fields shows that areas of a field can see a reduction in variation of LAI, however certain areas in a field seem unresponsive to N fertiliser be it under variable or flat-rate treatment. This is particularly noticeable in High Street Lane and Singford (refer to Figures 69-76 and 102-112 respectively). All fields showed variable LAI in the first image of the season showing that variable establishment of the crop provides a difficult hurdle to overcome regarding canopy management later in the growing year. For all fields, variable LAI in the first image does show similarities to soil type and EC variation (see EC maps and LAI images in appendices). The study has provided two possible explanations to the causes of in-field variability of yield, namely topography and establishment of the crop. It could be proposed that even establishment of the crop could reduce the in-field variation of LAI experienced, ultimately leading to more uniform yields.

## 5.3 Limitations

Although the investigation provided 58 sub-sample plots for the two treatments, producing a total of 1,070 points, the data set was limited to just 2013 or 2014. It should also be noted that only seven fields were analysed for the purpose of this study. Additional years, particularly those where UK crops experienced drought-like conditions or excessively wet conditions at the point of drilling may have provided some interesting data for the purpose of this study. It is important to note that between 2000 and 2016, monthly rainfall averaged 48.3mm. The 2013 harvest year received an average of 42.27mm and the 2014 harvest year received an average of 60.68mm. It could be suggested that in years of low soil moisture, the effect of soil type on yield may be more notable. Interestingly a drier drilling period for the 2013 crop (compared to 2014) produced the two highest yielding fields but it must be noted that these were located on the same farm.

Accuracy of yield data also needs to be mentioned. Plot design and sub sampling methodology certainly helped eliminate rogue data points from the combine, however, false readings may still exist in the data. Until the instrumentation utilised for yield mapping becomes more accurate this will be hard to address.

As each field provided flat-rate and variable-rate strips that saw the same N fertiliser applied, the influence of using liquid rather than solid fertilisers will not have affected the outcome of the data in terms of explaining in-field variation of yield. It could be argued that liquid would promote NUE, but in the years of 2013 and 2014, soil moisture levels were adequate to implement the successful uptake of N be it applied as solid or liquid. If additional years were to be scrutinised that experienced soil moisture depletion, the influence of product choice may have a more significant effect.

In-field measurement of OM was not undertaken which could have helped explain areas of high and low yield within field. No OM levels were recorded at the time of the soil scan or survey making it difficult to incorporate this information. However, it is fair to note that as OM levels take considerable time to change, sampling could have been undertaken at the time of this study to provide supplementary data. In addition to OM, no protein levels were recorded. It is important to not lose focus of the aims of variable-rate N application with many using the service as a way of optimising grain protein content rather than focusing exclusively on final yield.

# 6 Conclusion

Data collected in the investigation allowed the aims and objectives of the thesis to be addressed;

Is yield significantly different between areas of flat-rate and variable-rate treatment?

Although average yield of all sub-sample plots was higher under variable-rate treatment as opposed to flat-rate treatment, 4 out of 7 fields yielded higher under flat-rate treatment. Overall, no significant difference in the average yield between the two treatments was found. This suggests that variable application of N (+/- 20% of the average rate) did not enhance the yield of winter wheat and that traditional industry approaches to N planning and canopy management offer a suitable framework for devising N applications to increase yield.

Are there notable relationships between soil characteristics and yield?

No notable relationships between soil EC and yield were noted except for Hamstyles field, however, it is common to see relationships between soil characteristics and yield. If more fields were incorporated in this study, relationships between the two may have been present. In addition, the testing of macronutrients and pH through soil sampling provided readings that were non-yield limiting, potentially highlighting good overall farm management on all fields. If this were not the case, the impact of nutrient deficiency on yield may have been noticeable. The importance of topography, in particular the location of valleys, was highlighted with its ability to favour crop development and lead to high yields as shown in LAI imagery and yield maps. Both years provided enough rainfall to not jeopardise yield. Years of drought like conditions may have resulted in different average yield.

Is there a difference in the variation for yield and EC under flat-rate and variable-rate treatments?

Variation of yield was not significantly different between flat-rate and variable-rate treatment (p = 0.8356). MAD values for soil EC were neither more significantly varied in the sub sample plots under variable-rate treatment or flat-rate treatment (p = 0.7862).

Is variation in yield related to variation in EC?

EC variability led to variability of yield with this relationship being significant under flat-rate (p = 0.0213) and variable-rate treatment (p = 0.0176). This suggests that variable treatment provided no significant benefit in reducing yield variability. Other factors such as altitude, valley placement, rate of establishment and OM levels may also lead to variability of yield. If years that experienced drought like conditions were incorporated into this research, different relationships between EC variability and yield variability may have been noted.

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# 8 Appendices

Table 9. MAD values for yield and EC for each sub-sample plot and averages for all sub-sample plots combined for each field.

| Field | Plot | Yield (t/ha) MAD | EC (µS) MAD |
|---|---|---|---|
| Bugmore | F1 | 0.442 | 1.115 |
| | F2 | 1.222 | 0.560 |
| | F3 | 0.553 | 0.665 |
| | F4 | 0.574 | 0.486 |
| | F5 | 0.487 | 0.464 |
| | F6 | 0.469 | 0.535 |
| | F7 | 0.310 | 0.324 |
| | F8 | 0.478 | 0.684 |
| | V1 | 0.552 | 1.121 |
| | V2 | 0.720 | 0.614 |
| | V3 | 0.433 | 0.516 |
| | V4 | 0.322 | 0.234 |
| | V5 | 0.676 | 0.313 |
| | V6 | 1.491 | 0.640 |
| | V7 | 0.309 | 0.824 |
| | V8 | 0.522 | 1.069 |
| Chalk Churn | F1 | 0.629 | 1.982 |
| | F2 | 0.475 | 1.207 |
| | F3 | 0.602 | 2.466 |
| | F4 | 1.122 | 1.032 |
| | V1 | 0.652 | 2.698 |
| | V2 | 1.034 | 1.560 |
| | V3 | 0.633 | 1.695 |

| Field | Plot | Yield (t/ha) MAD | EC (µS) MAD |
|---|---|---|---|
| | V4 | 0.500 | 1.736 |
| Hamstyles | F1 | 1.426 | 1.013 |
| | F2 | 2.005 | 2.288 |
| | F3 | 0.865 | 3.736 |
| | F4 | 2.287 | 2.643 |
| | F5 | 0.570 | 1.485 |
| | F6 | 1.007 | 0.880 |
| | V1 | 1.431 | 1.358 |
| | V2 | 1.124 | 2.964 |
| | V3 | 0.784 | 1.014 |
| | V4 | 1.080 | 1.253 |
| | V5 | 1.917 | 3.018 |
| | V6 | 0.593 | 0.710 |
| High Street Lane | F1 | 1.829 | 2.250 |
| | F2 | 1.338 | 2.599 |
| | F3 | 0.994 | 1.410 |
| | V1 | 1.109 | 2.515 |
| | V2 | 0.817 | 2.453 |
| | V3 | 1.307 | 1.394 |
| Home Field | F1 | 0.711 | 0.856 |
| | F2 | 0.718 | 1.047 |
| | F3 | 0.459 | 1.218 |
| | V1 | 0.839 | 0.374 |
| | V2 | 0.674 | 1.148 |
| | V3 | 0.896 | 0.489 |
| Singford | F1 | 0.894 | 0.622 |
| | F2 | 0.898 | 2.485 |
| | V1 | 1.197 | 0.859 |
| | V2 | 1.017 | 1.624 |

| Field | Plot | Yield (t/ha) MAD | EC (µS) MAD |
|---|---|---|---|
| Weston Bottom | F1 | 1.209 | 0.802 |
| | F2 | 1.022 | 1.077 |
| | F3 | 0.751 | 1.044 |
| | V1 | 1.070 | 0.948 |
| | V2 | 1.126 | 0.916 |
| | V3 | 0.829 | 1.217 |

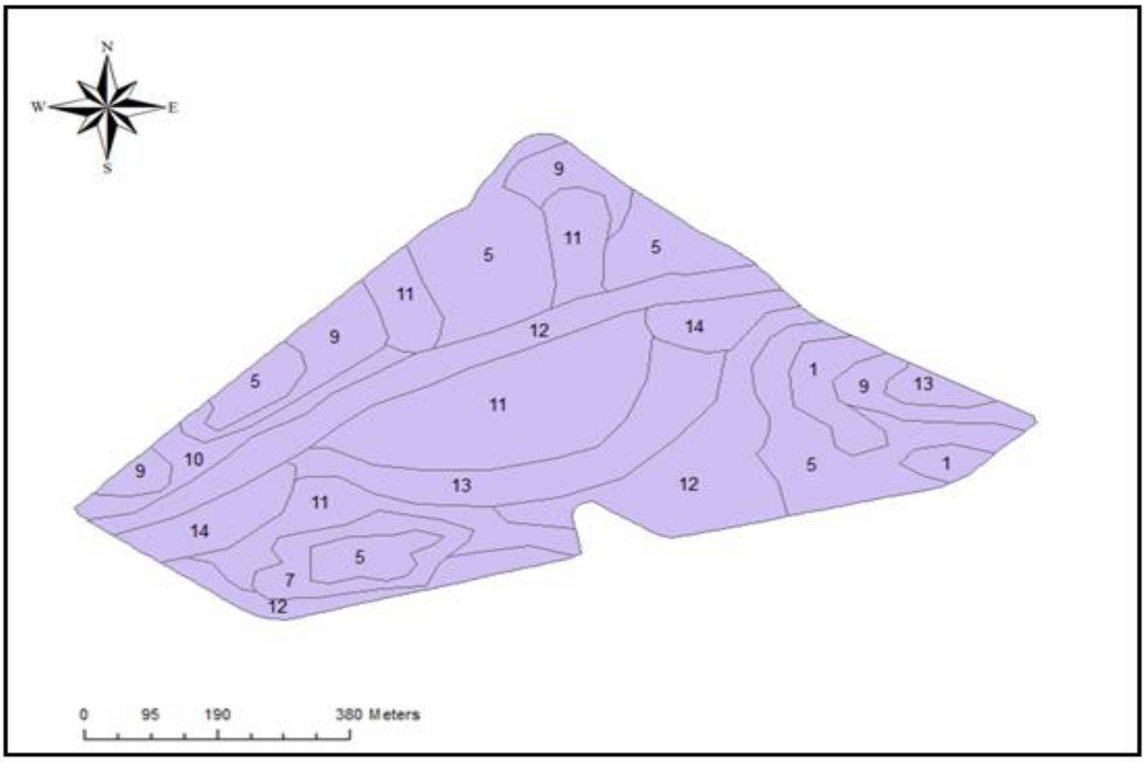


Figure 14. Soil type for Bugmore (33.20 ha).

| | Topsoil | Stone Content (Topsoil) | Subsoil |
|---|---|---|---|
| 1 | Medium Silty Clay Loam | Slight (Chalky) | Chalk Rubble below 25-30cm (or Solid Chalk) |
| 5 | Medium Silty Clay Loam | Slight (Chalky) | Very Stony below 30-50cm (or Chalky) |
| 7 | Medium Heavy Silty Clay Loam | Slight | Chalk Rubble below 25-30cm (or Solid Chalk) |
| 9 | Medium Heavy Silty Clay Loam | Slight (Slightly Chalky) | Chalk Rubble below 35-50cm (or Solid Chalk) |
| 10 | Medium Heavy Silty Clay Loam | Moderate | Very Stony below 50-80cm (or Chalky) |
| 11 | Heavy Silty Clay Loam | Slight | Chalk Rubble below 40-60cm (in places) |
| 12 | Heavy Silty Clay Loam | Moderate | Very Stony below 50-80cm (or Chalky) |
| 13 | Heavy Silty Clay Loam | Slight | Very Stony below 50-80cm (or Chalky) |
| 14 | Heavy Silty Clay Loam | Slight | Silty Clay below 35cm, over Moderately Stony below 50-80cm (or Chalky) |

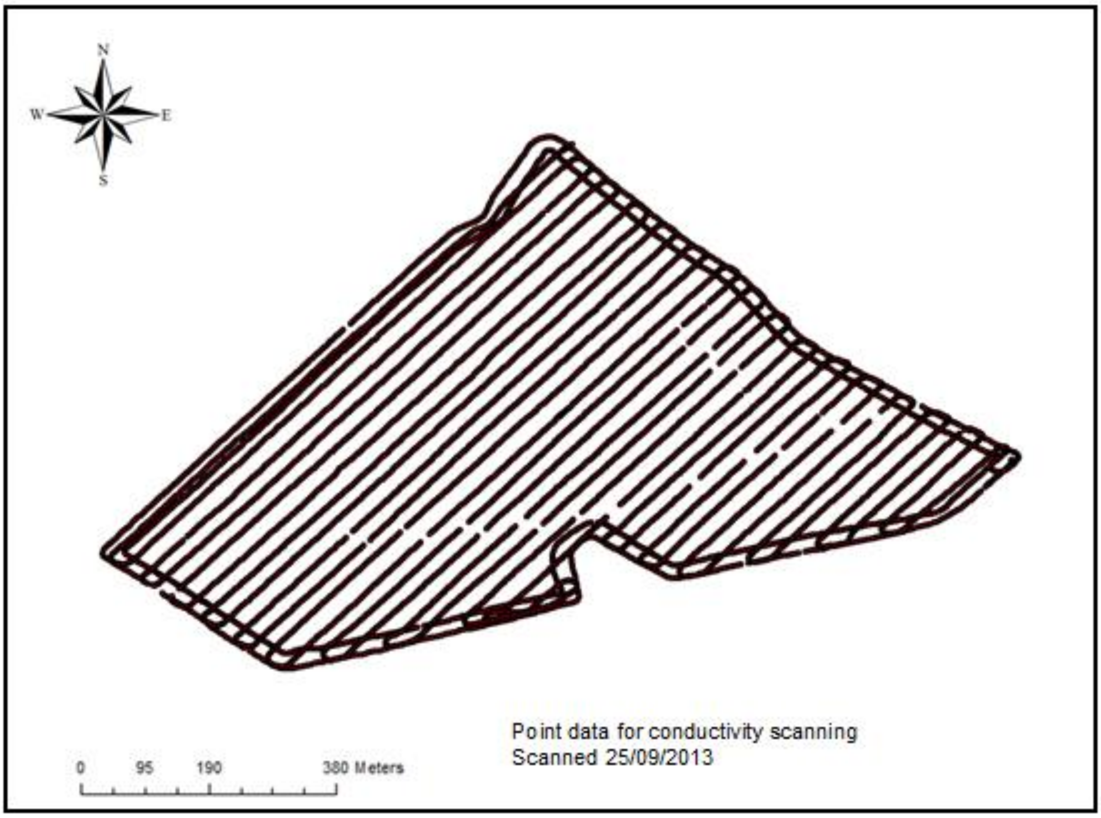


Figure 15. EC point location for Bugmore.

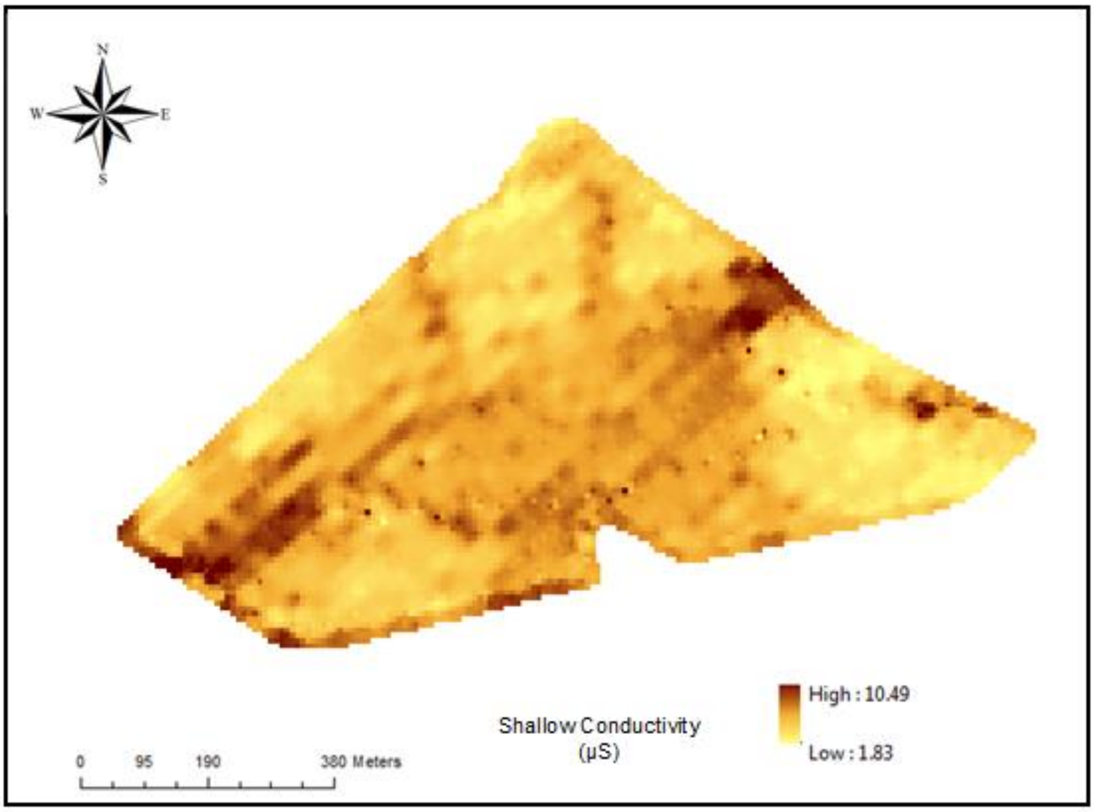


Figure 16. Shallow EC for Bugmore.

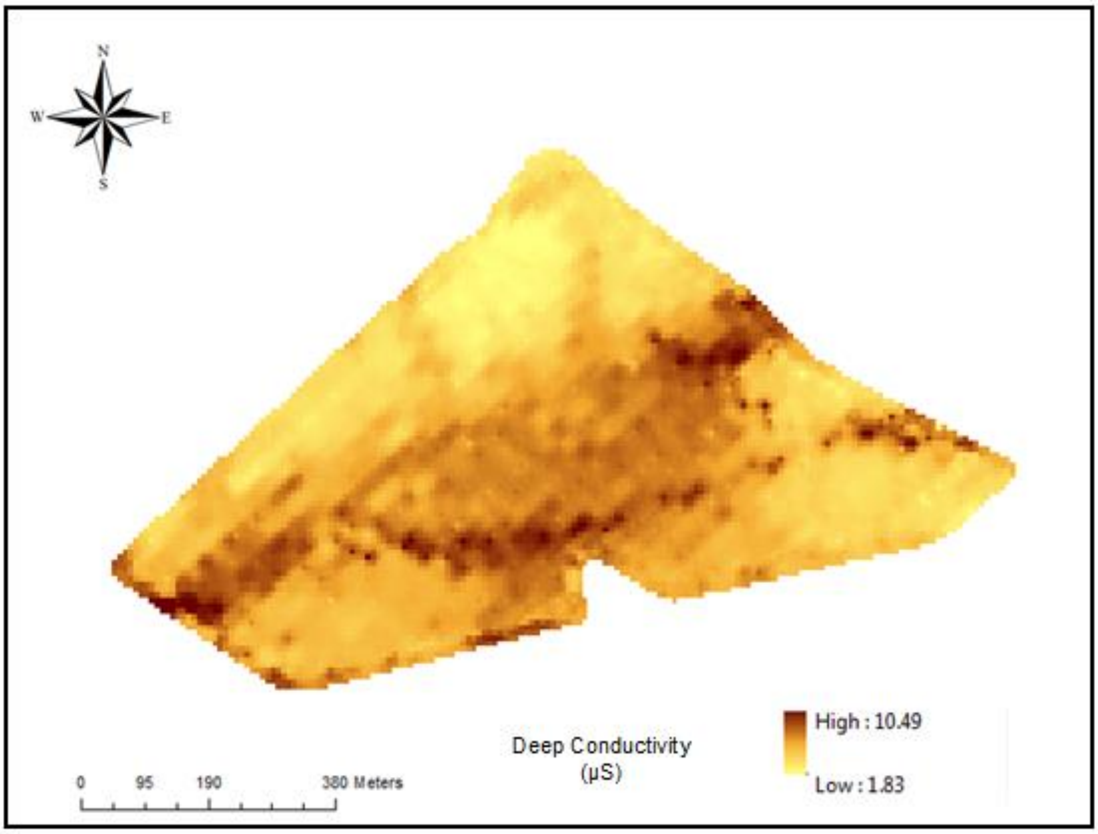


Figure 17. Deep EC for Bugmore.

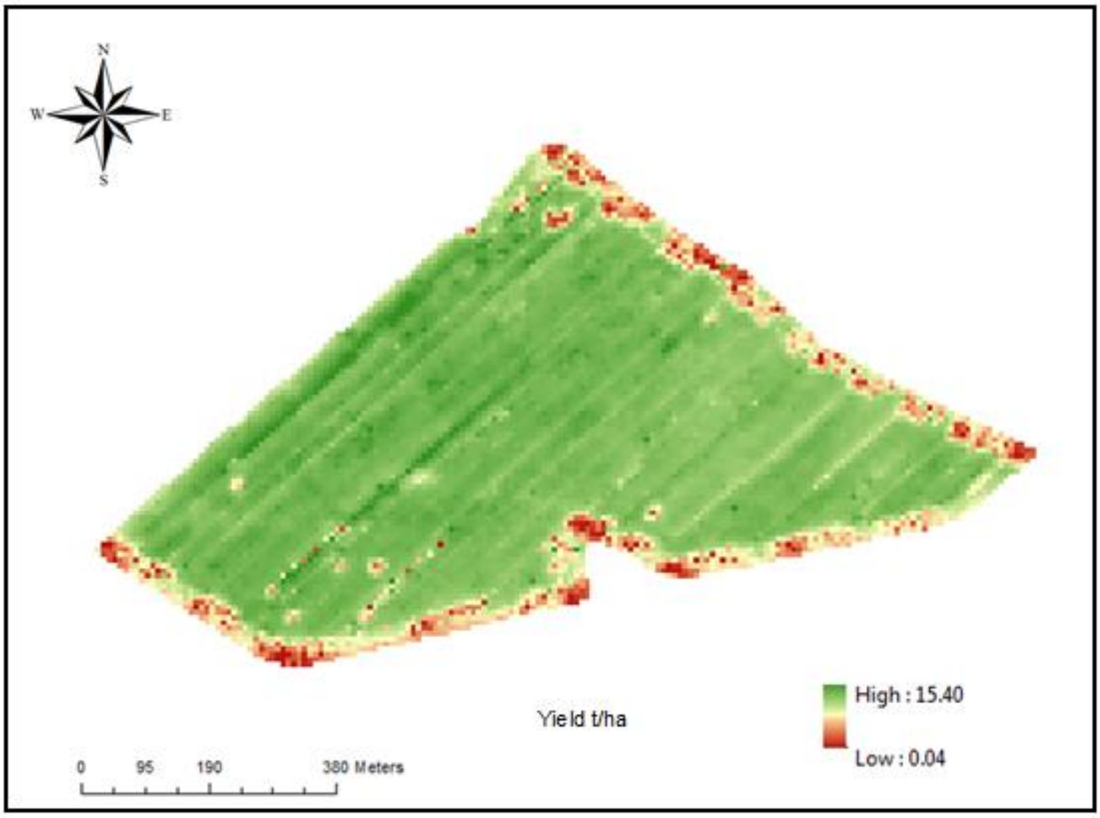


Figure 18. Bugmore 2014 Yield.

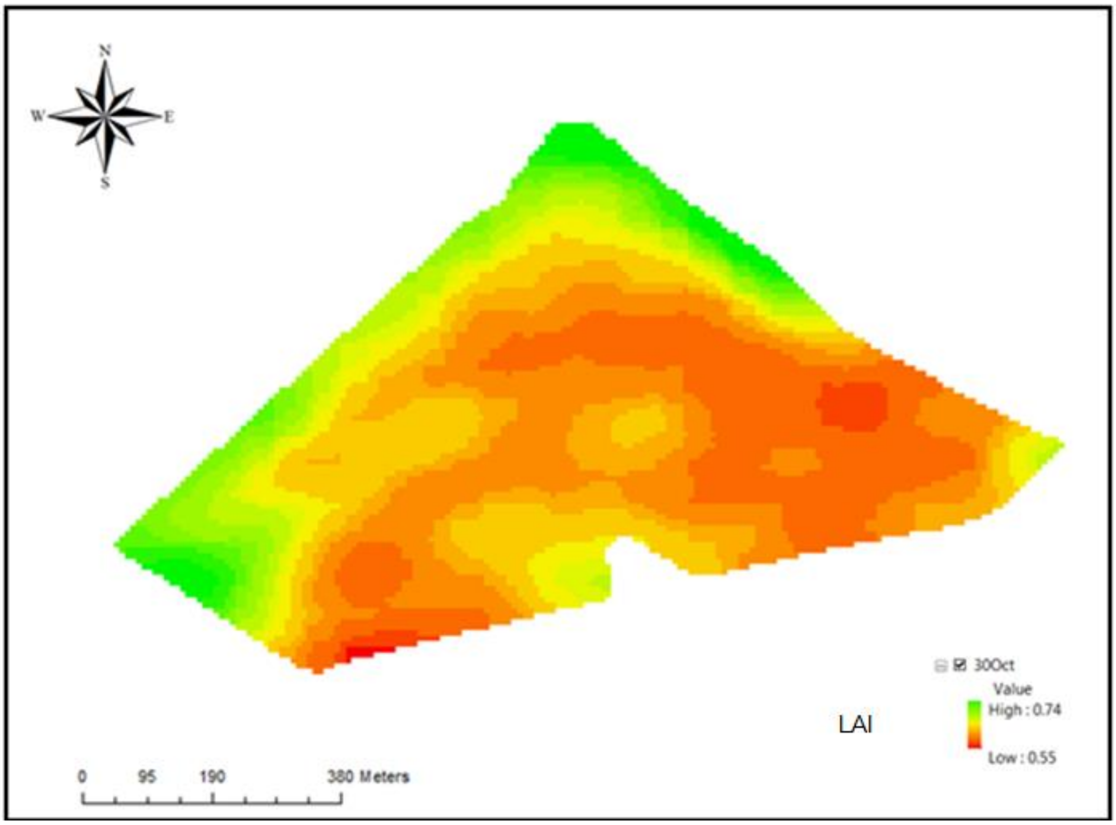


Figure 19. Bugmore LAI 30/10/13.

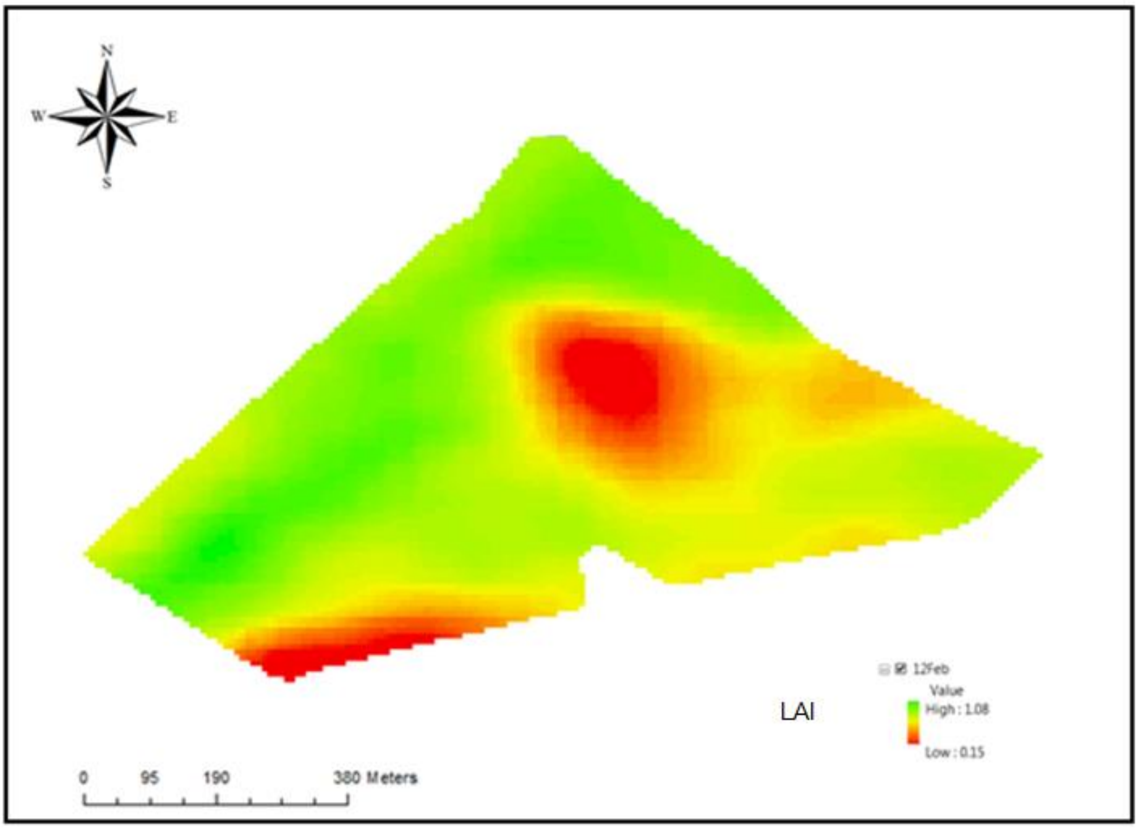


Figure 20. Bugmore LAI 12/02/14.

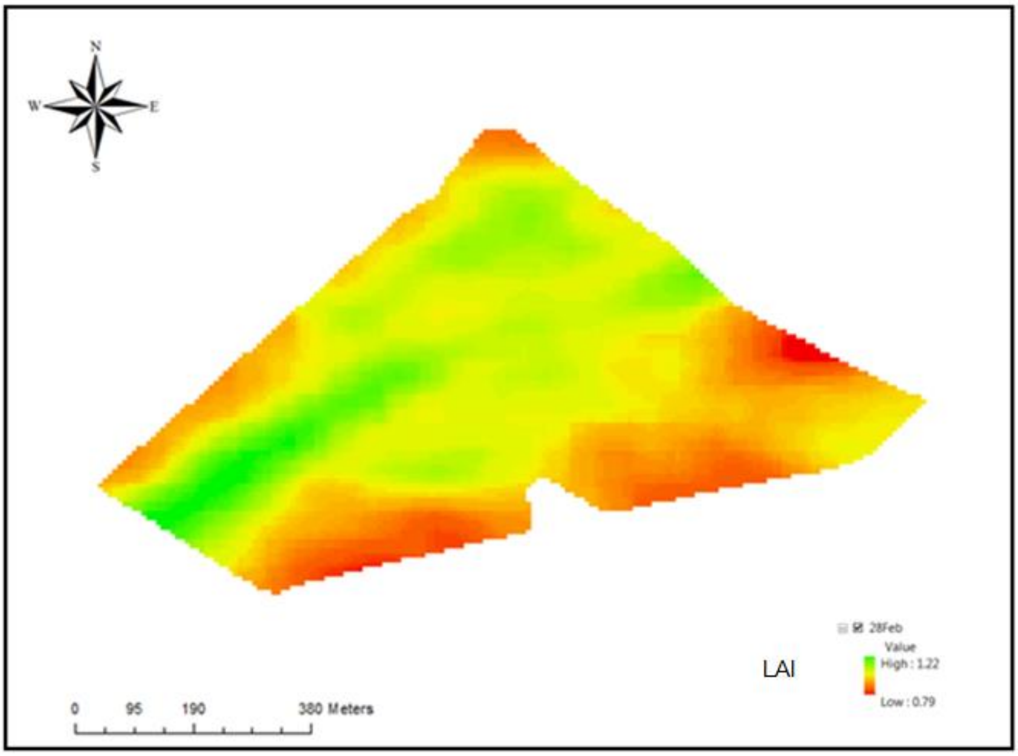


Figure 21. Bugmore LAI 28/02/14.

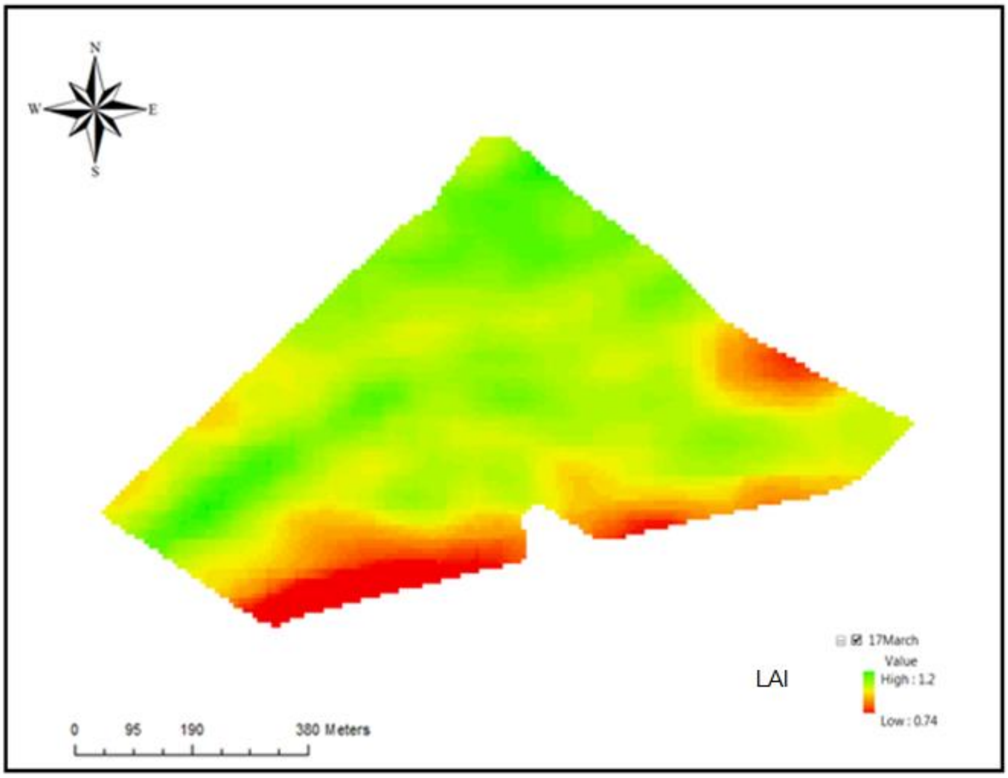


Figure 22. Bugmore LAI 17/03/14.

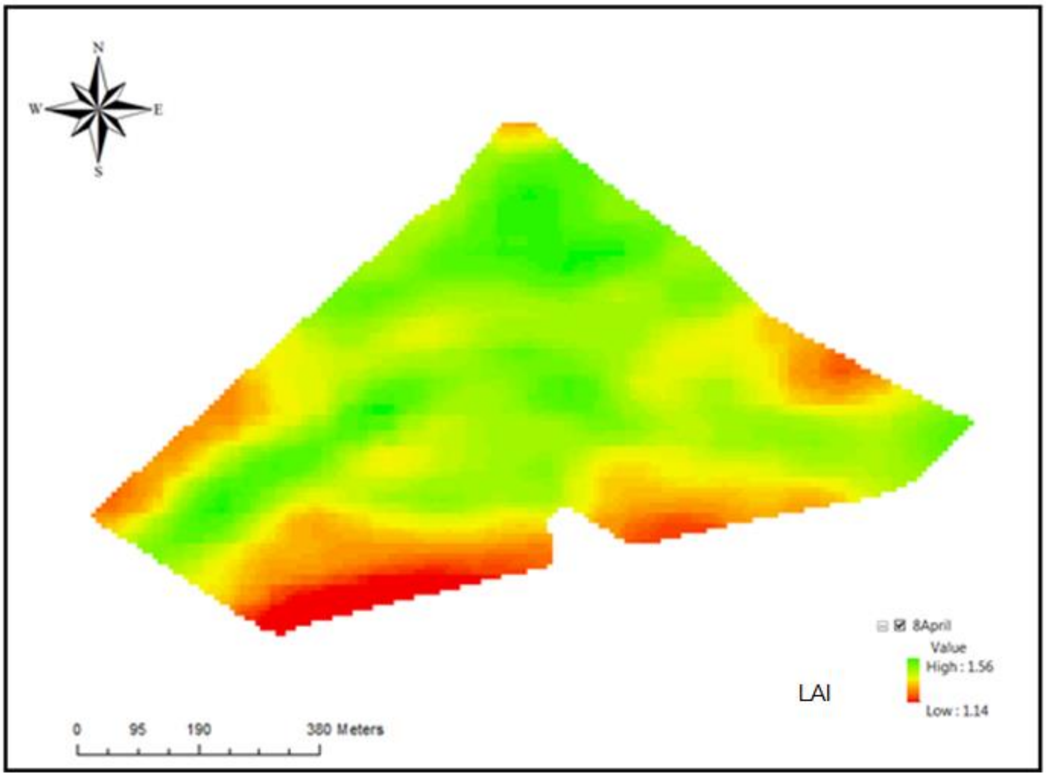


Figure 23. Bugmore LAI 08/04/14.

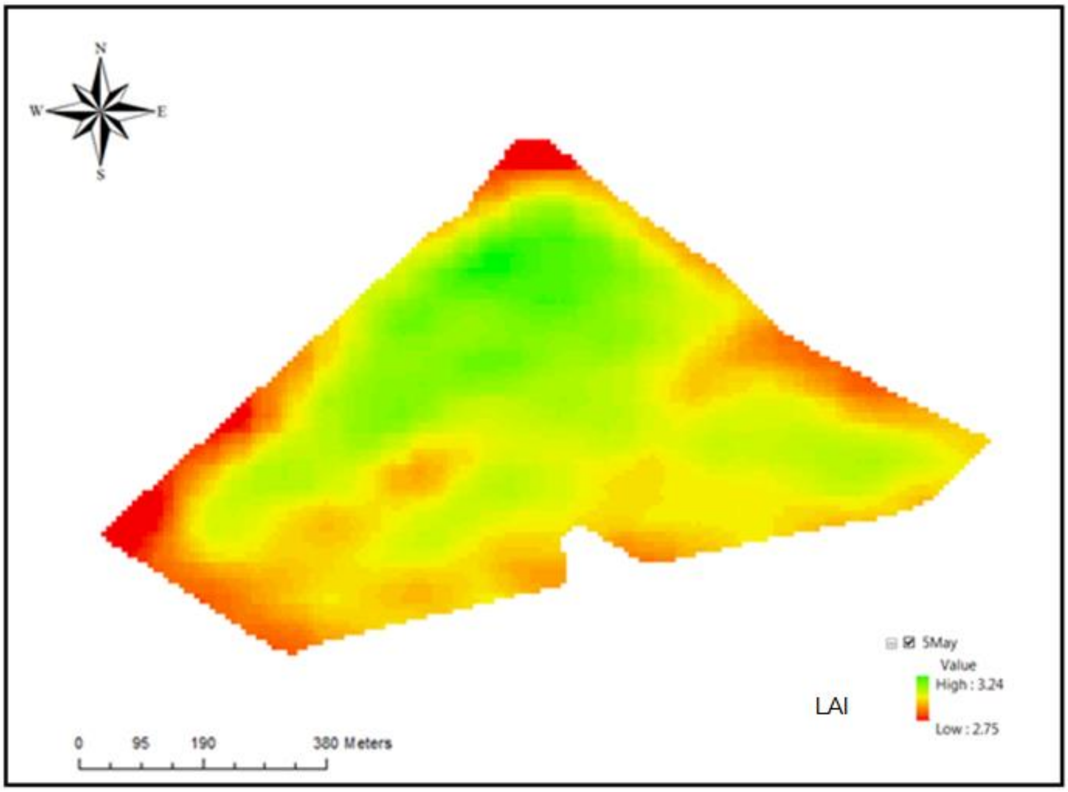


Figure 24. Bugmore LAI 05/05/14.

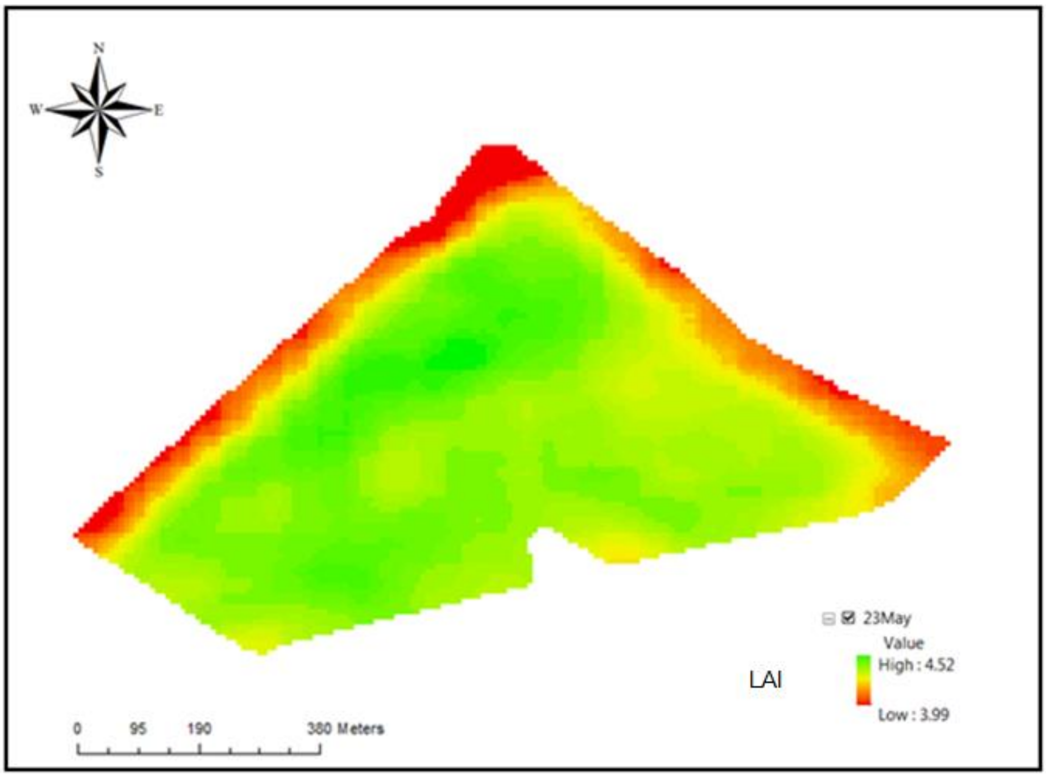


Figure 25. Bugmore LAI 23/05/14.

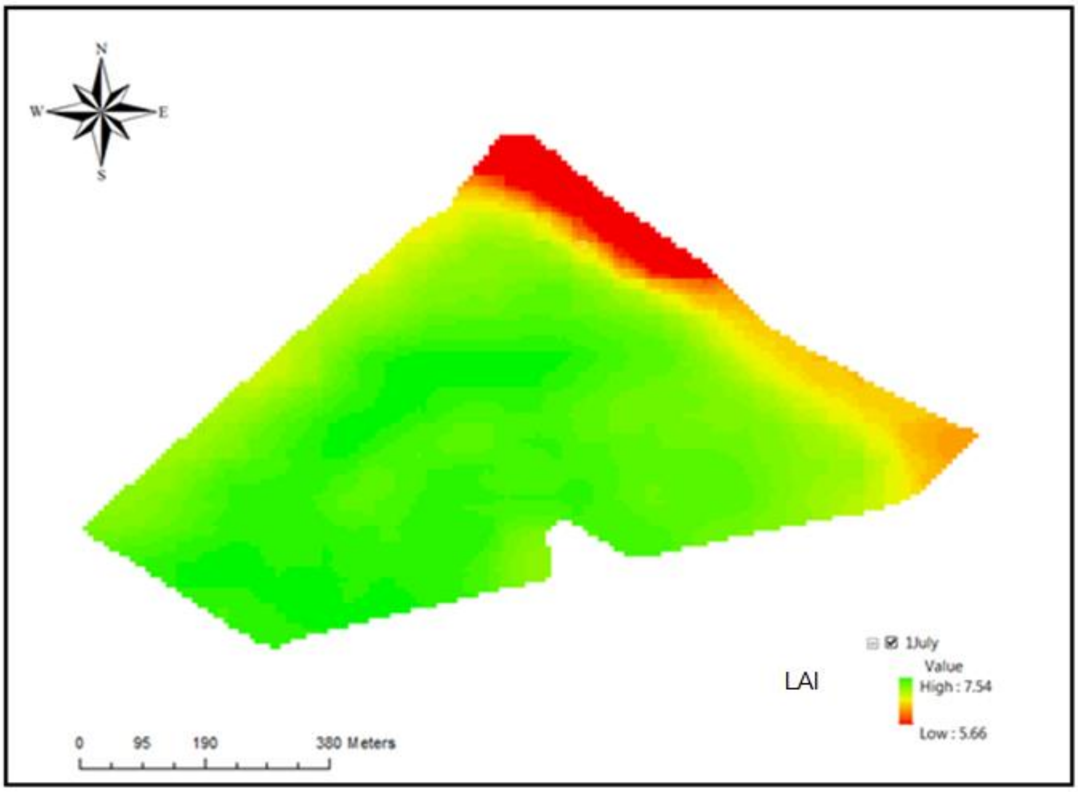
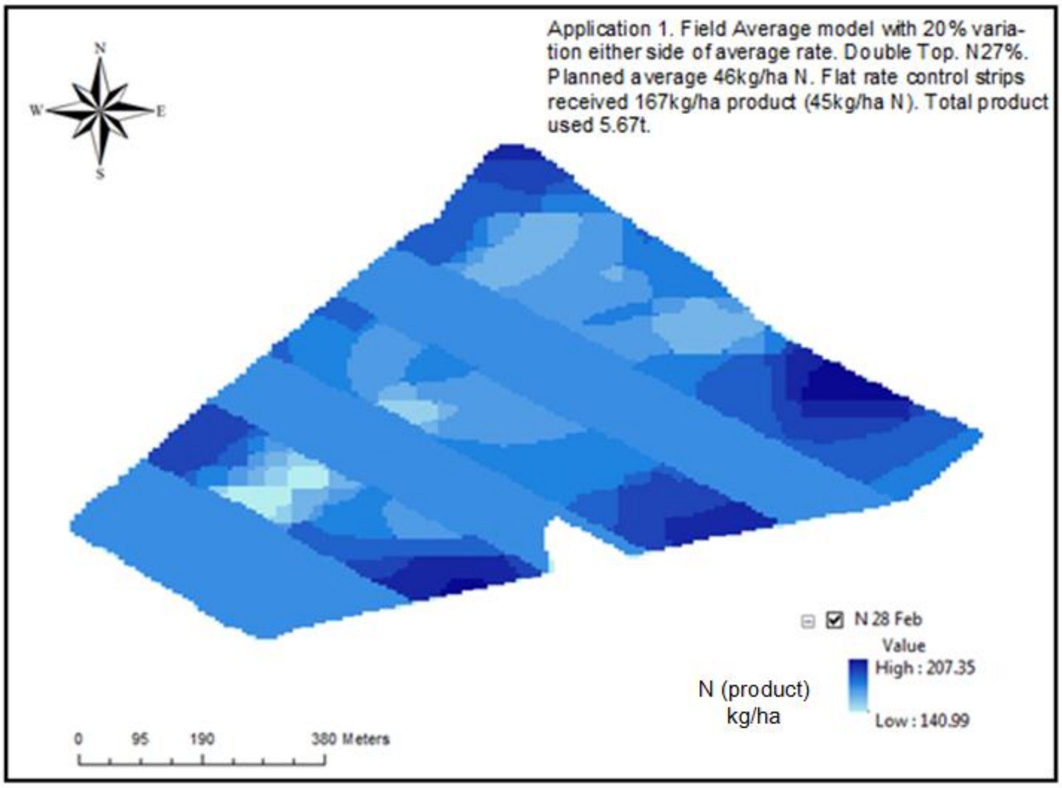
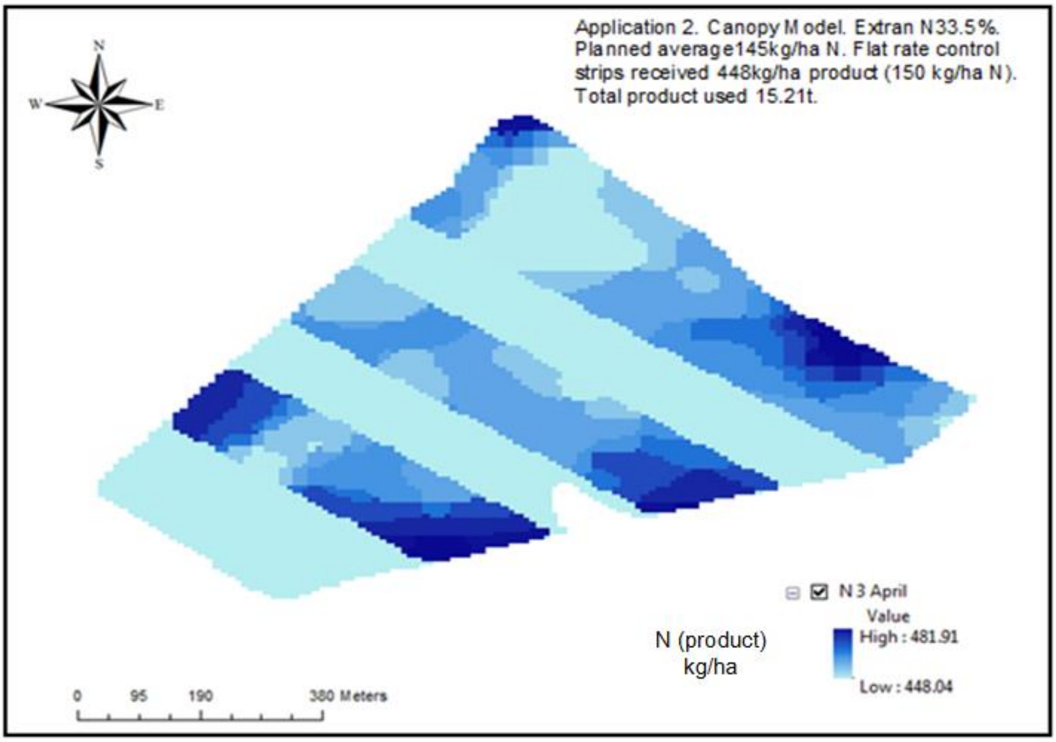


Figure 26. Bugmore LAI 01/07/14.



Application 1. Field Average model with 20% variation either side of average rate. Double Top. N27%. Planned average 46kg/ha N. Flat rate control strips received 167kg/ha product (45kg/ha N). Total product used 5.67t.

Figure 27. Bugmore N Application 28/02/14.



Application 2. Canopy Model. Extran N33.5%. Planned average145kg/ha N. Flat rate control strips received 448kg/ha product (150 kg/ha N). Total product used 15.21t.

Figure 28. Bugmore N Application 03/04/14.

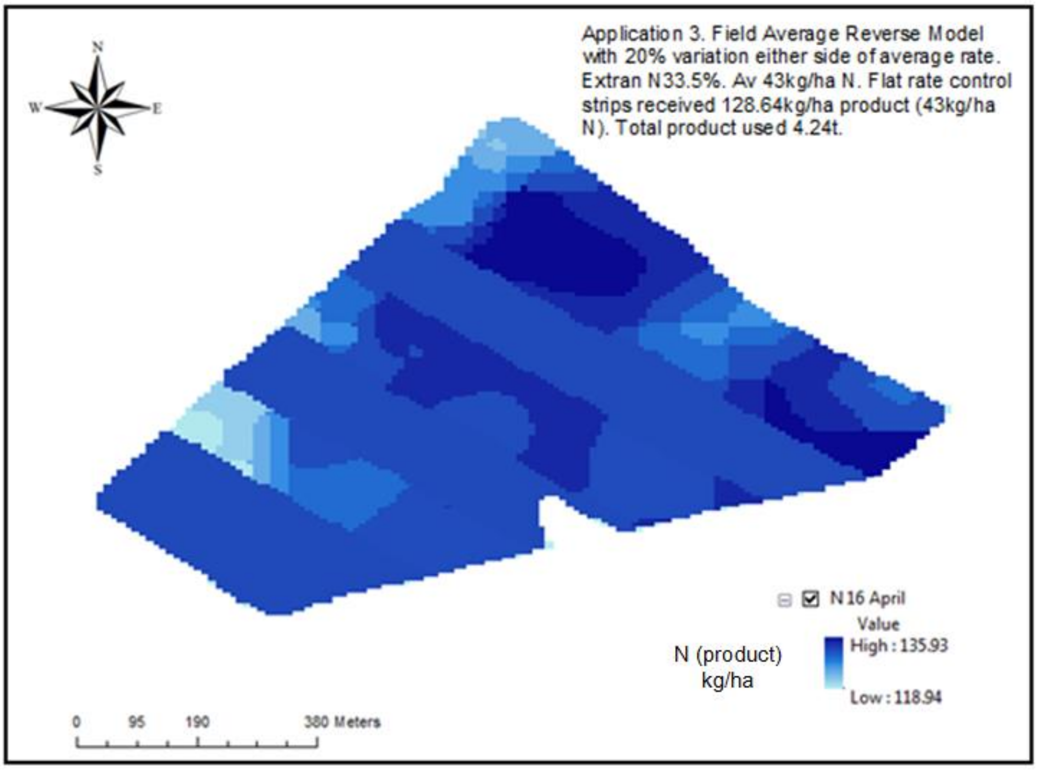

Application 3. Field Average Reverse Model with 20% variation either side of average rate. Extran N33.5%. Av 43kg/ha N. Flat rate control strips received 128.64kg/ha product (43kg/ha N). Total product used 4.24t.

Figure 29. Bugmore N Application 16/04/14.

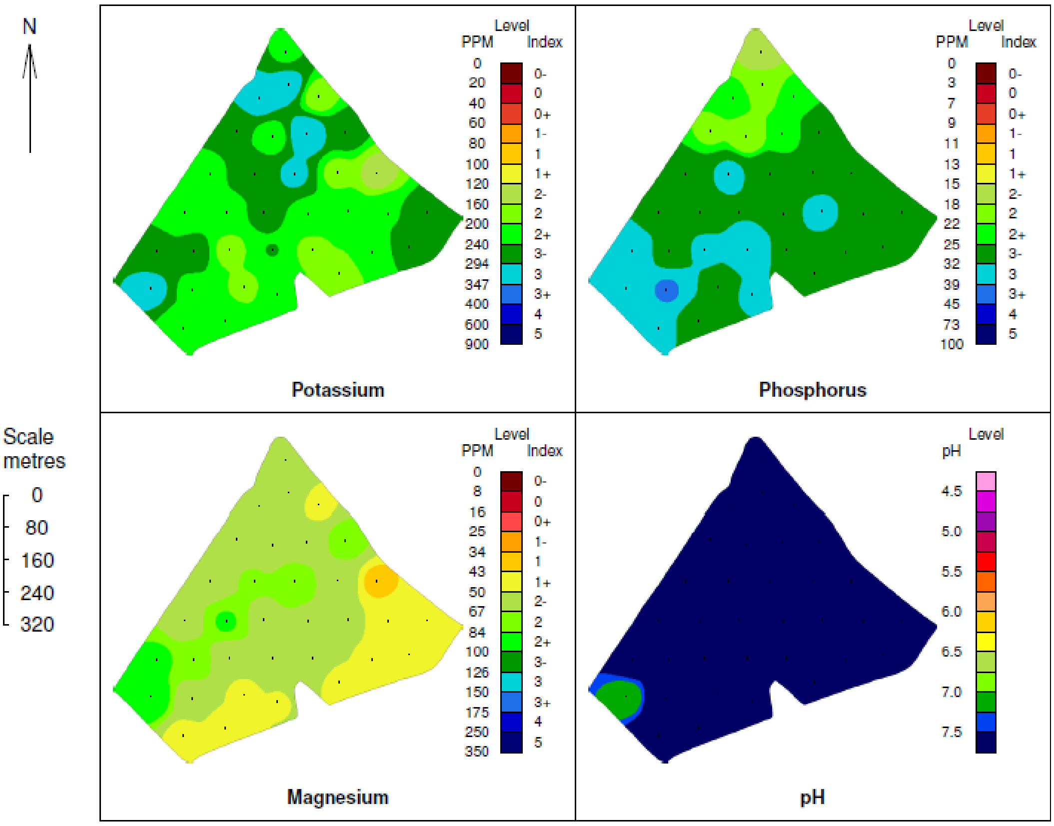


Figure 30. P, K ,Mg and pH sampling results for Bugmore. Sampled 06/10/2010.

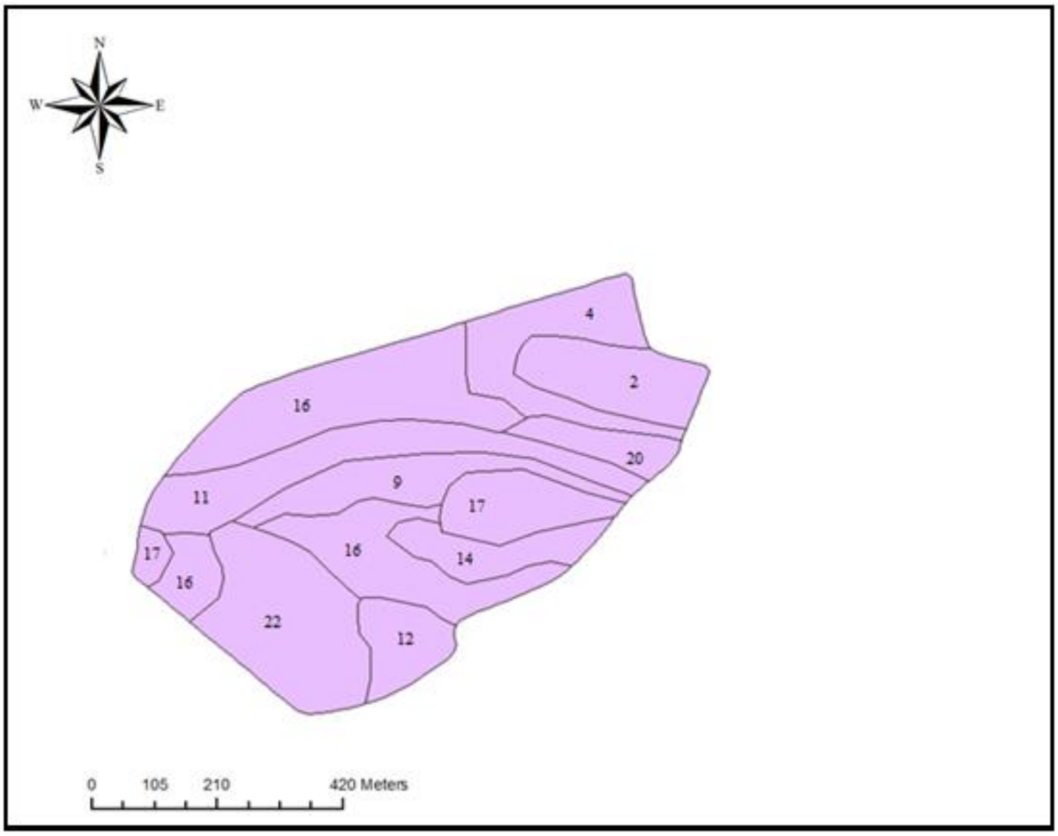


Figure 31. Soil Type for Chalk Churn (28.79 ha).

| | Topsoil | Stone Content (Topsoil) | Subsoil |
|---|---|---|---|
| **2** | Medium Sandy Clay Loam | High | Very Stony |
| **4** | Medium Silty Clay Loam | High | Very Stony |
| **9** | Medium Heavy Sandy Clay Loam | High | Very Stony |
| **11** | Medium Heavy Silty Clay Loam | Moderate | Moderately Stony |
| **14** | Medium Heavy Silty Clay Loam | Moderate | Very Stony |
| **16** | Heavy Silty Clay Loam | Slight | Heavy Silty Clay Loam |
| **17** | Heavy Sandy Clay Loam | Moderate | Heavy Sandy Clay Loam |
| **20** | Heavy Sandy Clay Loam | Very High | Sandy Clay |
| **22** | Sandy Clay | Moderate | Loamy Clay |

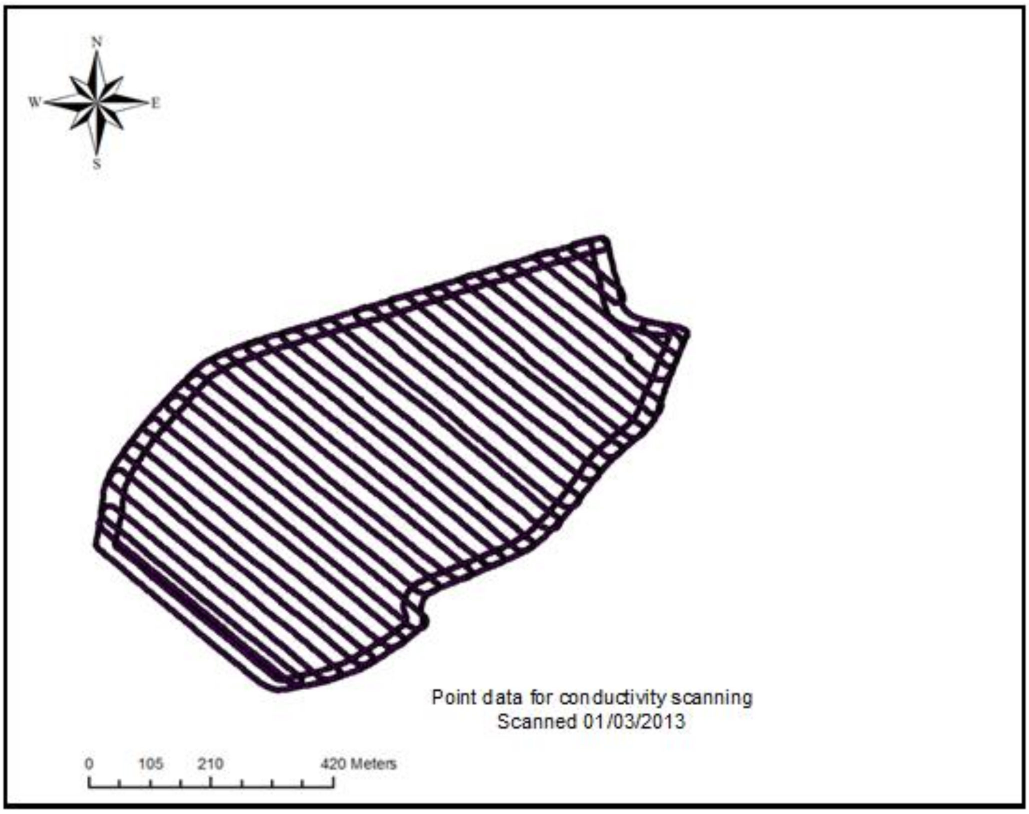


Figure 32. EC point location for Chalk Churn.

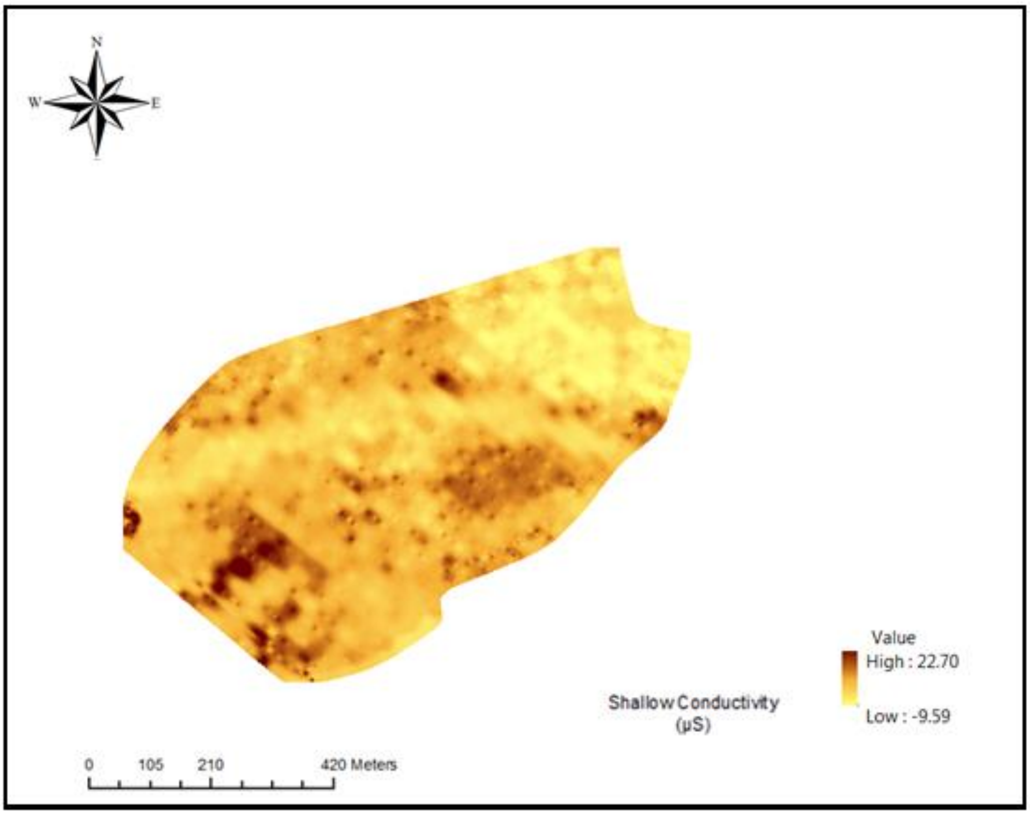


Figure 33. Shallow EC for Chalk Churn.

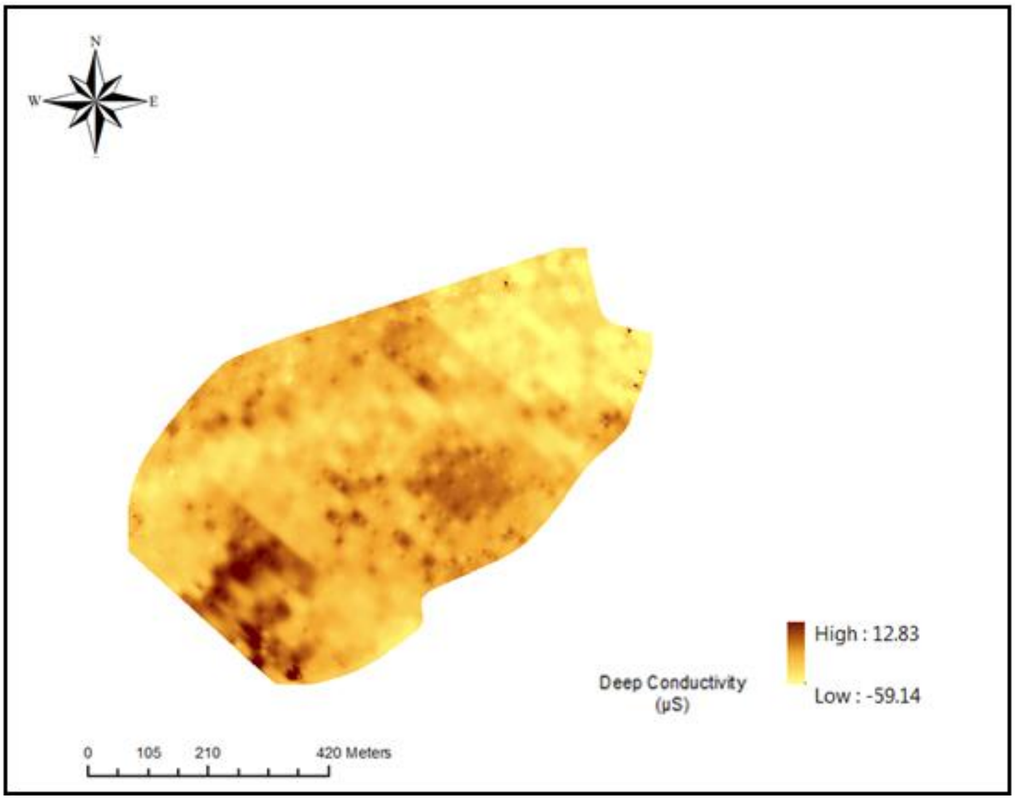


Figure 34. Deep EC for Chalk Churn.

Figure 35. Chalk Churn 2014 Yield.

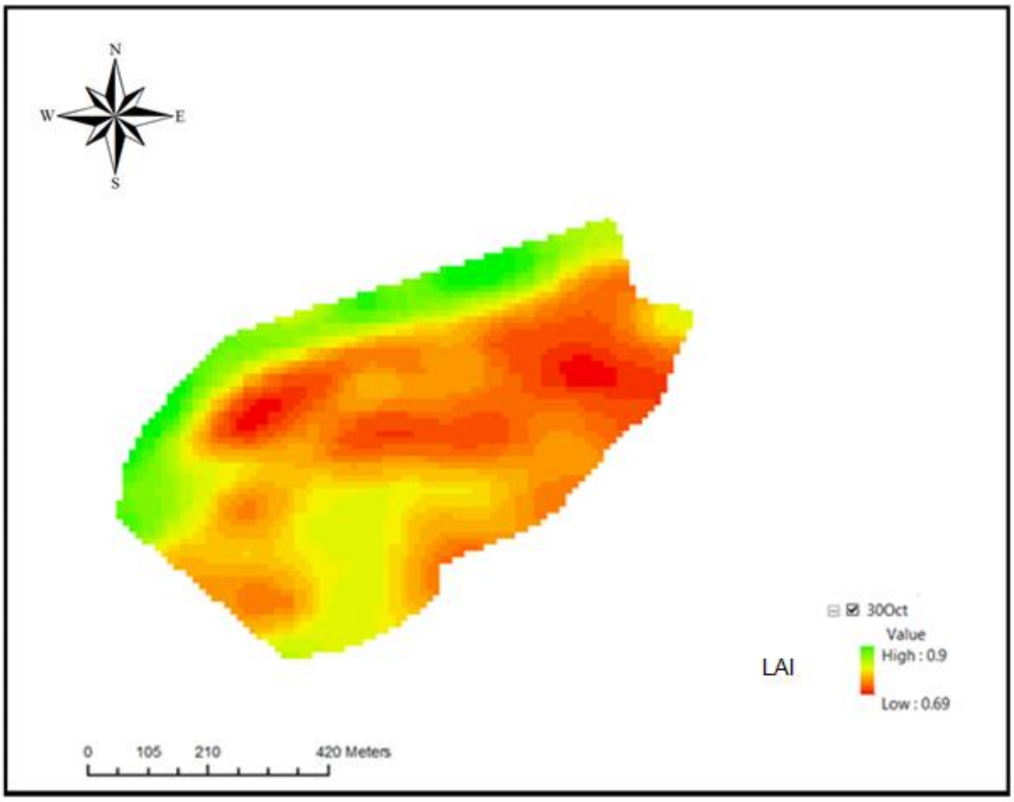


Figure 36. Chalk Churn LAI 30/10/13.

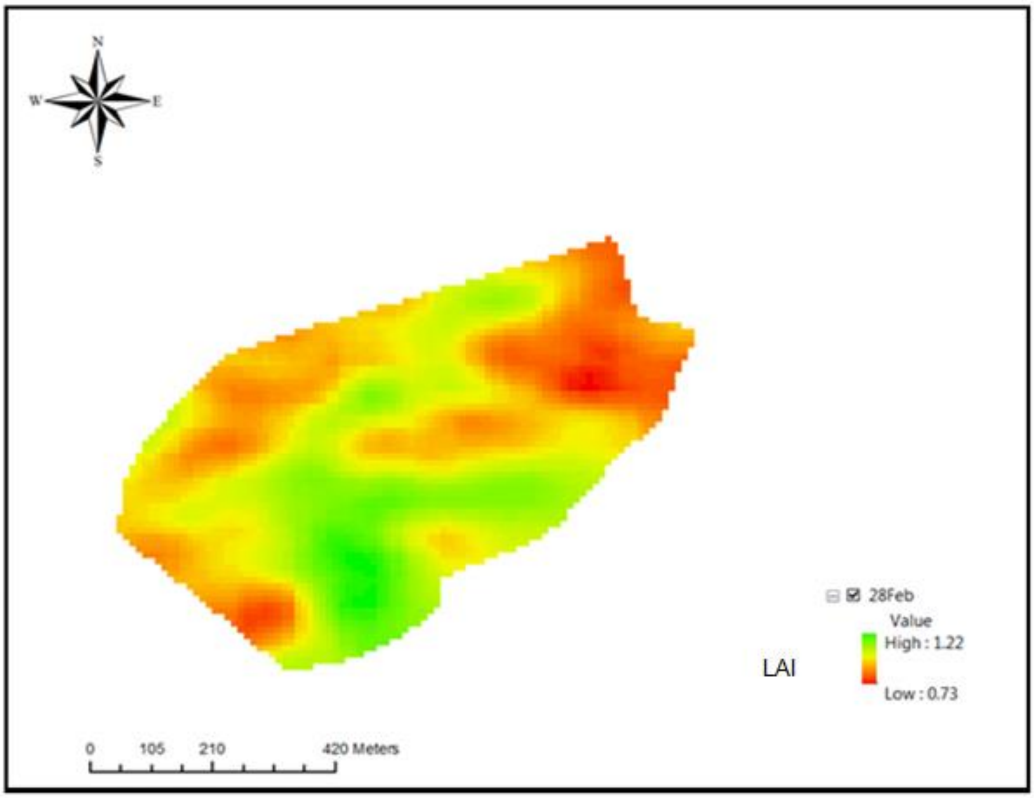


Figure 37. Chalk Churn LAI 28/02/14.

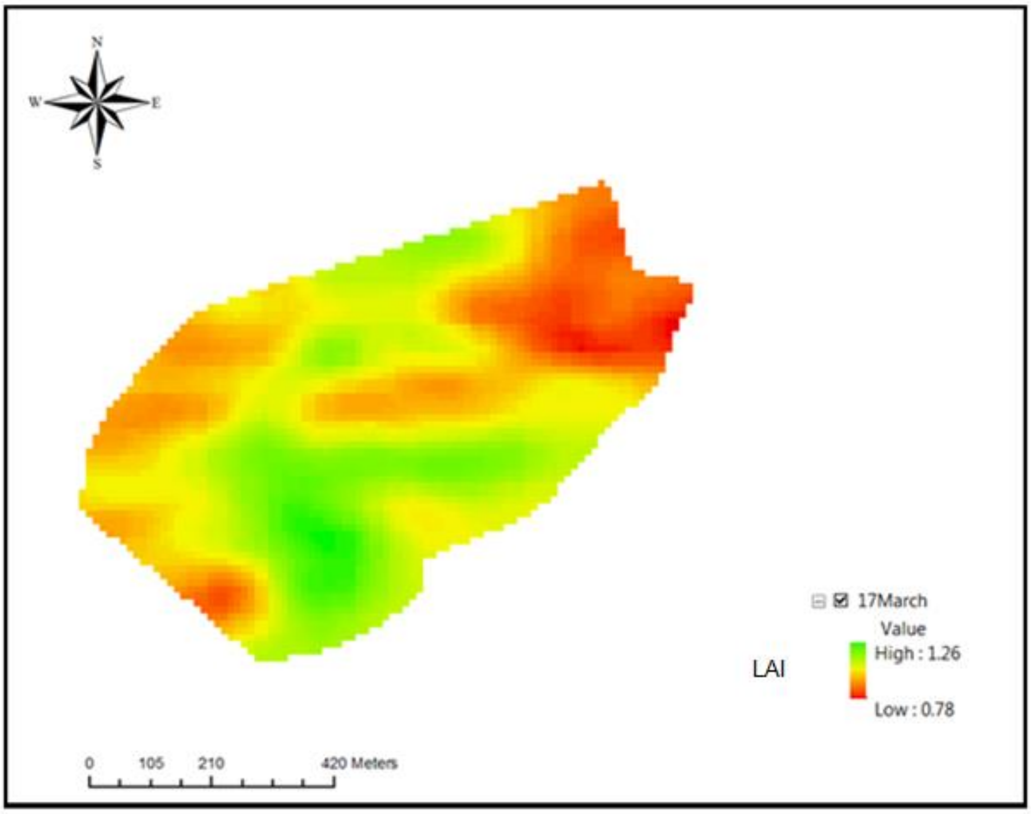


Figure 38. Chalk Churn LAI 17/03/14.

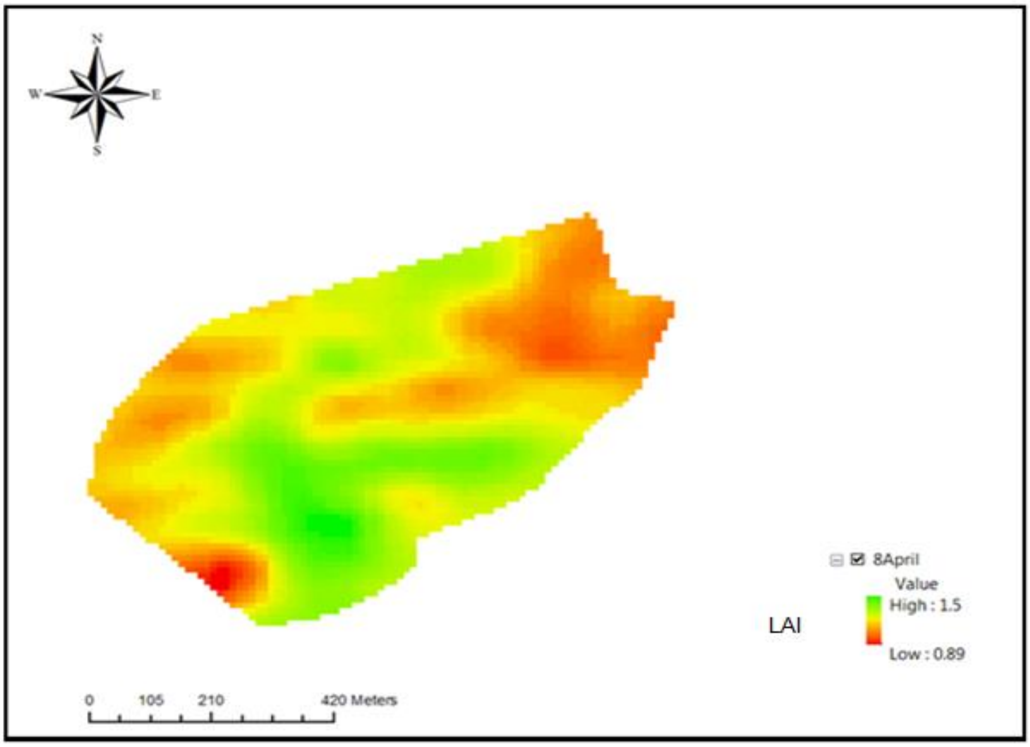


Figure 39. Chalk Churn LAI 08/04/14.

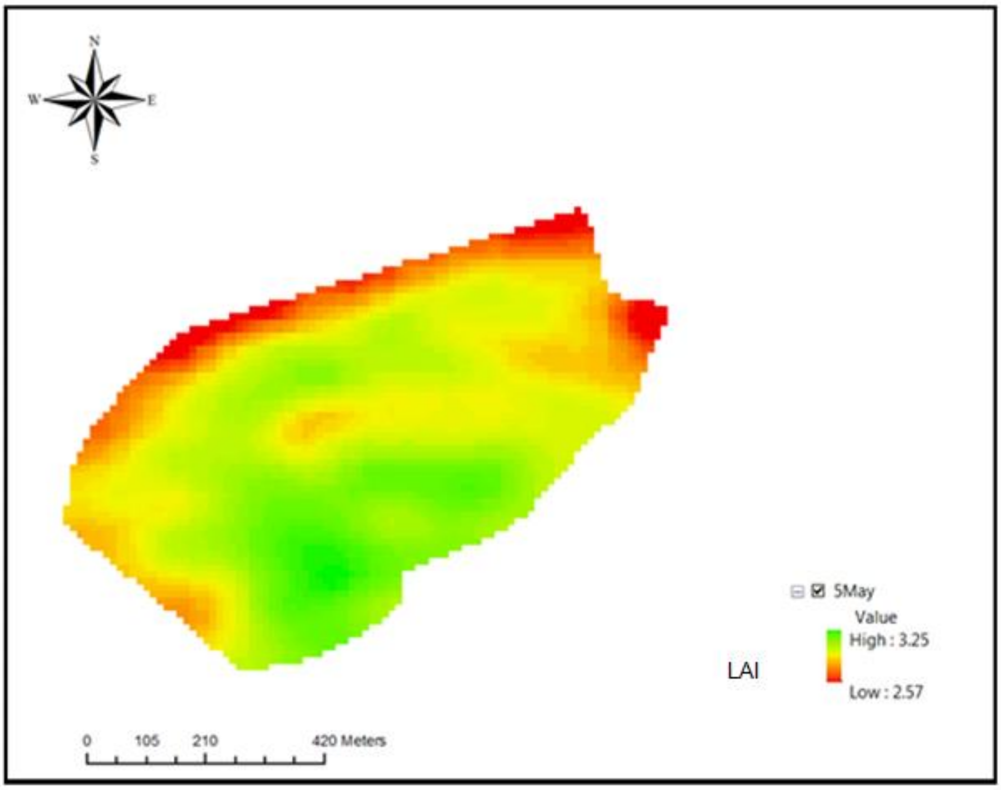


Figure 40. Chalk Churn LAI 05/05/14.

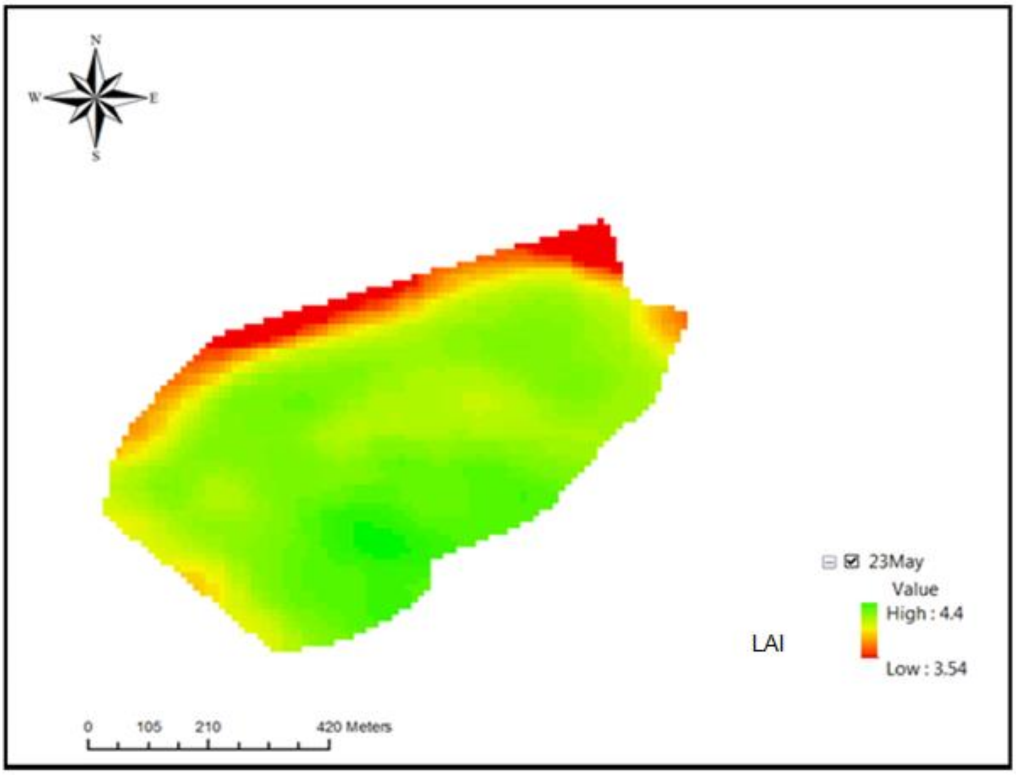


Figure 41. Chalk Churn LAI 23/05/14.

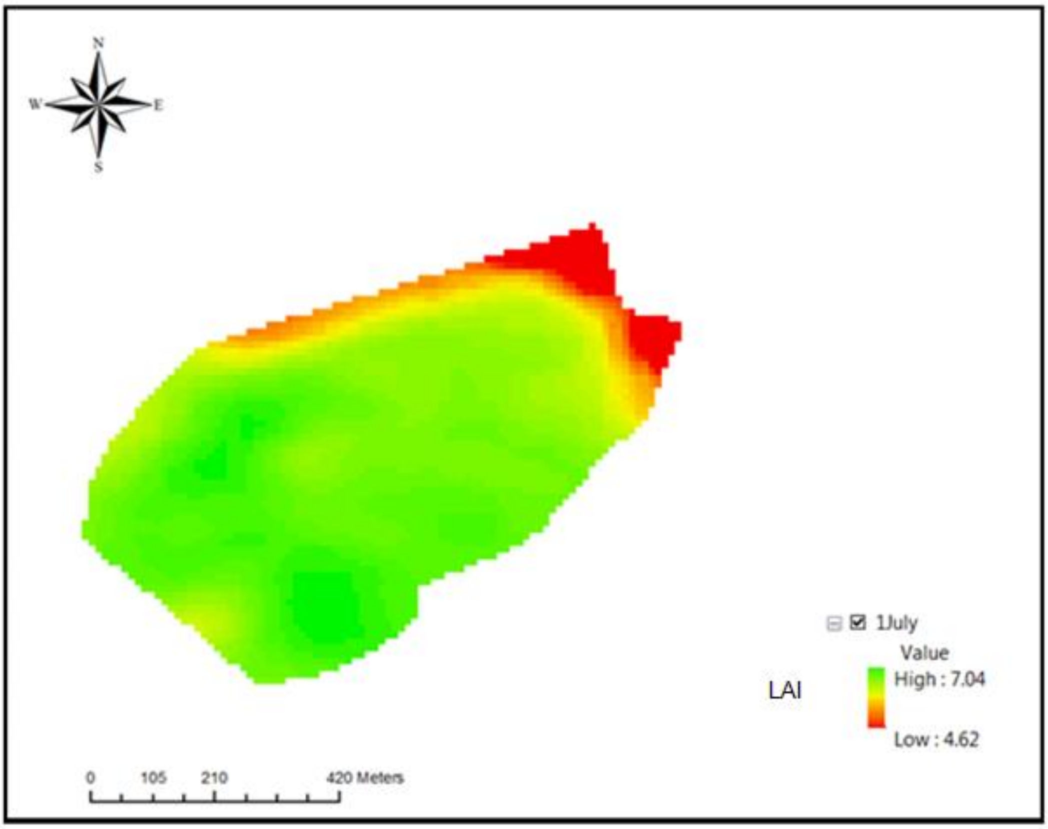


Figure 42. Chalk Churn LAI 01/07/14.

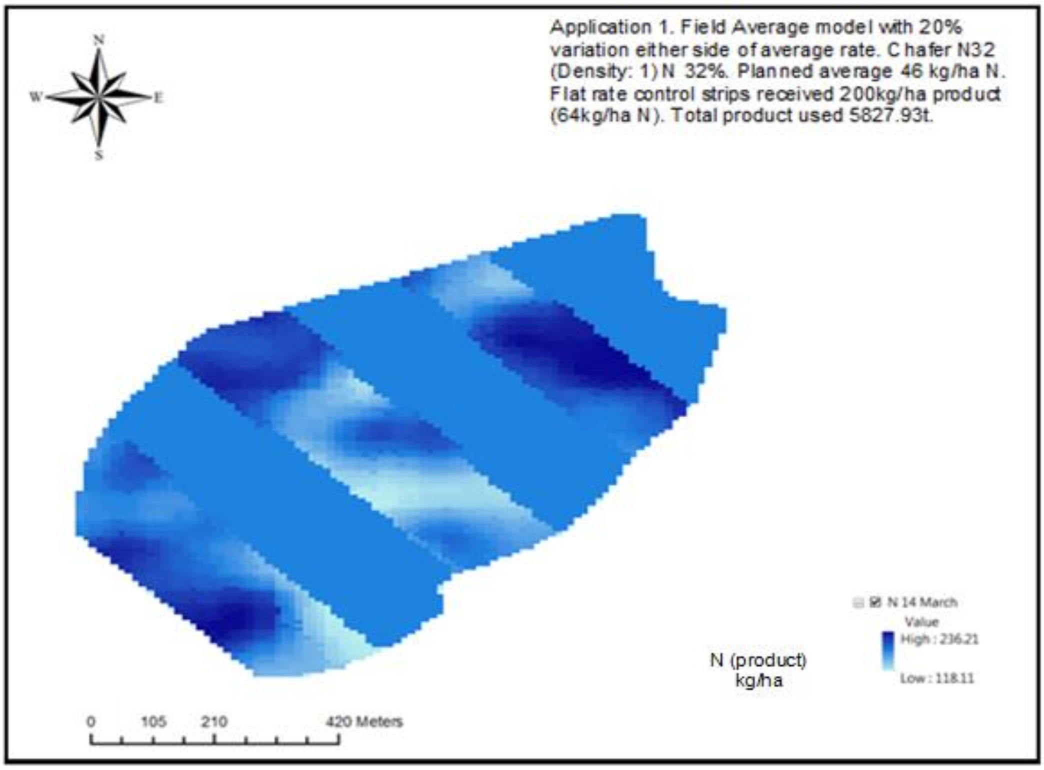

Application 1. Field Average model with 20% variation either side of average rate. Chafer N32 (Density: 1) N 32%. Planned average 46 kg/ha N. Flat rate control strips received 200kg/ha product (64kg/ha N). Total product used 5827.93t.

Figure 43. Chalk Churn N Application 14/03/14.

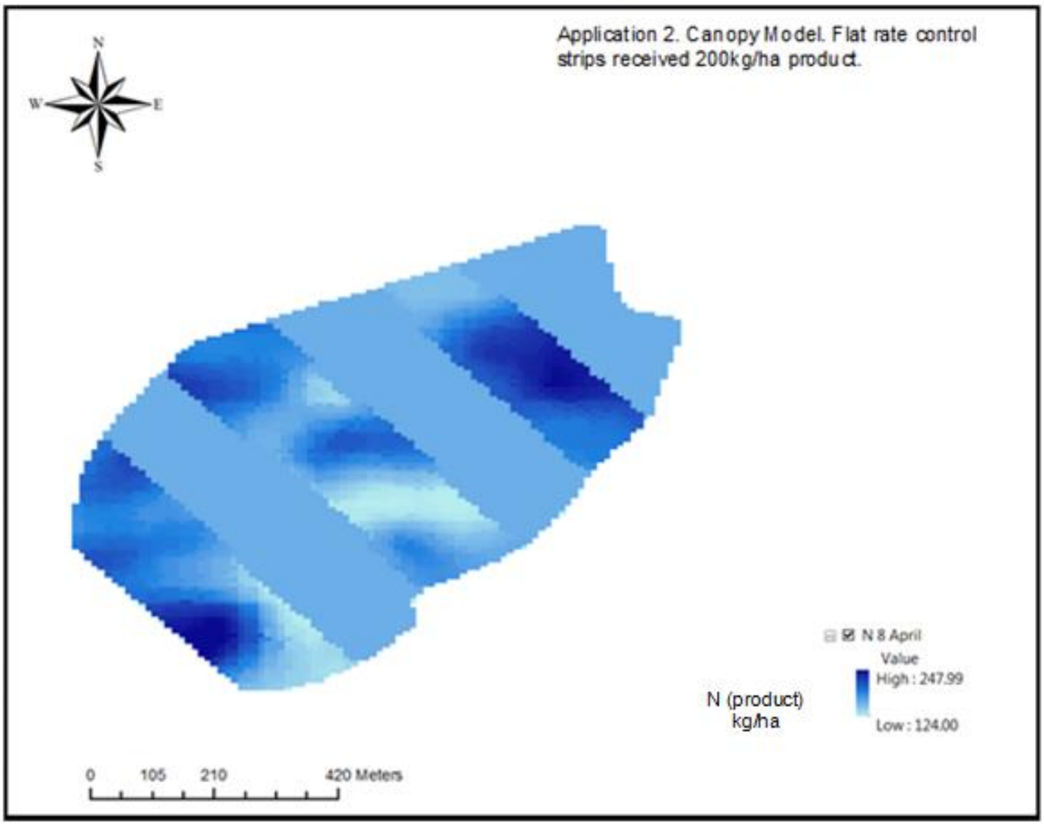


Figure 44. Chalk Churn N Application 08/04/14.

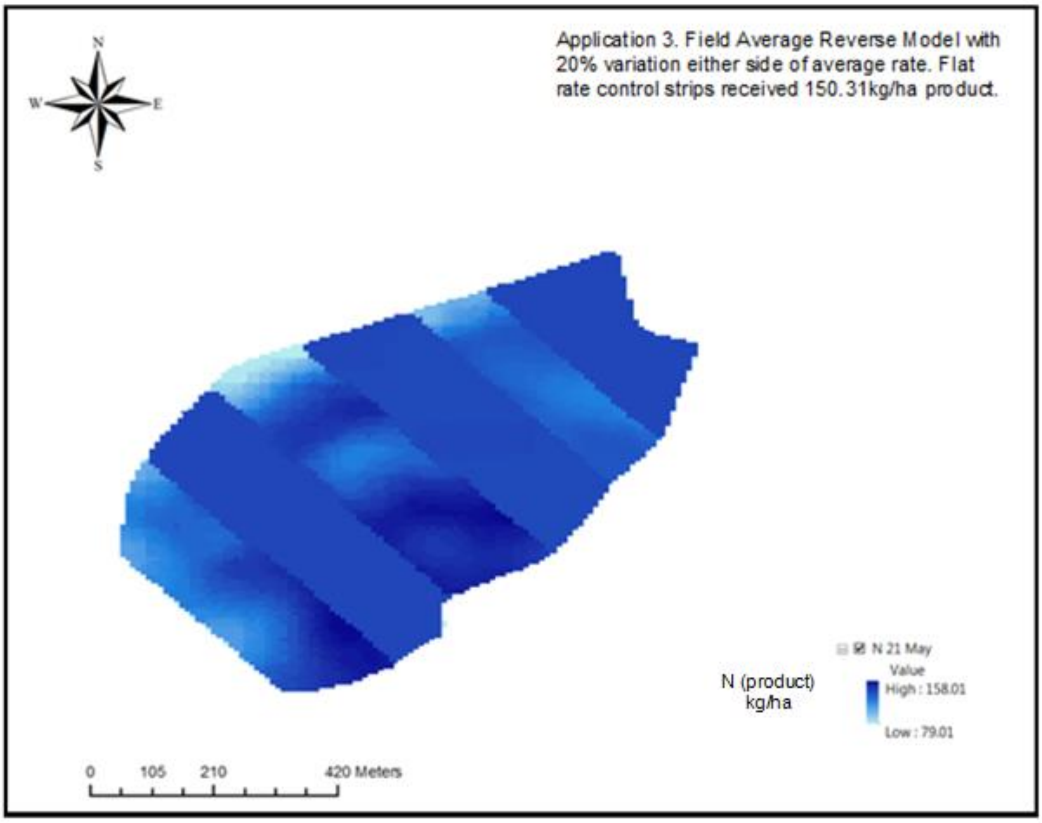


Figure 45. Chalk Churn N Application 21/05/14.

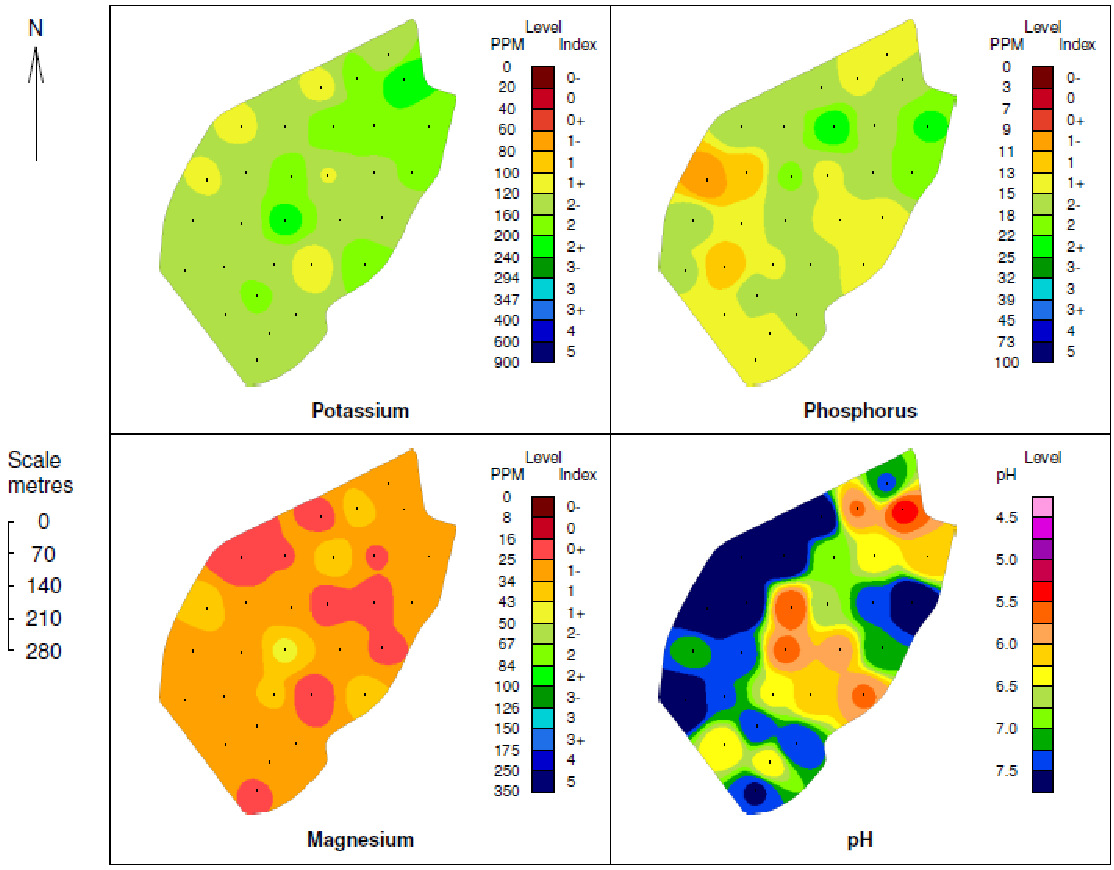


Figure 46. P, K, Mg and pH sampling results for Chalk Churn. Sampled 12/08/2010.

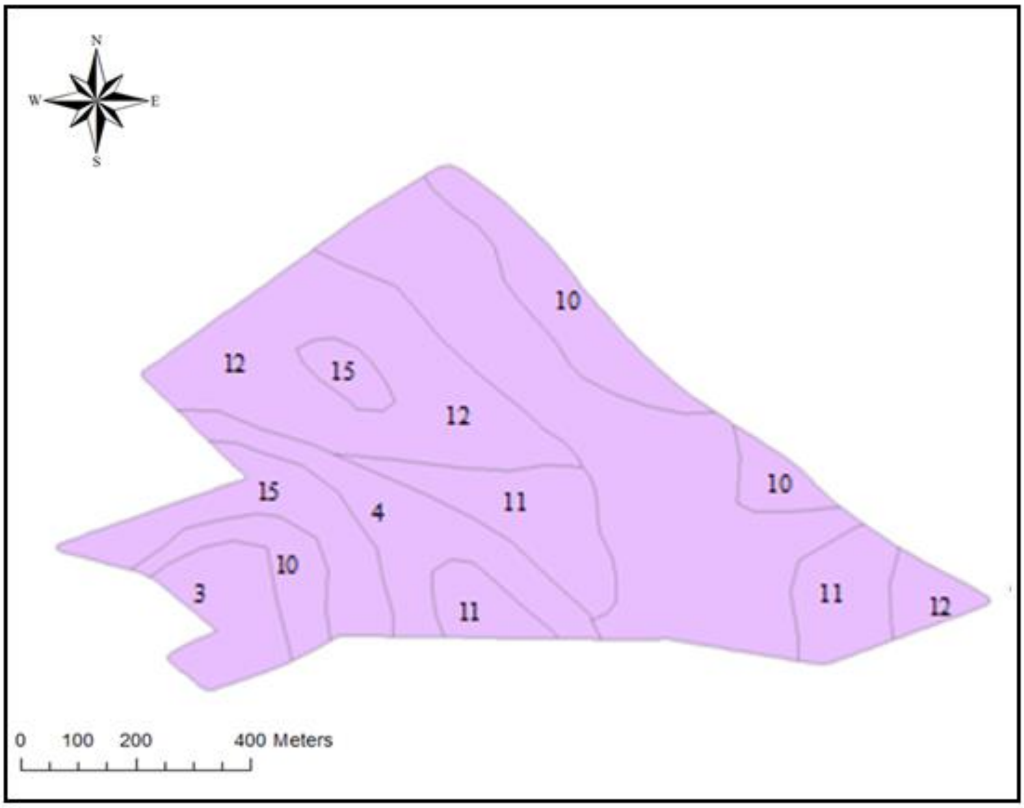


Figure 47. Soil Type for Hamstyles (47.47 ha).

| | Topsoil | Stone Content (Topsoil) | Subsoil |
|---|---|---|---|
| **3** | Medium Clay Loam | High | Medium Clay Loam to depth |
| **4** | Medium Silty Clay Loam | Moderate | Medium Silty Clay Loam over Chalk below 70cm |
| **10** | Heavy Clay Loam | Slight | Heavy Clay Loam over Loamy Clay below 60cm |
| **11** | Heavy Silty Clay Loam | Slight | Silty Clay below 30cm |
| **12** | Silty Clay | Very Slight | Silty Clay becoming heavier with depth |
| **15** | Medium Heavy over Clay | Slight | Medium Clay becoming heavier with depth |

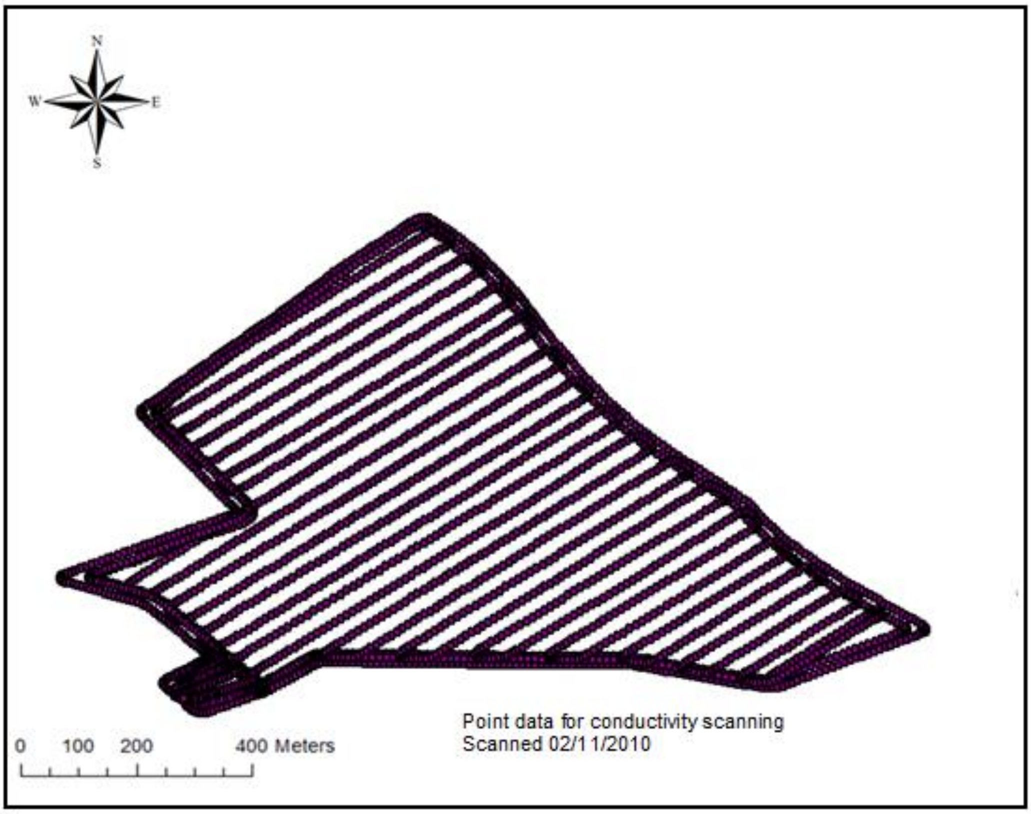


Figure 48. EC Point location for Hamstyles.

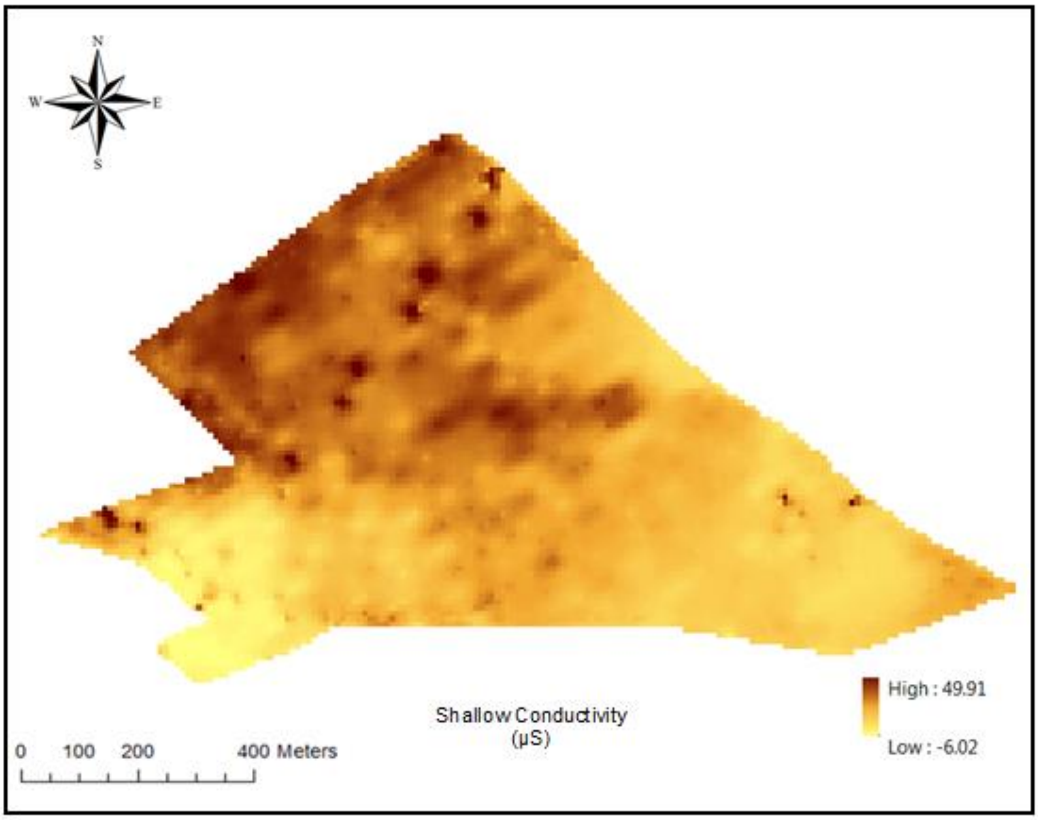


Figure 49. Shallow EC for Hamstyles.

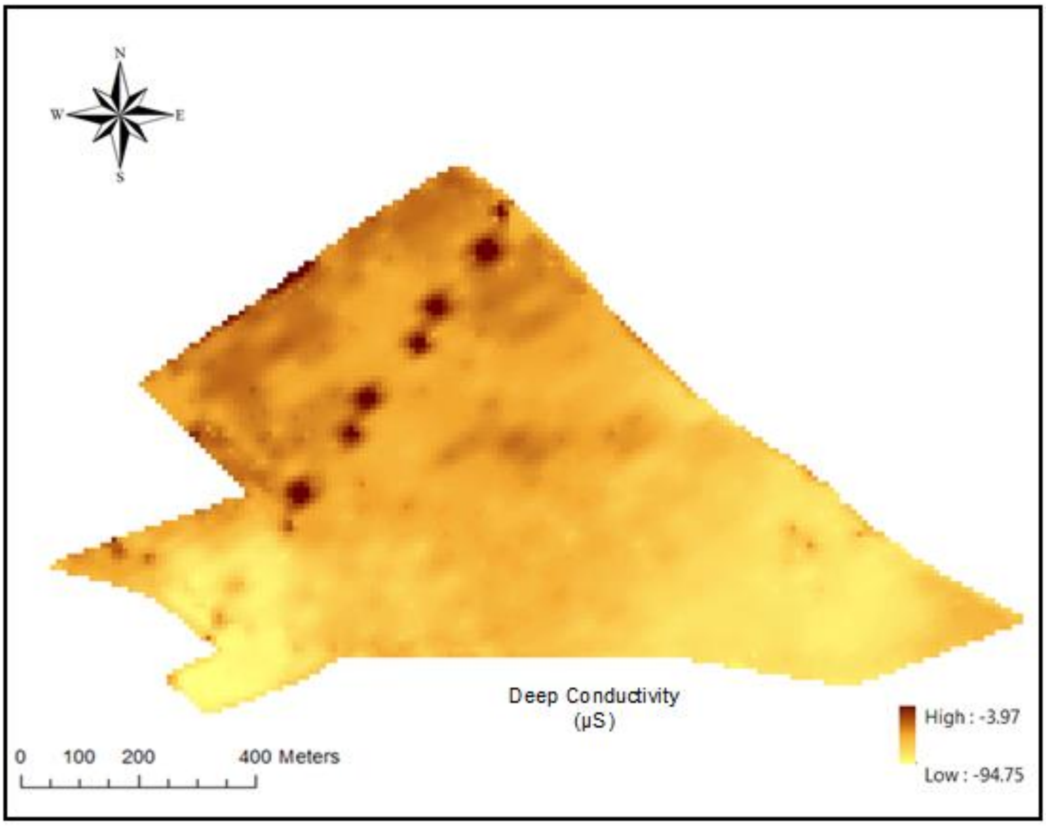


Figure 50. Deep EC for Hamstyles.

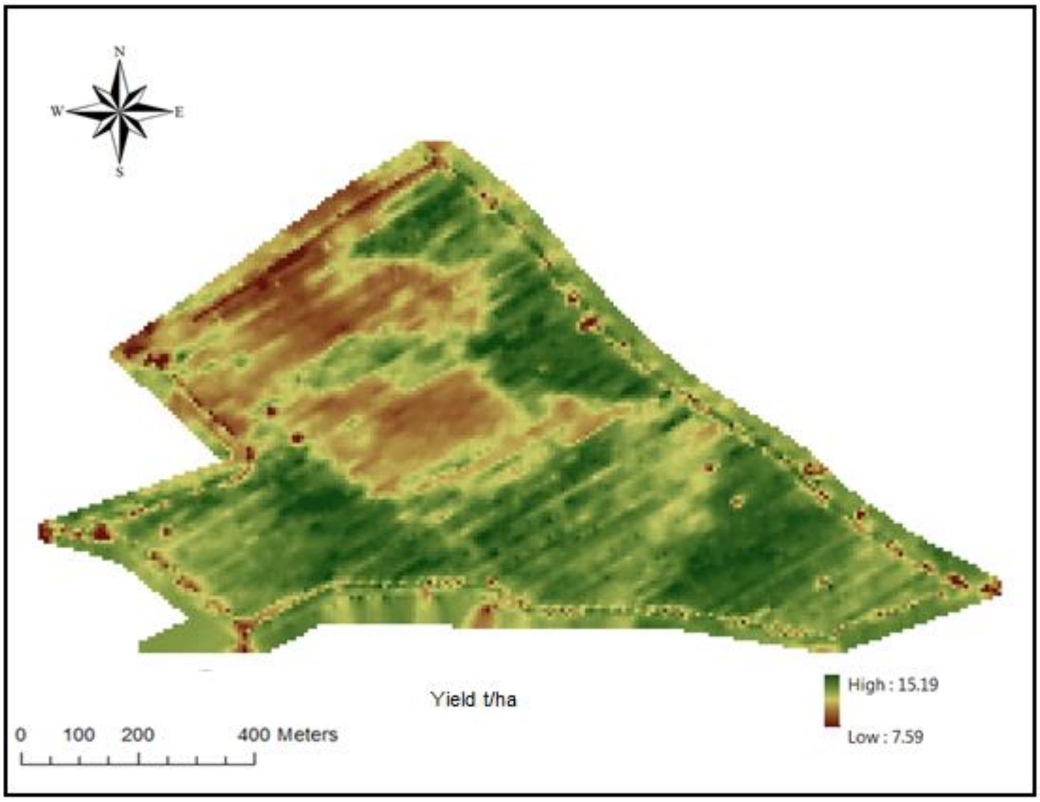


Figure 51. Hamstyles 2014 Yield.

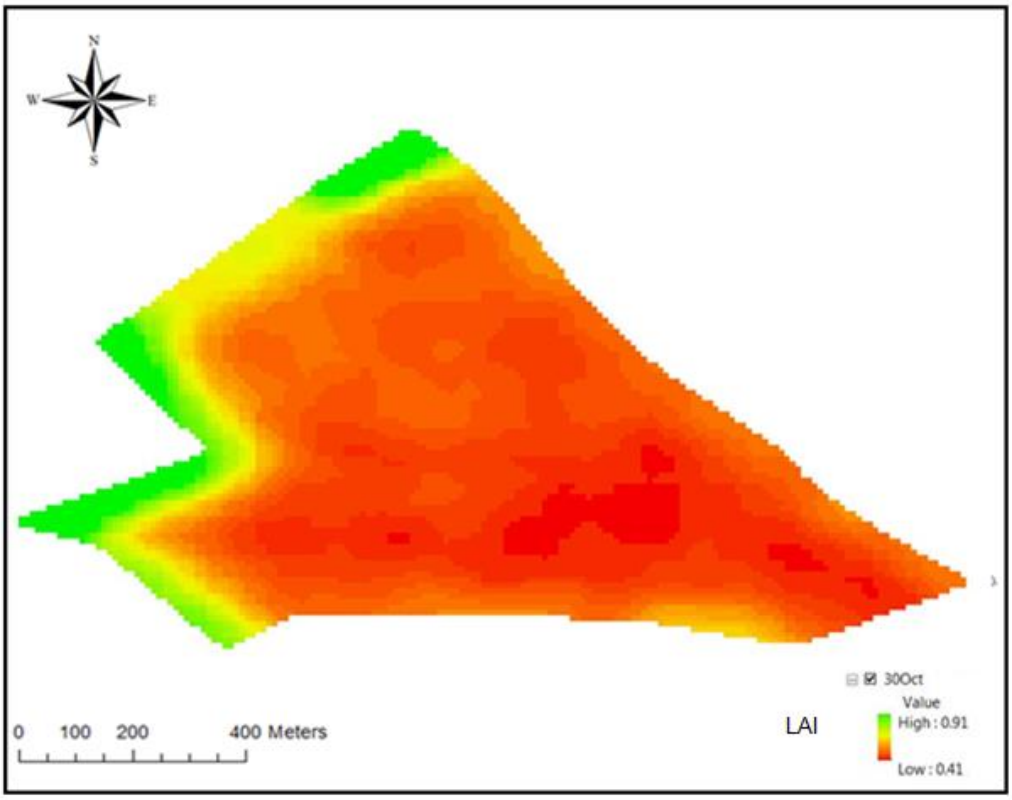


Figure 52. Hamstyles LAI 30/10/13.

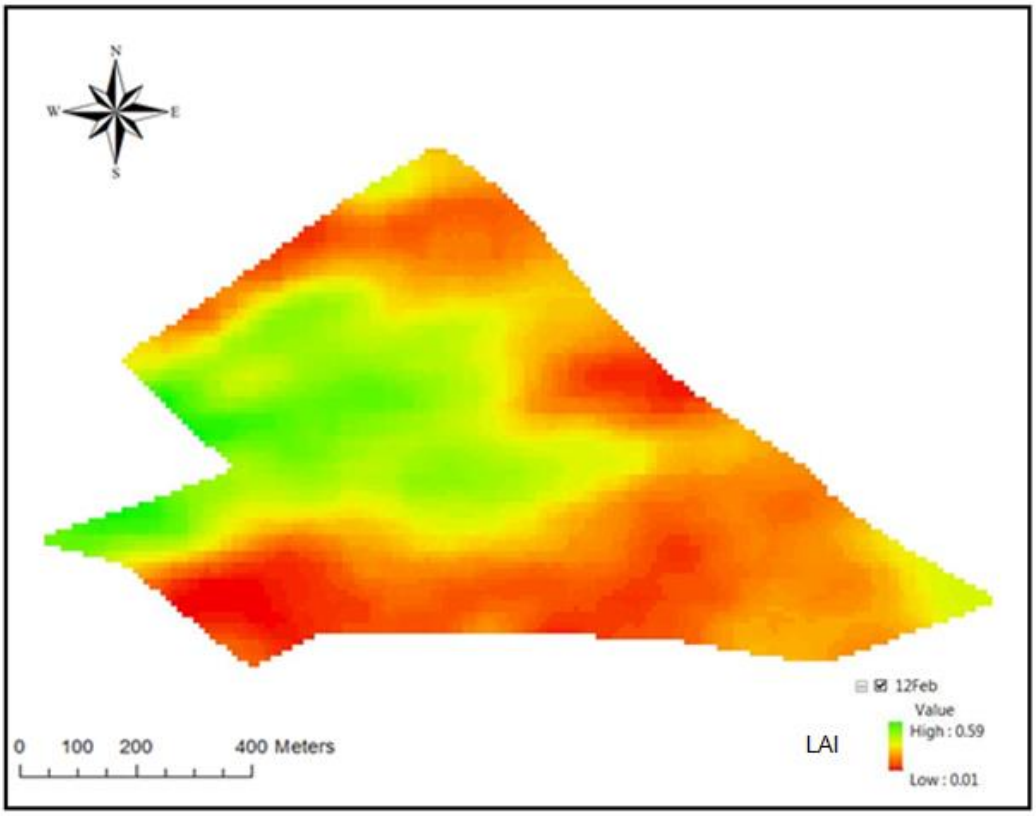


Figure 53. Hamstyles LAI 12/02/14.

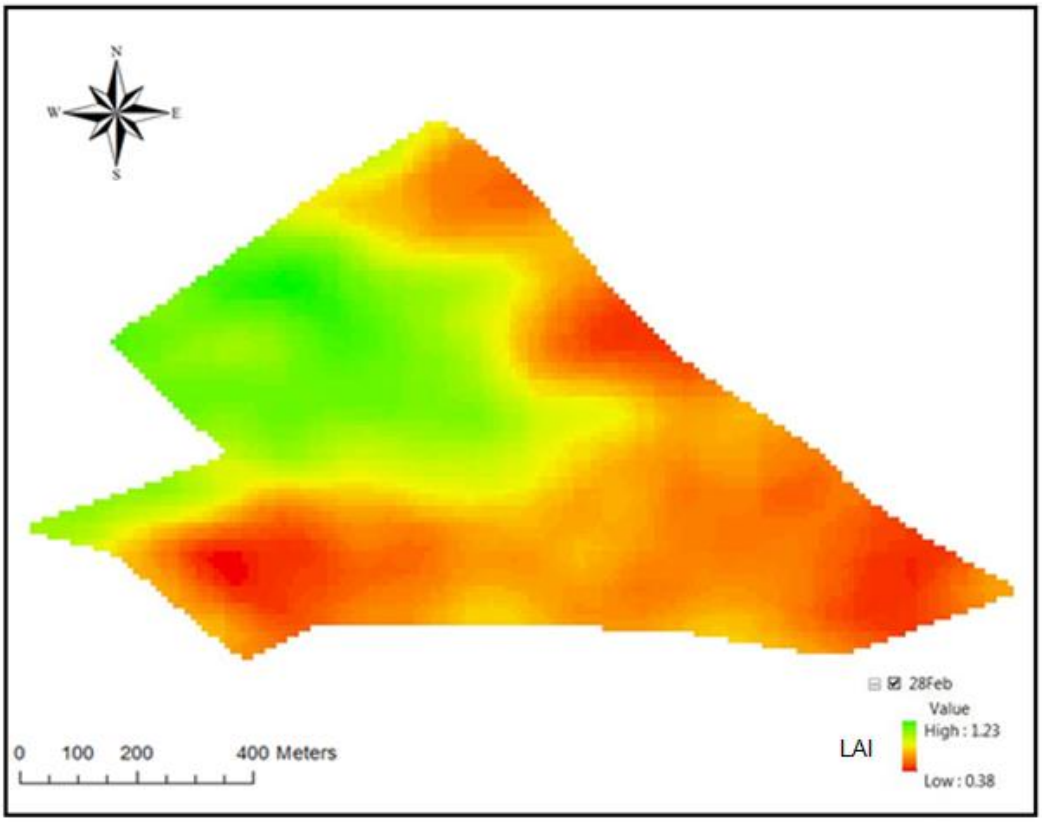


Figure 54. Hamstyles LAI 28/02/14.

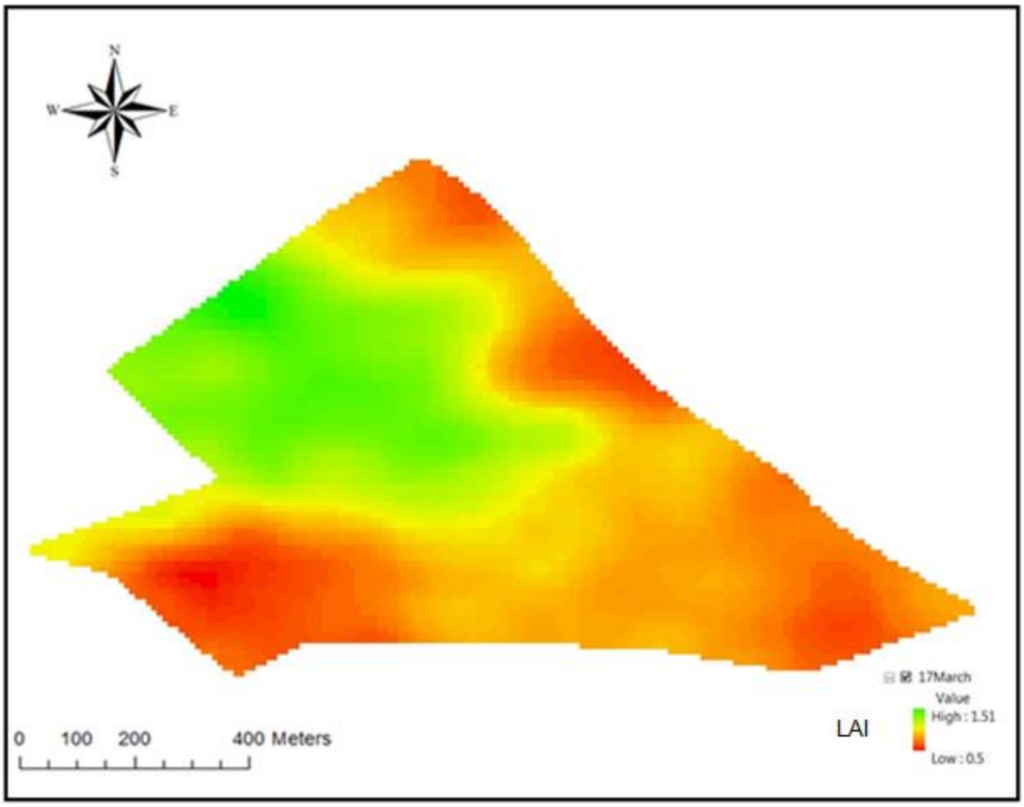


Figure 55. Hamstyles LAI 17/03/14.

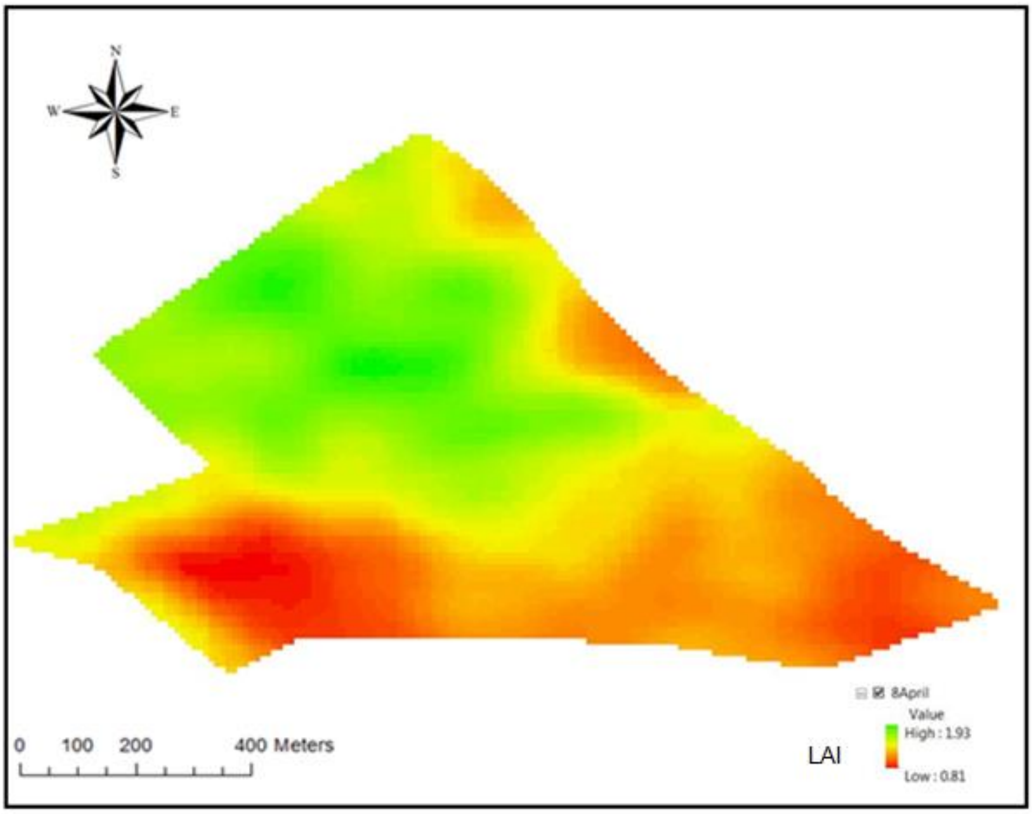


Figure 56. Hamstyles LAI 08/04/14.

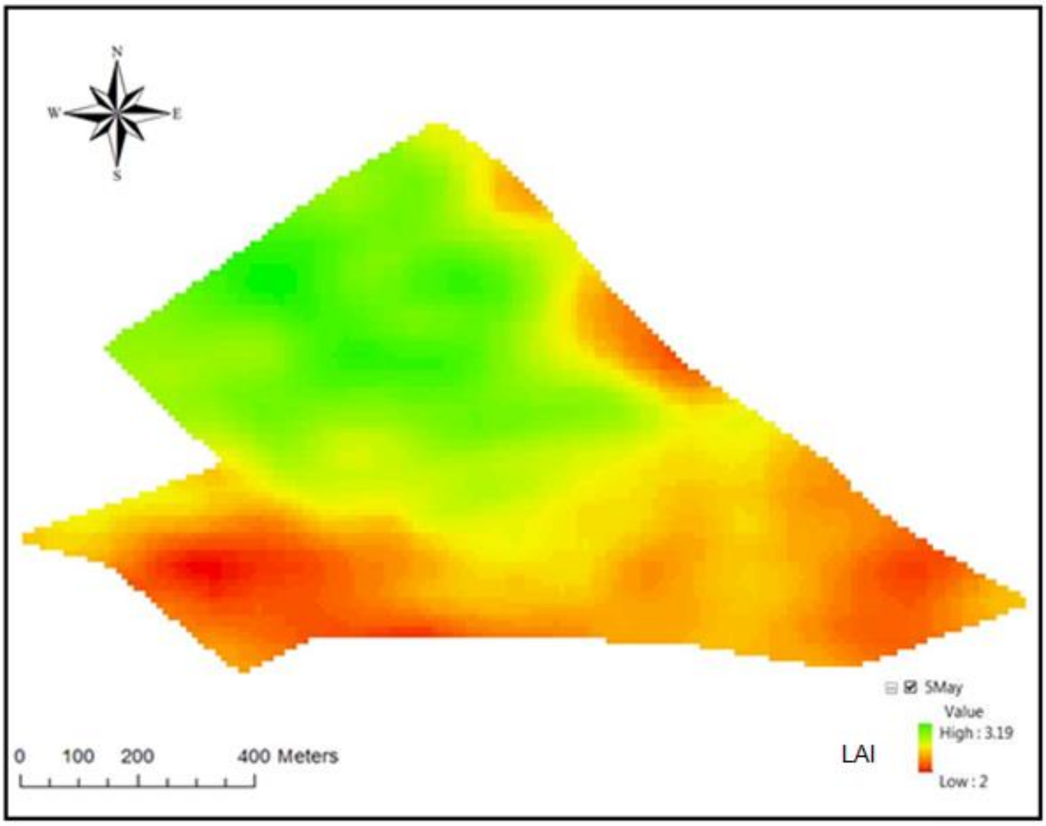


Figure 57. Hamstyles LAI 05/05/14.

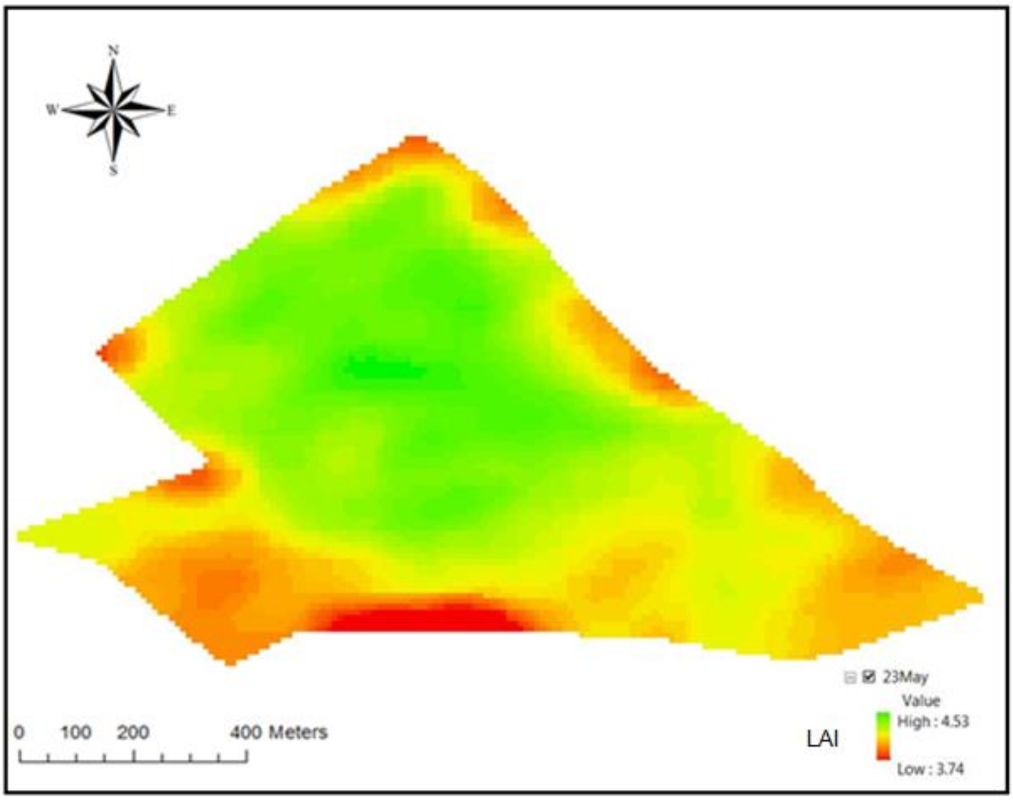


Figure 58. Hamstyles LAI 23/05/14.

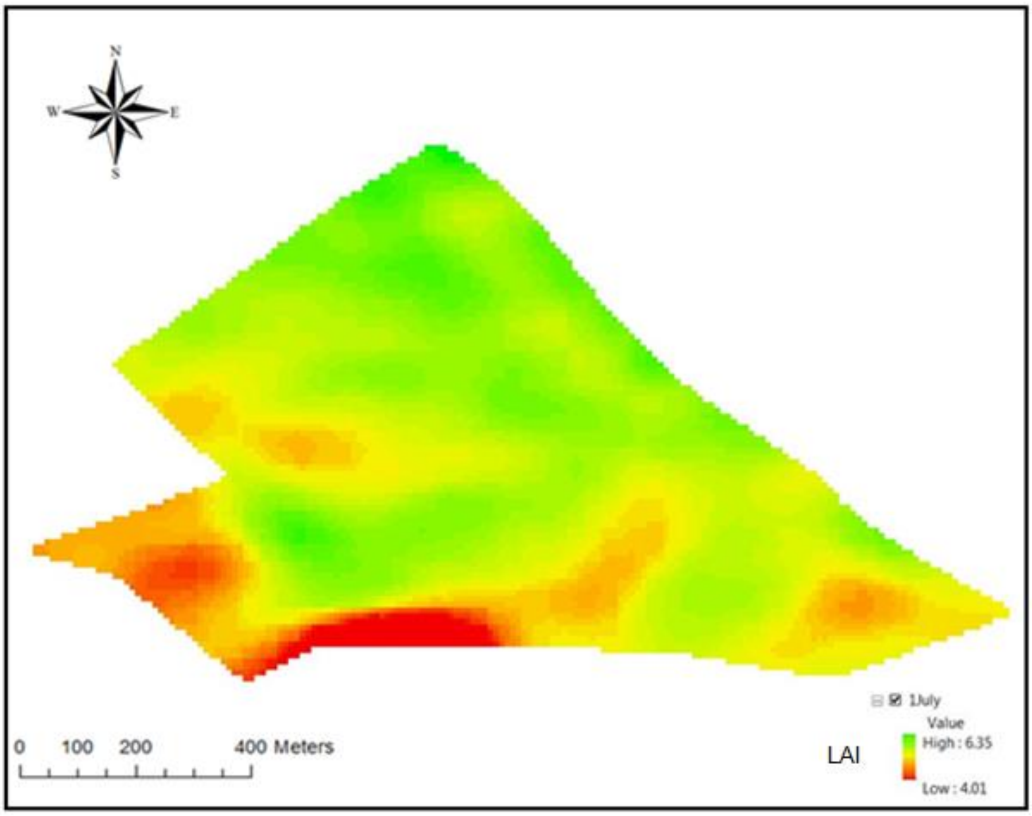
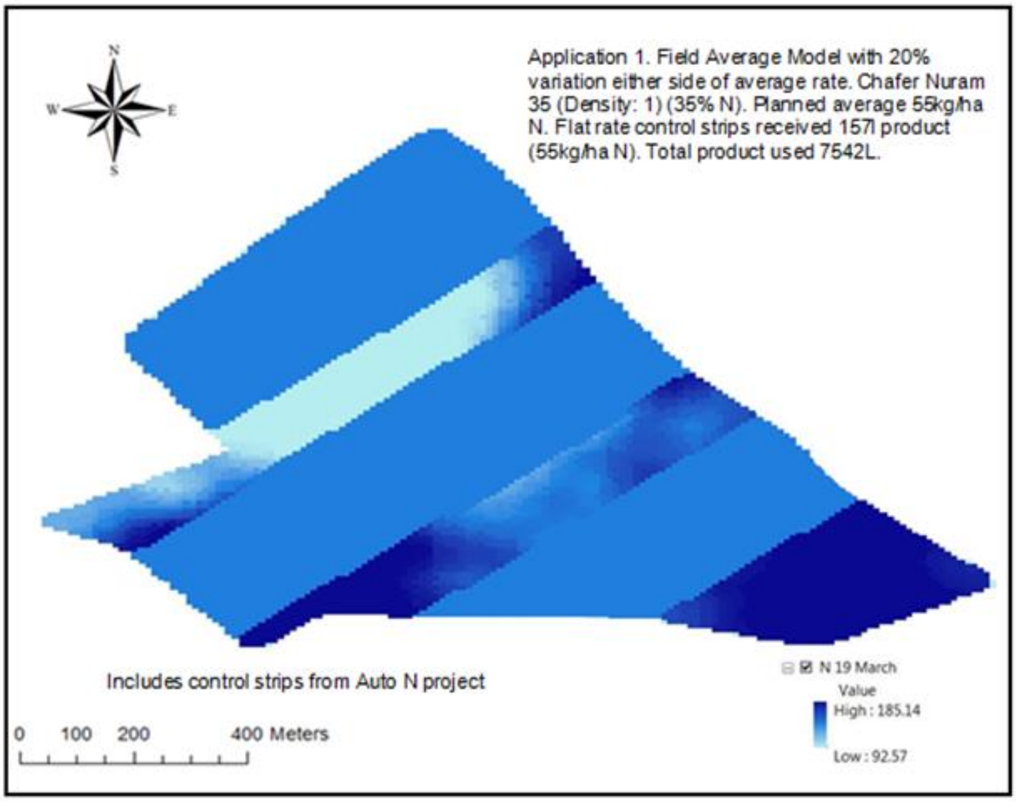
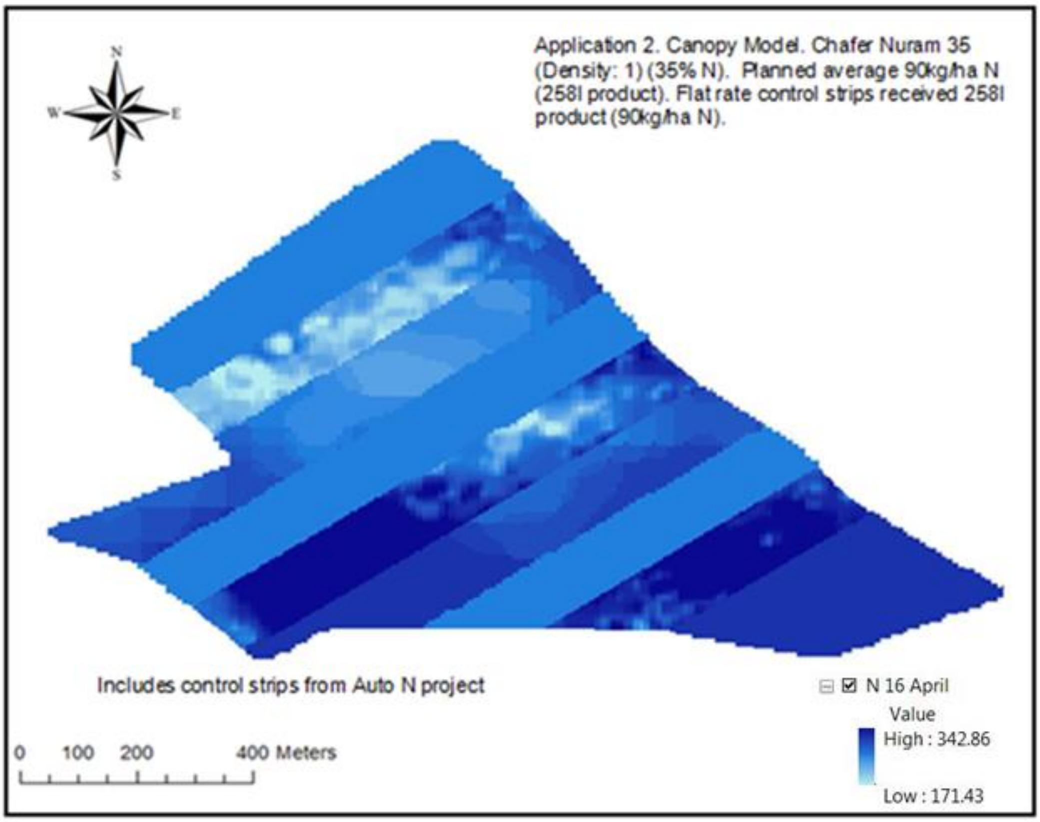


Figure 59. Hamstyles LAI 01/07/14.


Application 1. Field Average Model with 20% variation either side of average rate. Chafer Nuram 35 (Density: 1) (35% N). Planned average 55kg/ha N. Flat rate control strips received 157l product (55kg/ha N). Total product used 7542L.

Includes control strips from Auto N project

Figure 60. Hamstyles N Application 19/03/14.


Application 2. Canopy Model. Chafer Nuram 35 (Density: 1) (35% N). Planned average 90kg/ha N (258l product). Flat rate control strips received 258l product (90kg/ha N).

Includes control strips from Auto N project

Figure 61. Hamstyles N Application 16/04/14.

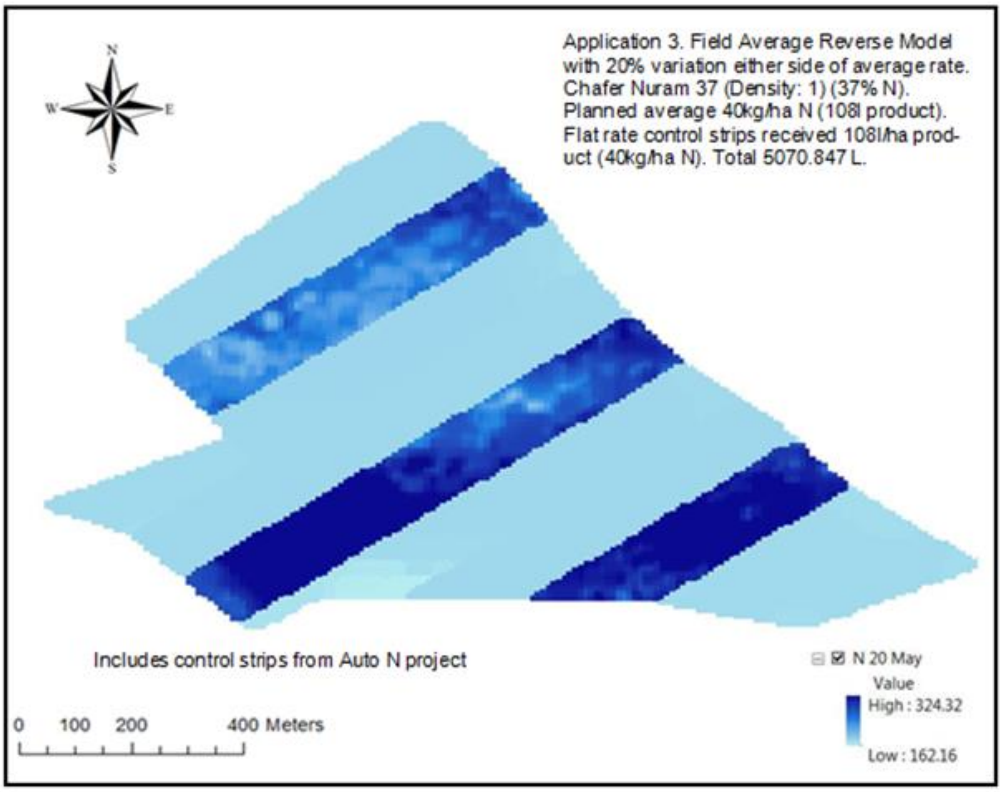


Figure 62. Hamstyles N Application 20/05/14.

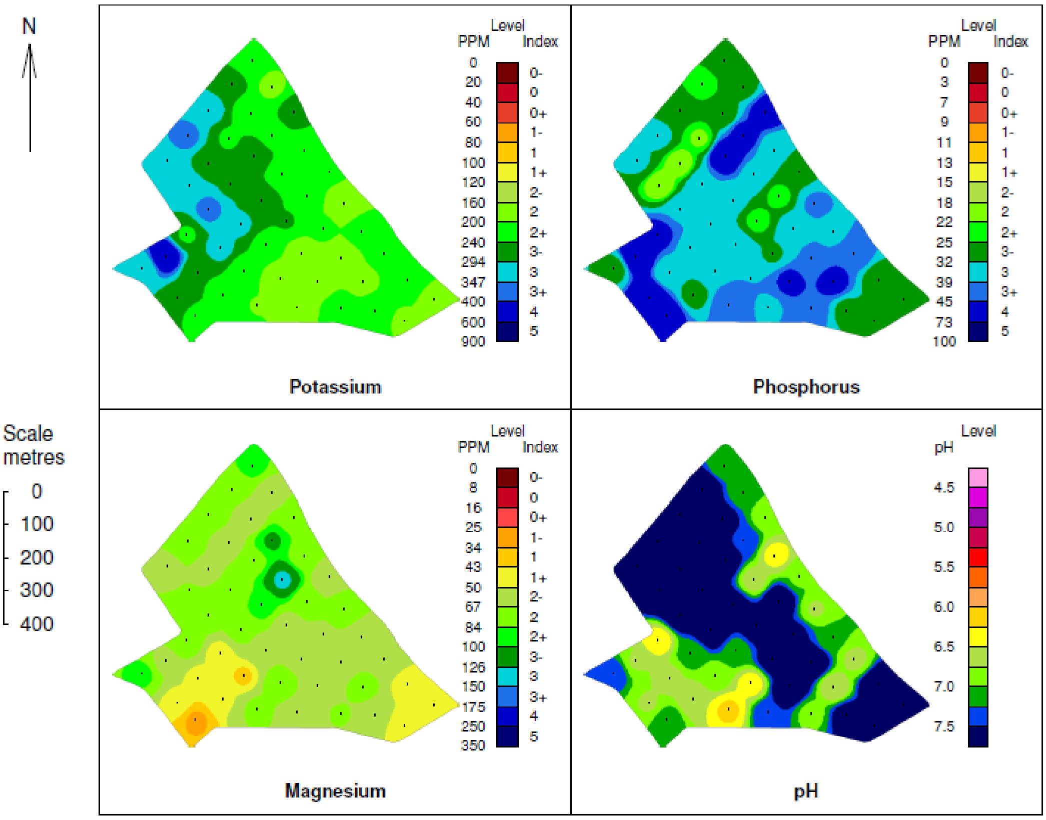


Figure 63. P,K,Mg and pH sampling results for Hamstyles. Sampled 04/10/2011.

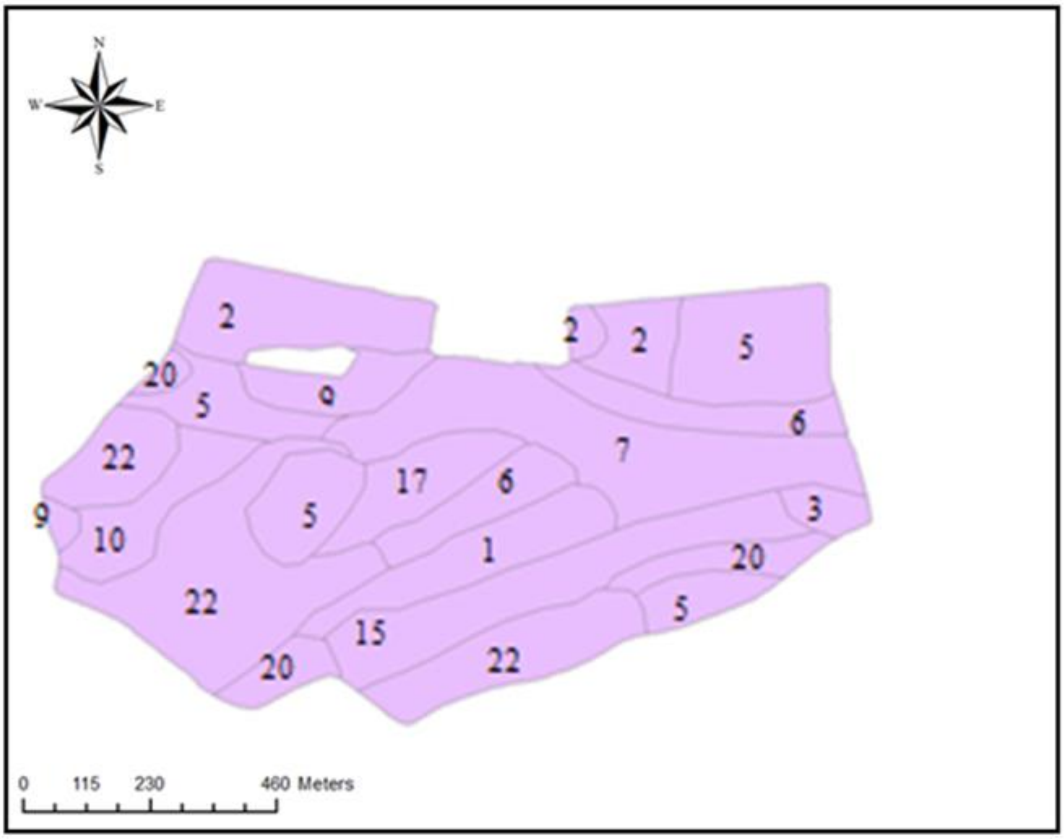


Figure 64. Soil Type for High Street Lane (44.61 ha).

| | Topsoil | Stone Content (Topsoil) | Subsoil |
|---|---|---|---|
| **1** | Sandy Loam | Slight | Loamy Sand below 50cm |
| **2** | Medium Sandy Clay Loam | Very High | Very Stony below 20-25cm |
| **3** | Medium Silty Clay Loam, Chalky | Slight to Moderate | Chalky below 25-35cm |
| **5** | Medium Sandy Clay Loam | Very High | Very Stony below 50cm |
| **6** | Medium Clay Loam (Slightly Chalky) | Moderate | Chalky below 25-35cm |
| **9** | Medium Heavy Sandy Clay Loam | High | Very Stony below 30-50cm |
| **10** | Medium Heavy Sandy Clay Loam | Slight | Medium Heavy Sandy Clay Loam to depth |
| **15** | Heavy Silty Clay Loam | Moderate | Chalky below 30-50cm |
| **17** | Heavy Sandy Clay Loam | Moderate | Sandy Clay below 30cm |
| **20** | Heavy Sandy Clay Loam | Very High | Sandy Clay below 30-35cm, very stony below 70cm |
| **22** | Sandy Clay | Moderate | Loamy Clay below 30-35cm |

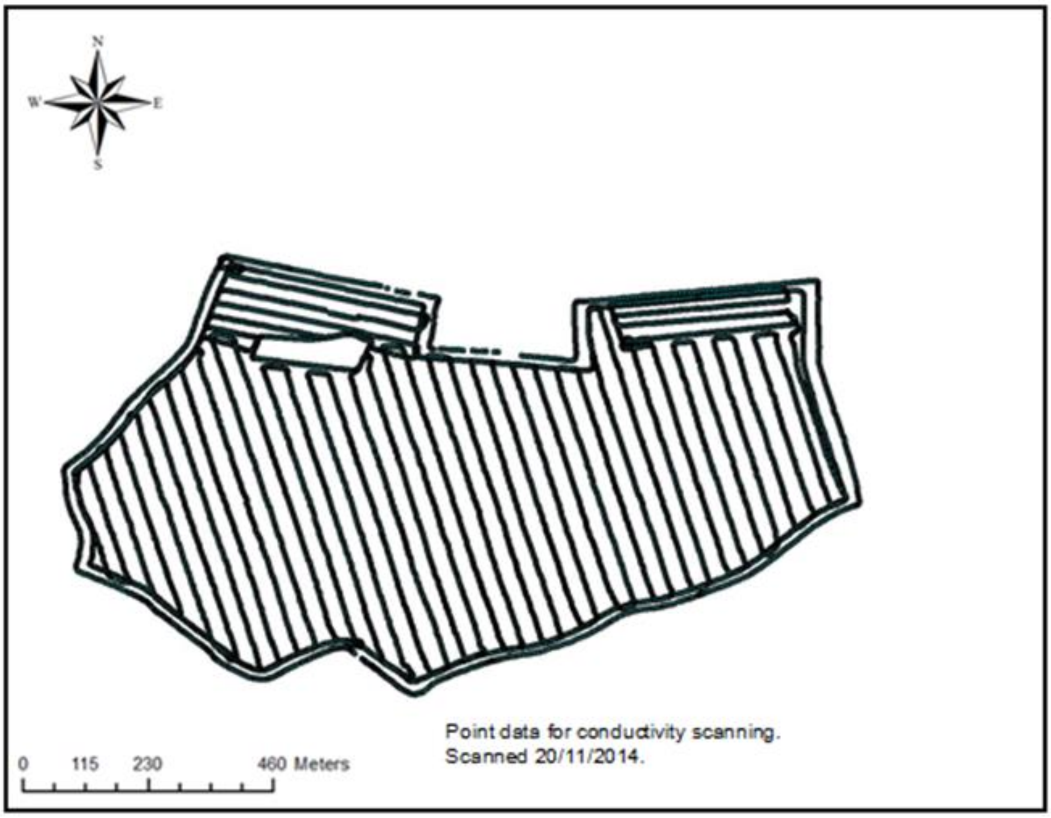


Figure 65. EC Point location for High Street Lane.

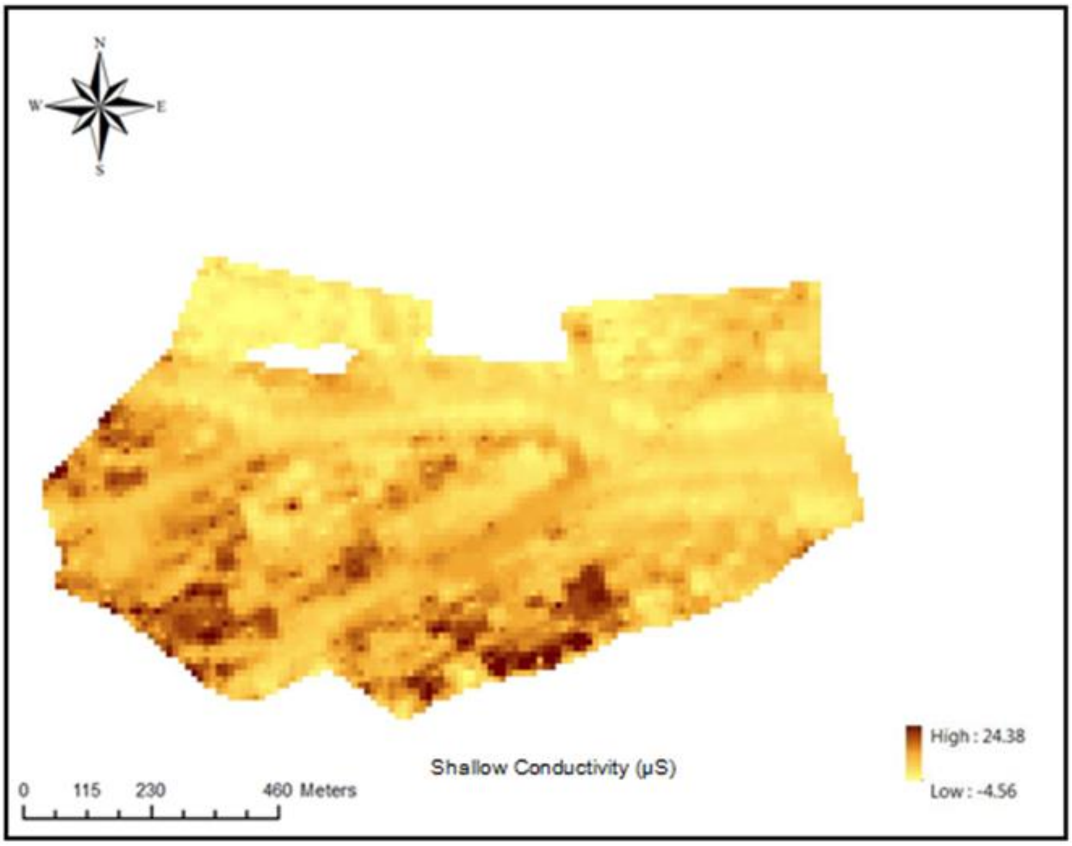


Figure 66. Shallow EC for High Street Lane.

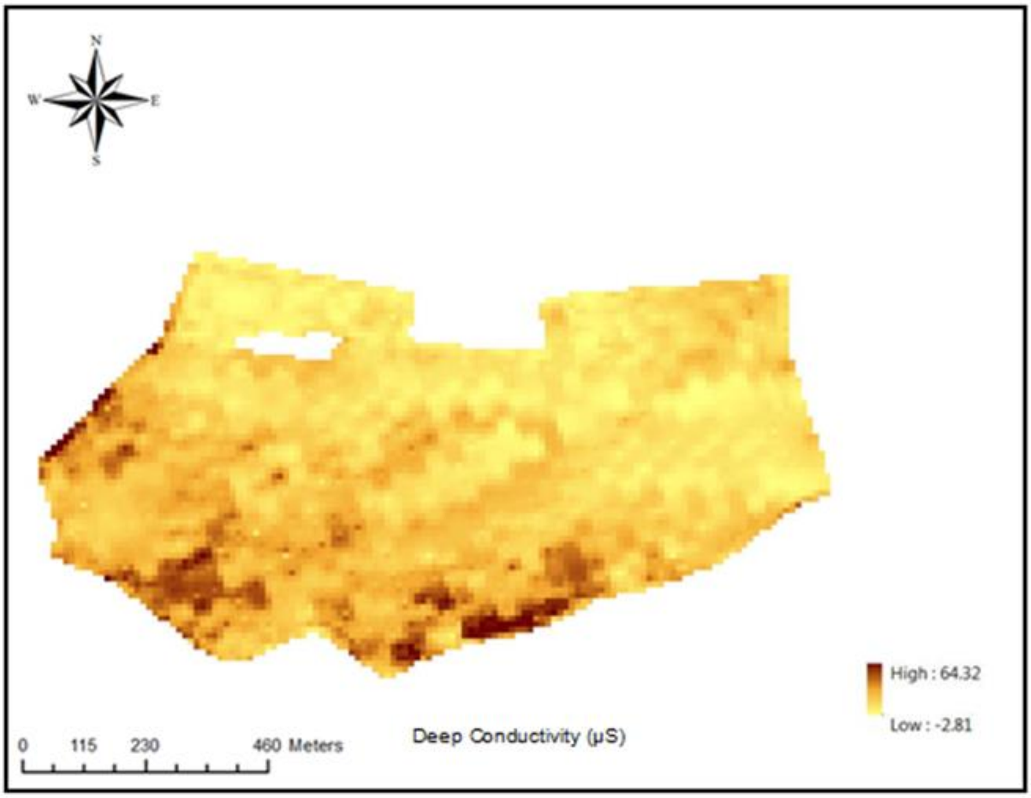


Figure 67. Deep EC for High Street Lane.

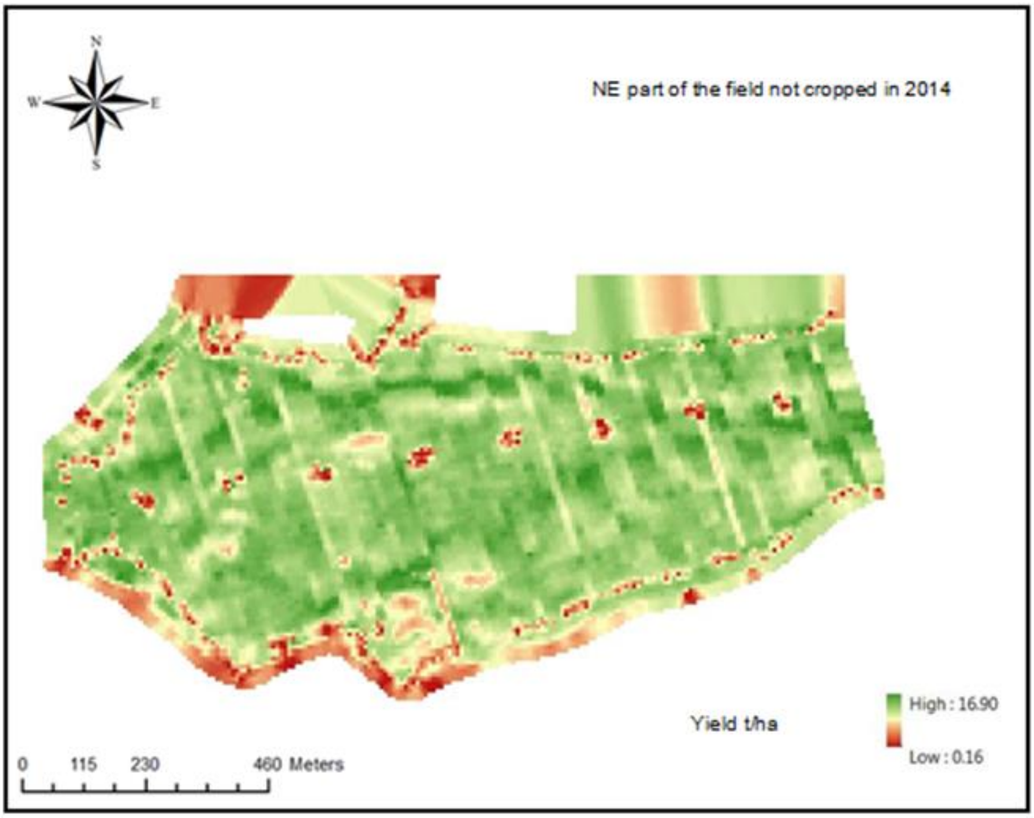


Figure 68. High Street Lane 2014 Yield.

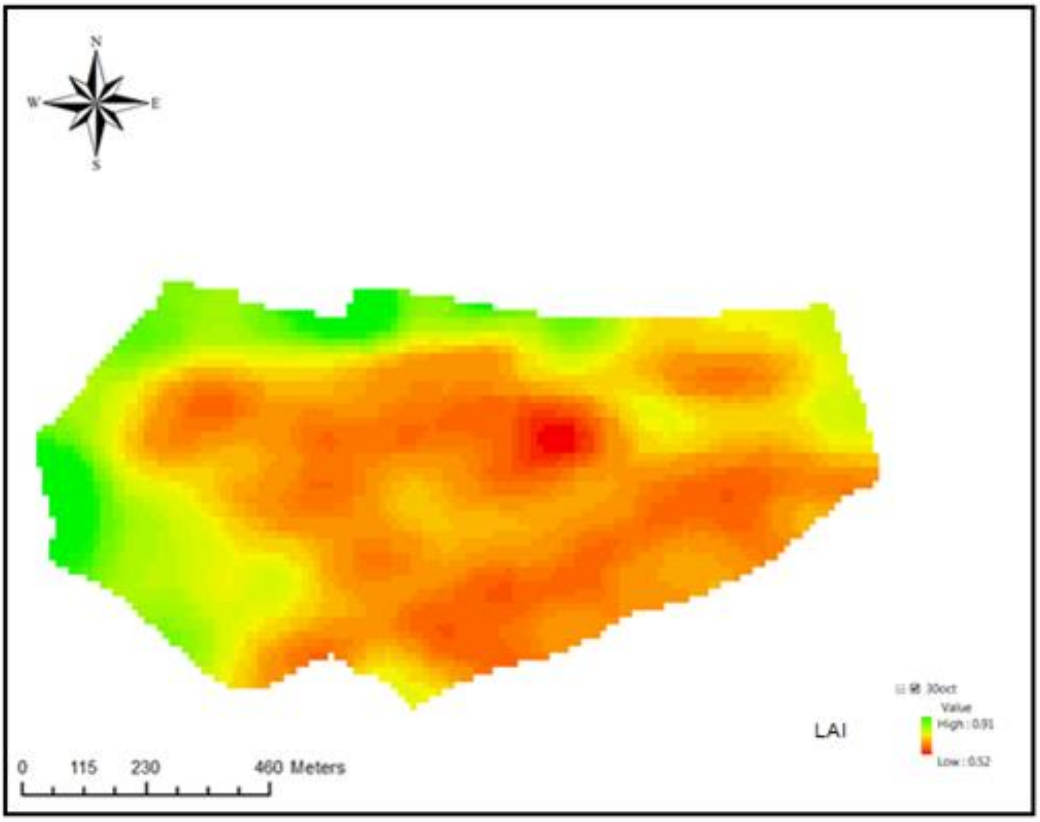


Figure 69. High Street Lane LAI 30/10/13.

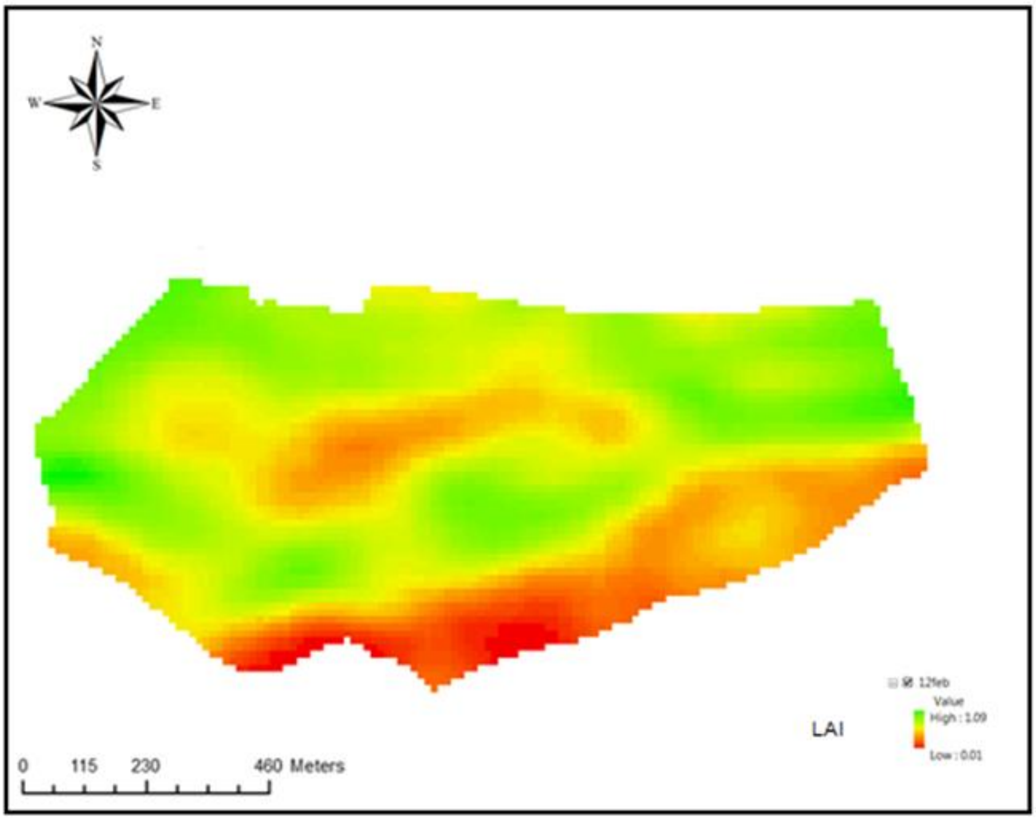


Figure 70. High Street Lane LAI 12/02/14.

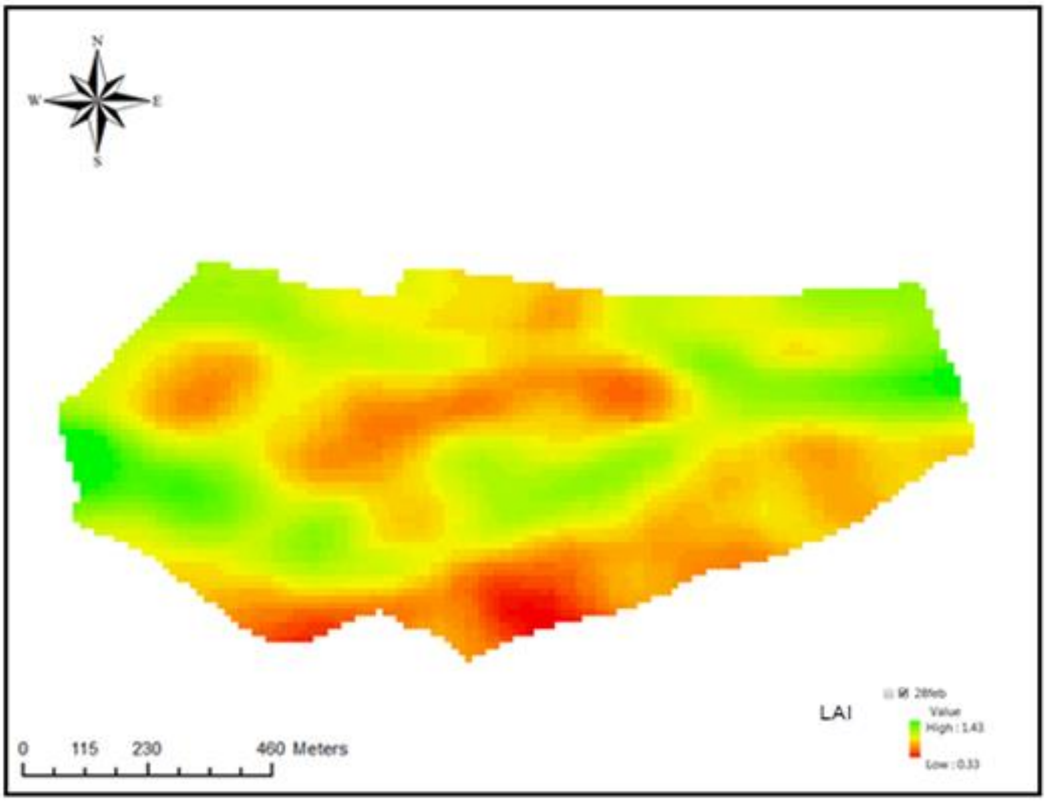


Figure 71. High Street Lane LAI 28/02/14.

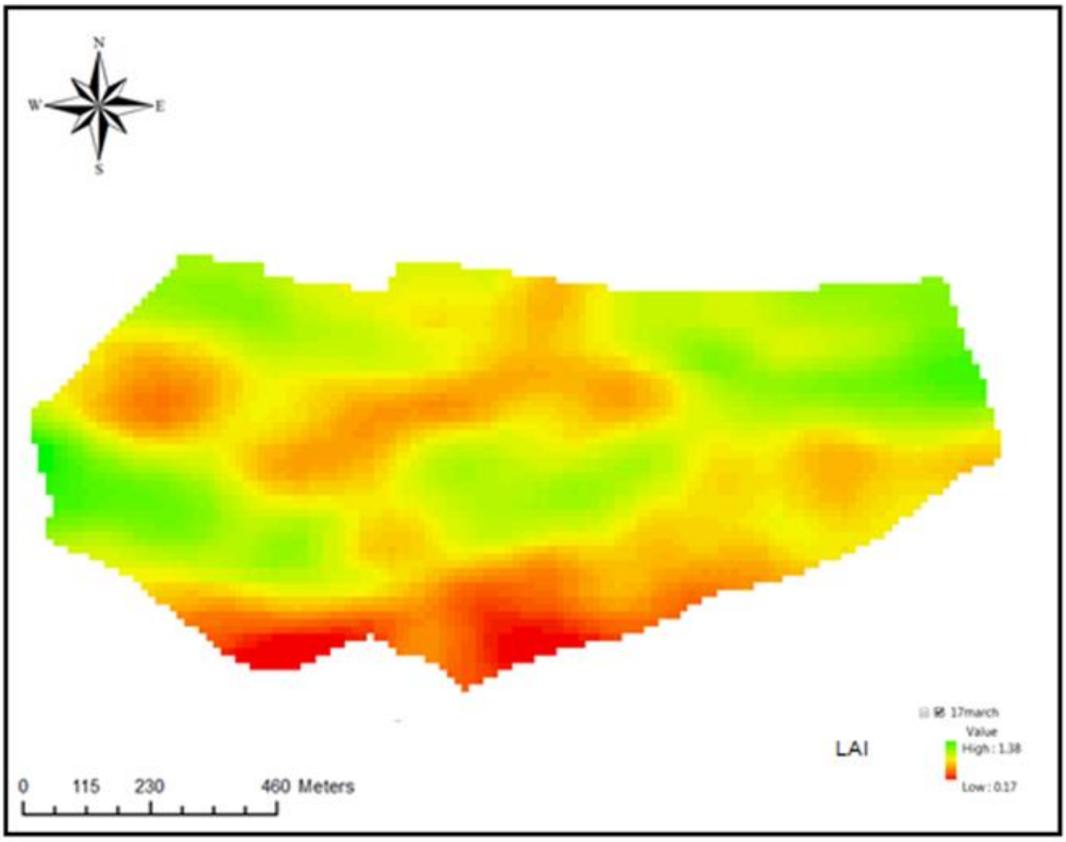


Figure 72. High Street Lane LAI 12/03/14.

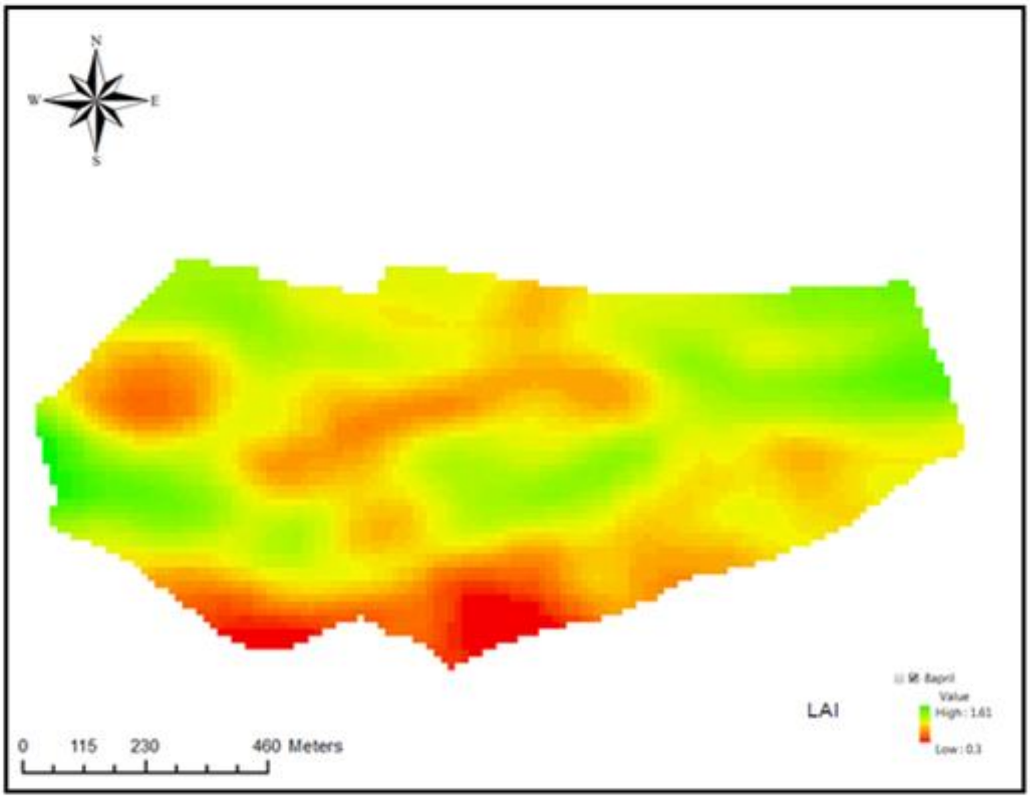


Figure 73. High Street Lane LAI 08/04/14.

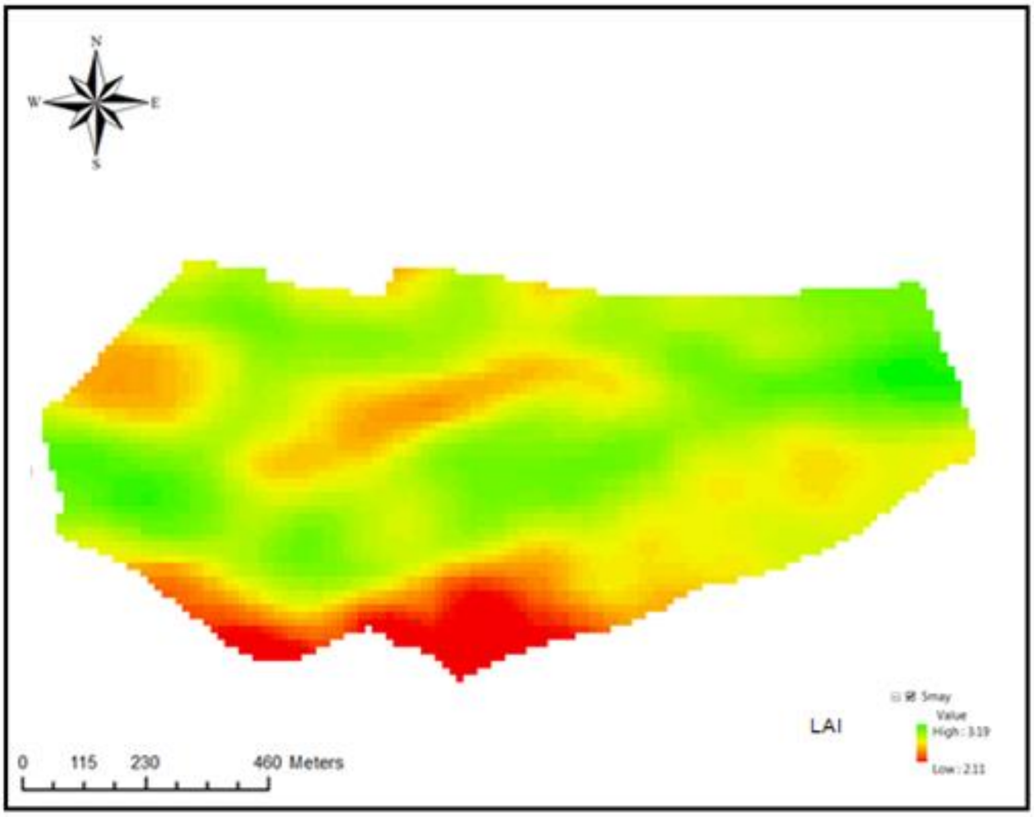


Figure 74. High Street Lane LAI 05/05/14.

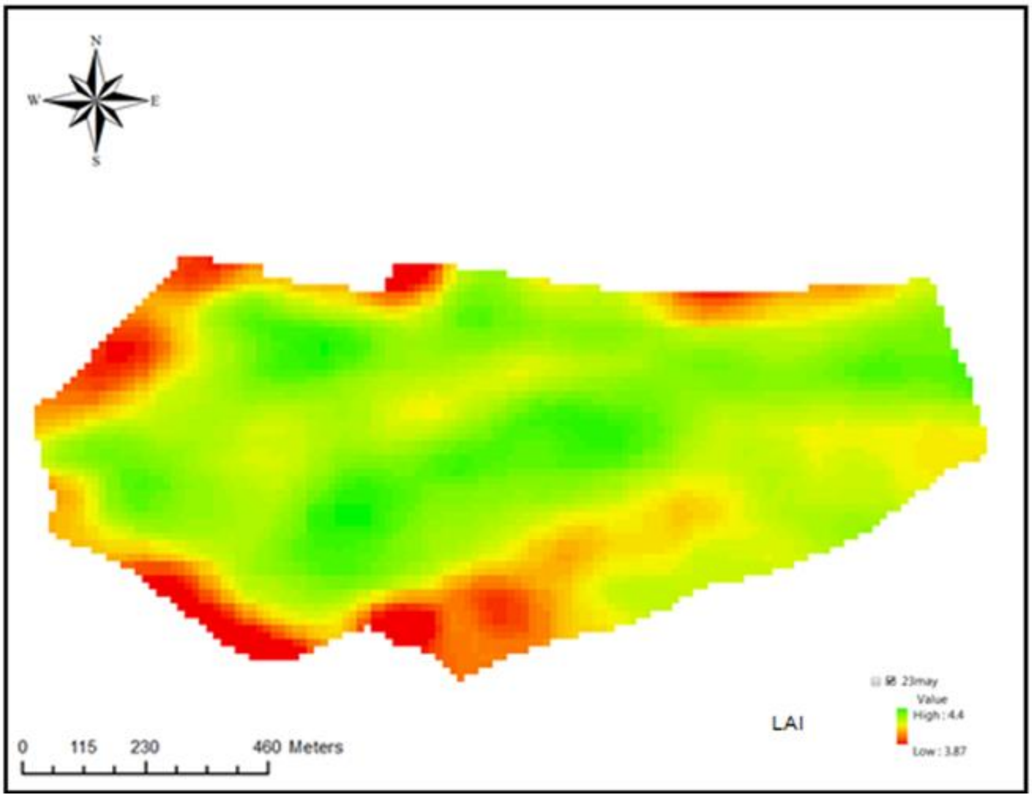


Figure 75. High Street Lane LAI 23/05/14.

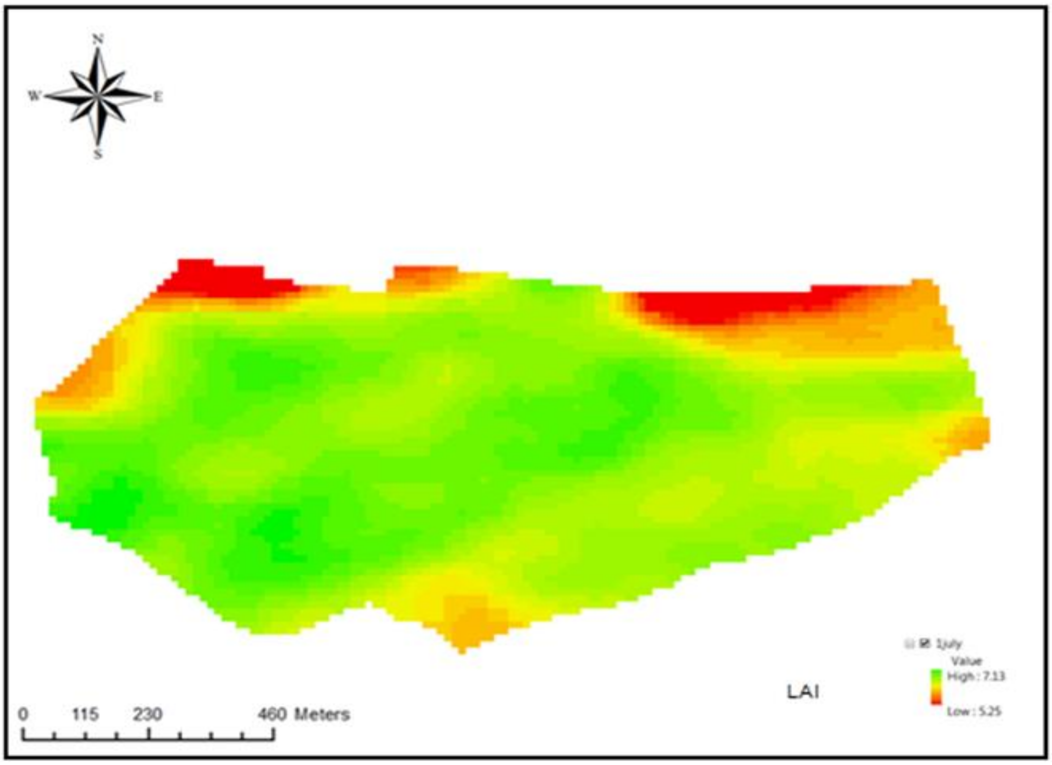


Figure 76. High Street Lane LAI 01/07/14.

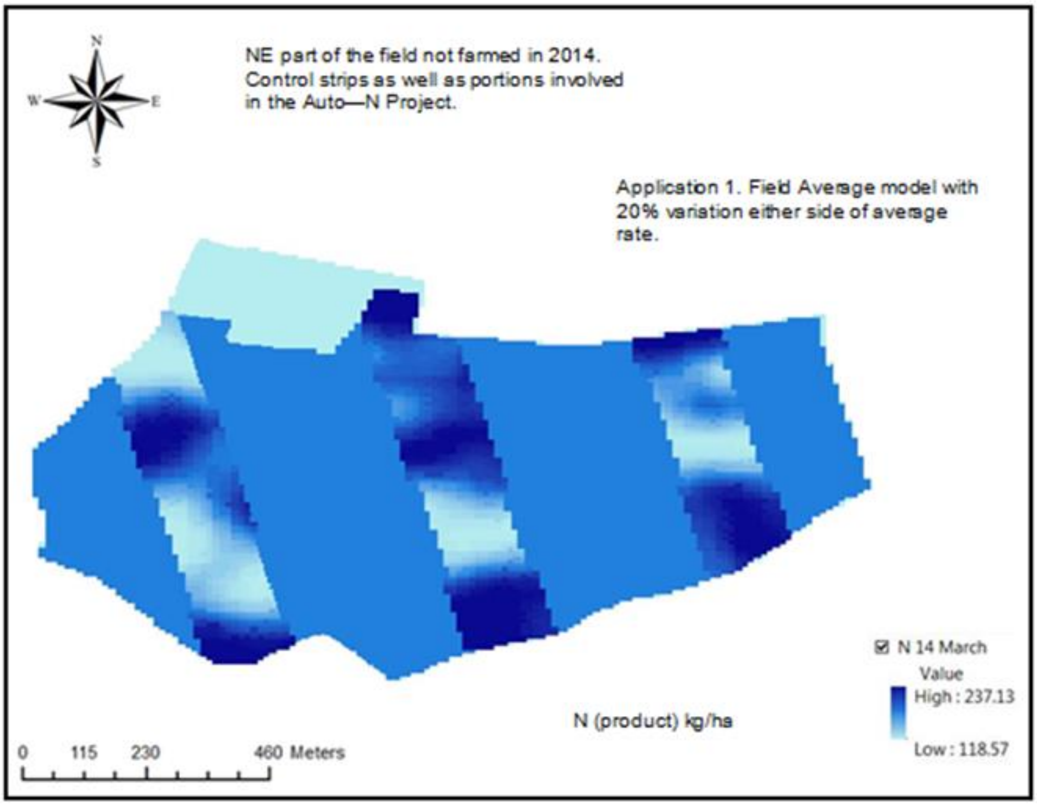


Figure 77. High Street Lane N Application 14/03/14.

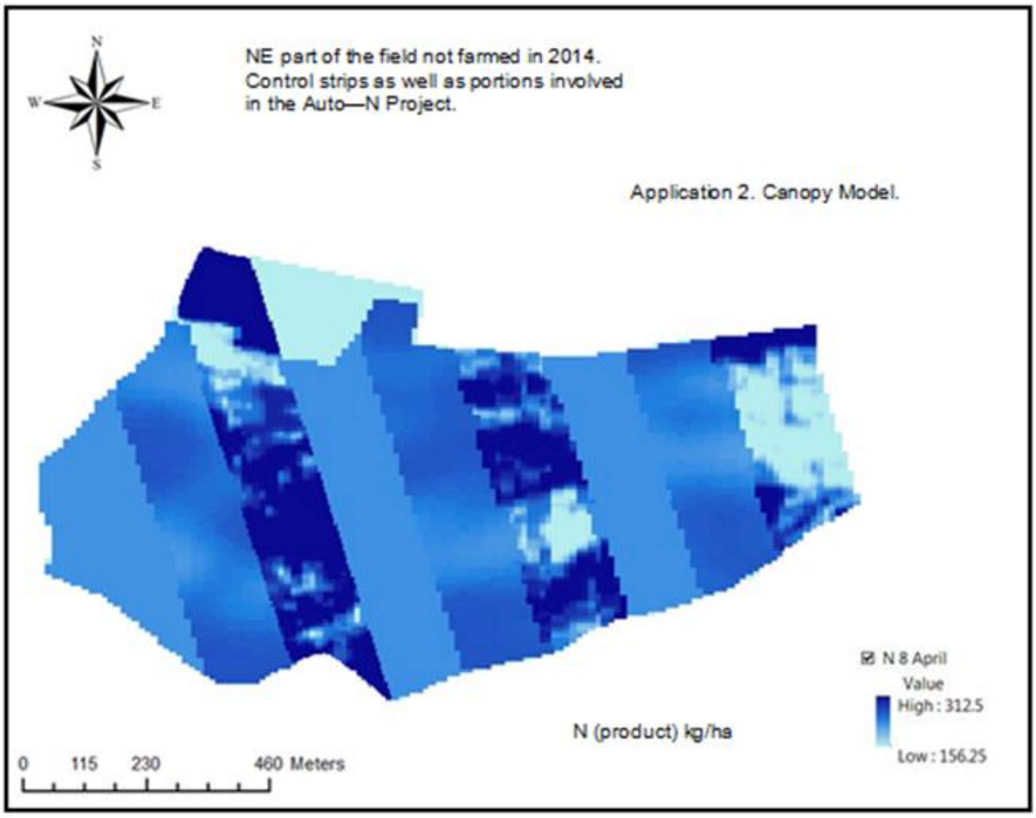


Figure 78. High Street Lane N Application 08/04/14.

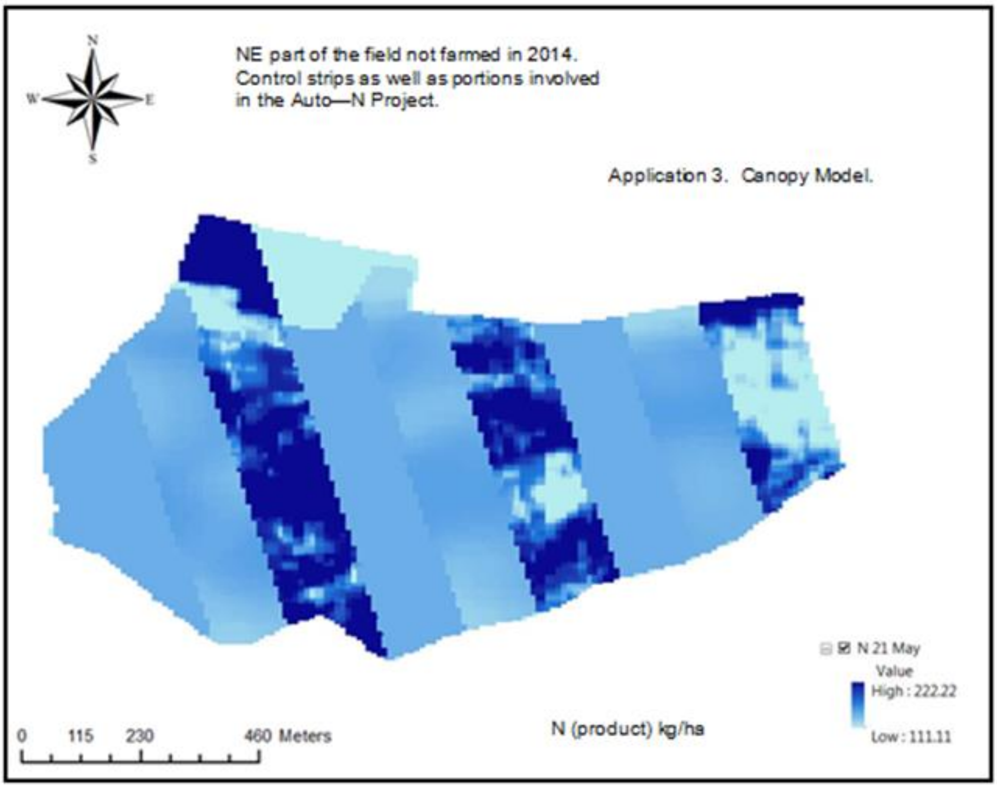


Figure 79. High Street Lane N Application 21/05/14.

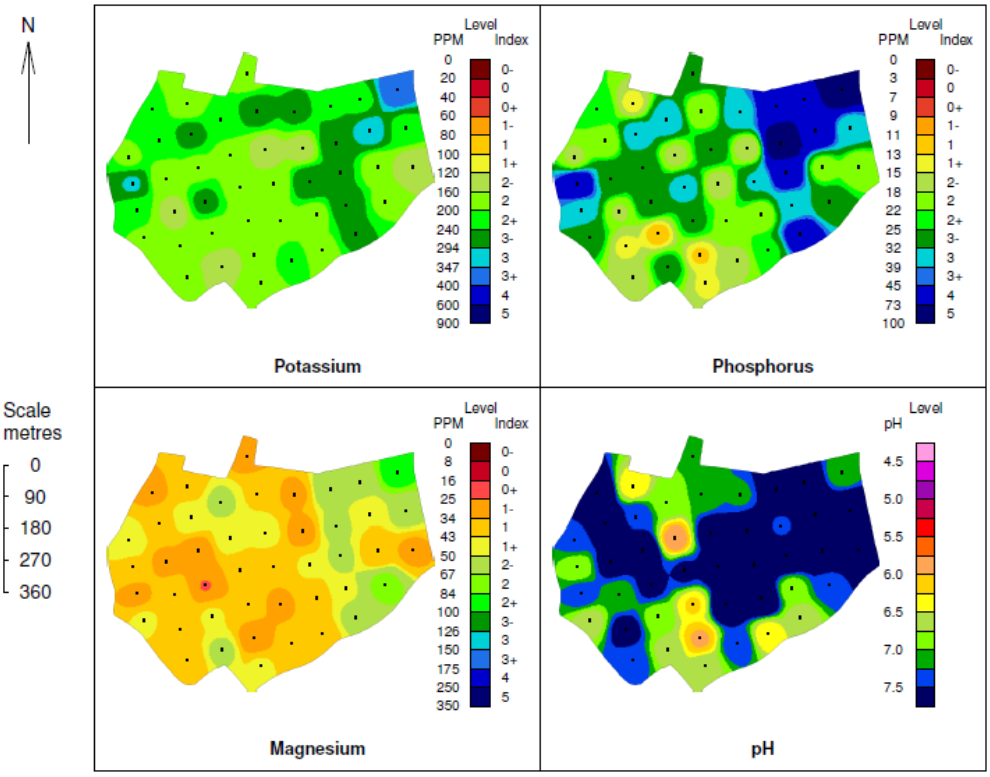


Figure 80. P, K ,Mg and pH sampling results for High Street Lane. Sampled 18/08/2013.

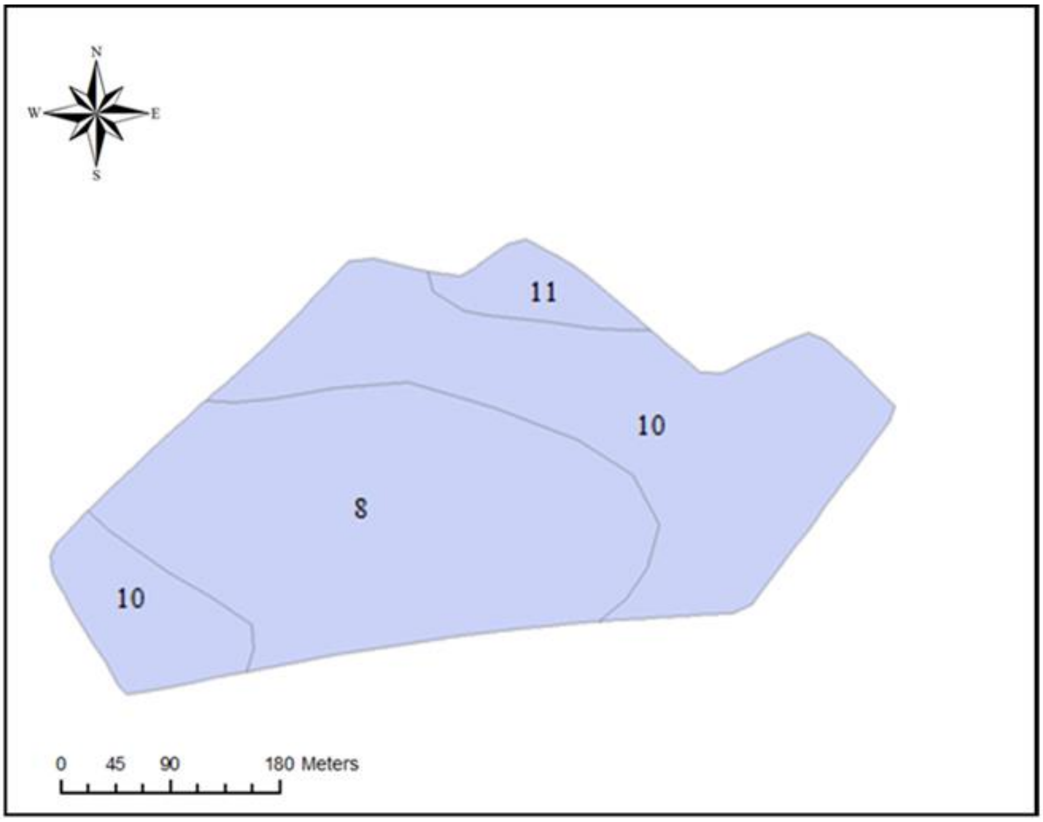


Figure 81. Soil Type for Home Farm (10.14 ha).

| | Topsoil | Stone Content (Topsoil) | Subsoil |
|---|---|---|---|
| **8** | Medium Clay Loam | Moderate | Very Stony |
| **10** | Medium Heavy Sandy Clay Loam | Slight | Medium Heavy Sandy Clay Loam |
| **11** | Medium Heavy Silty Clay Loam | Moderate | Moderately Stony |

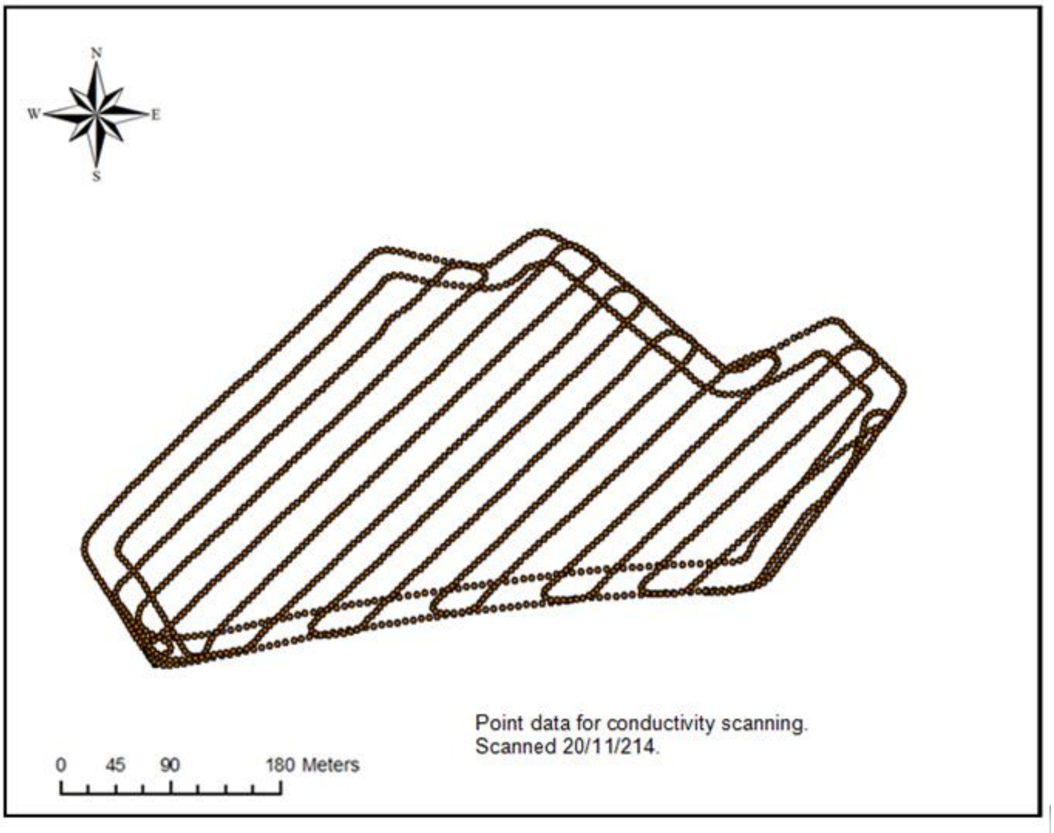


Figure 82. EC Point location for Home Farm.

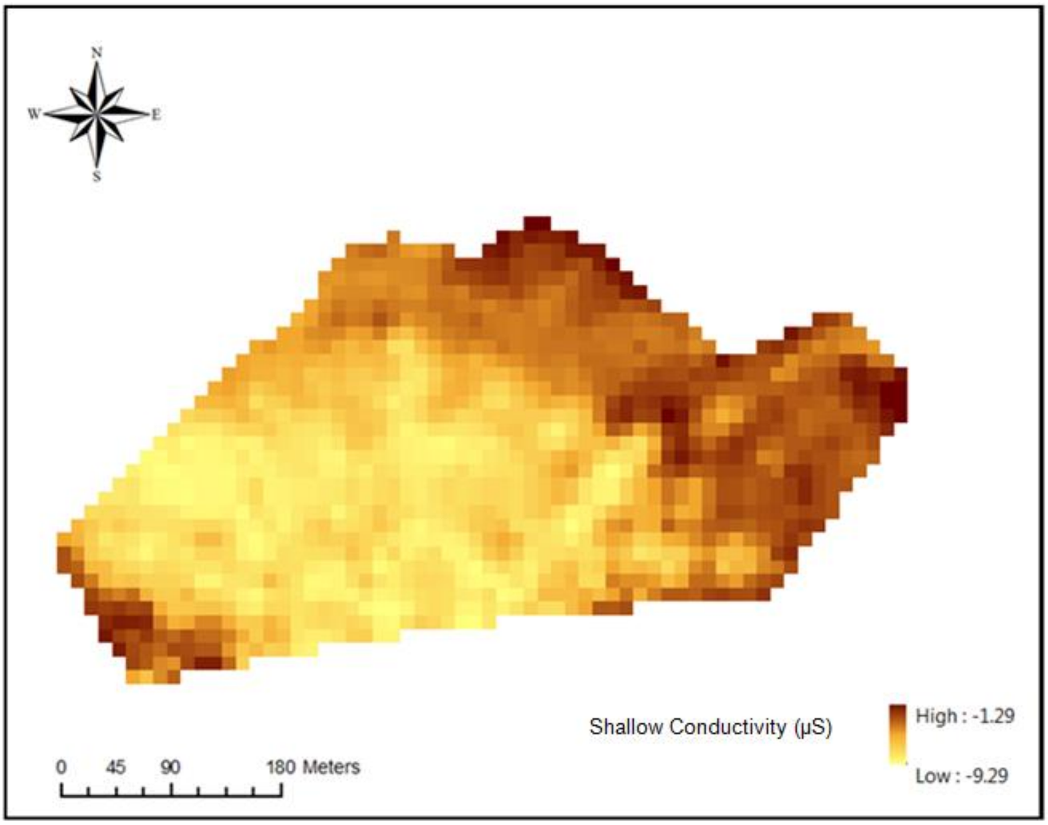


Figure 83. Shallow EC for Home Farm.

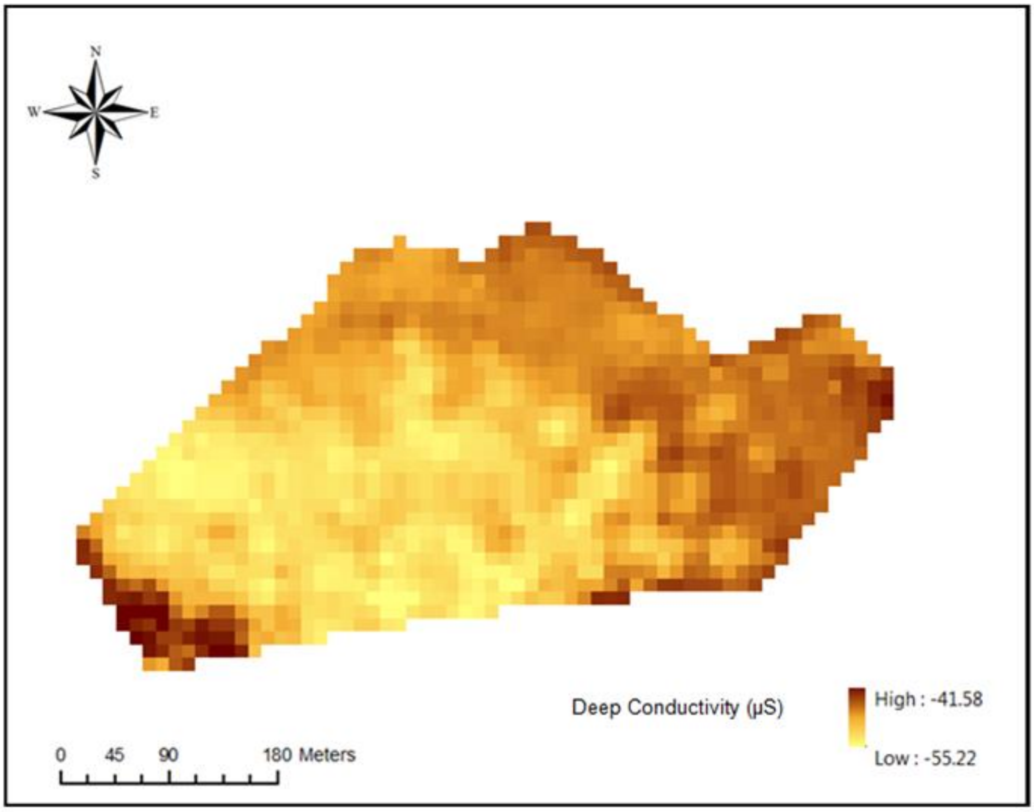


Figure 84. Deep EC for Home Farm.

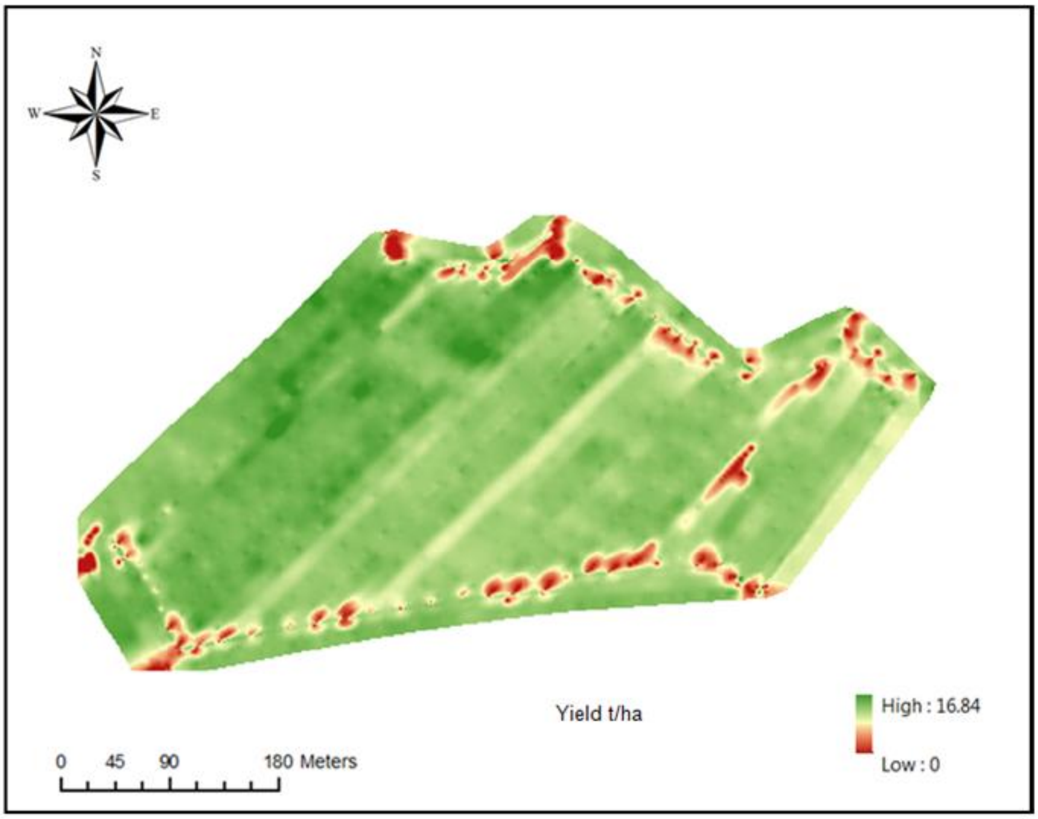


Figure 85. Home Farm Yield 2014.

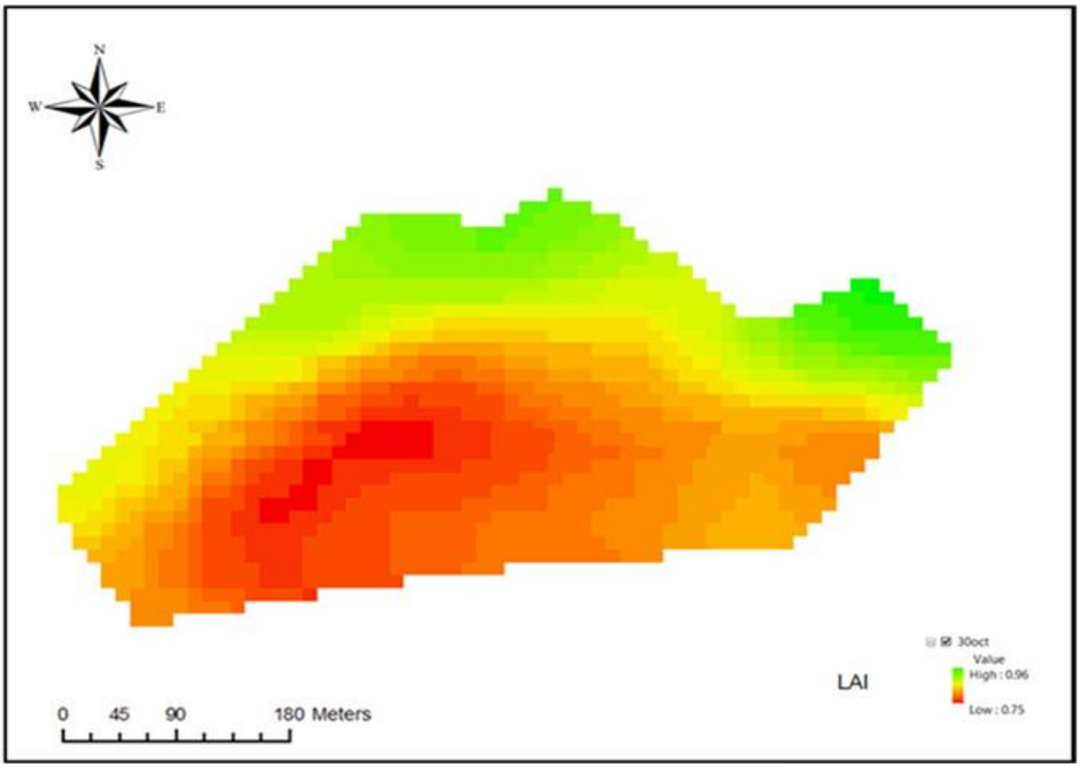


Figure 86. Home Farm LAI 30/10/13.

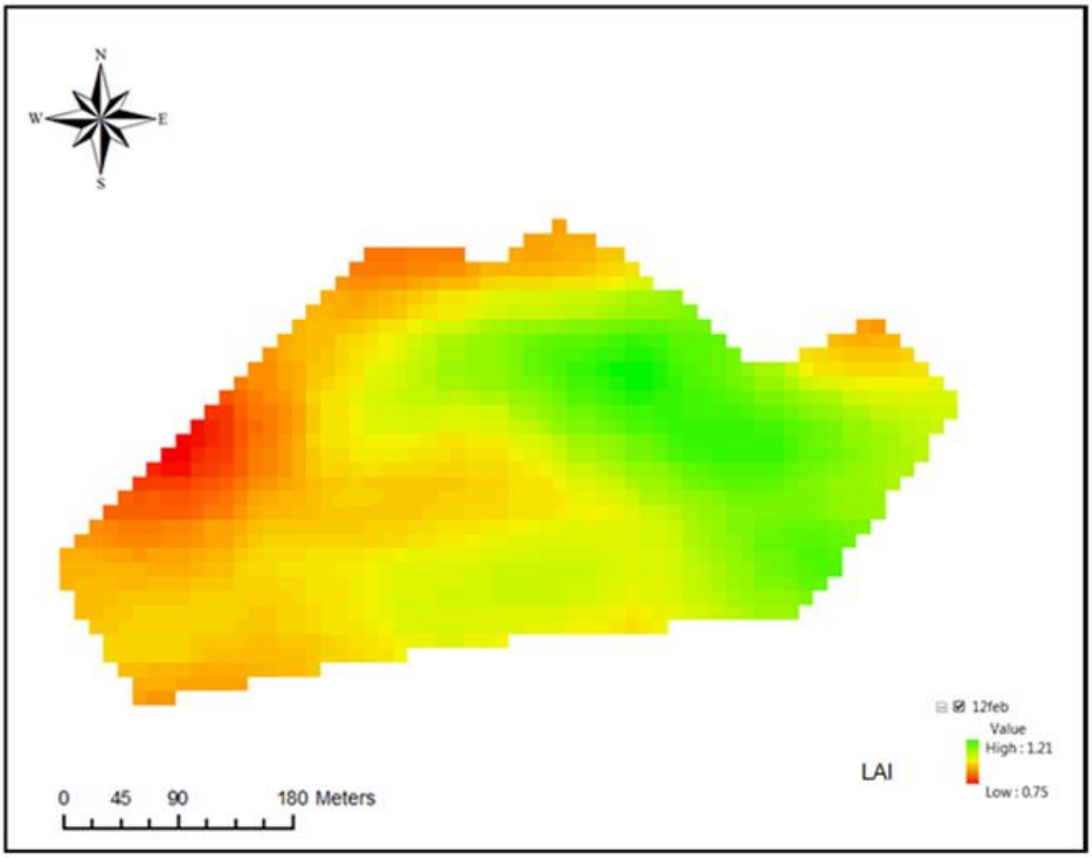


Figure 87. Home Farm LAI 12/02/14.

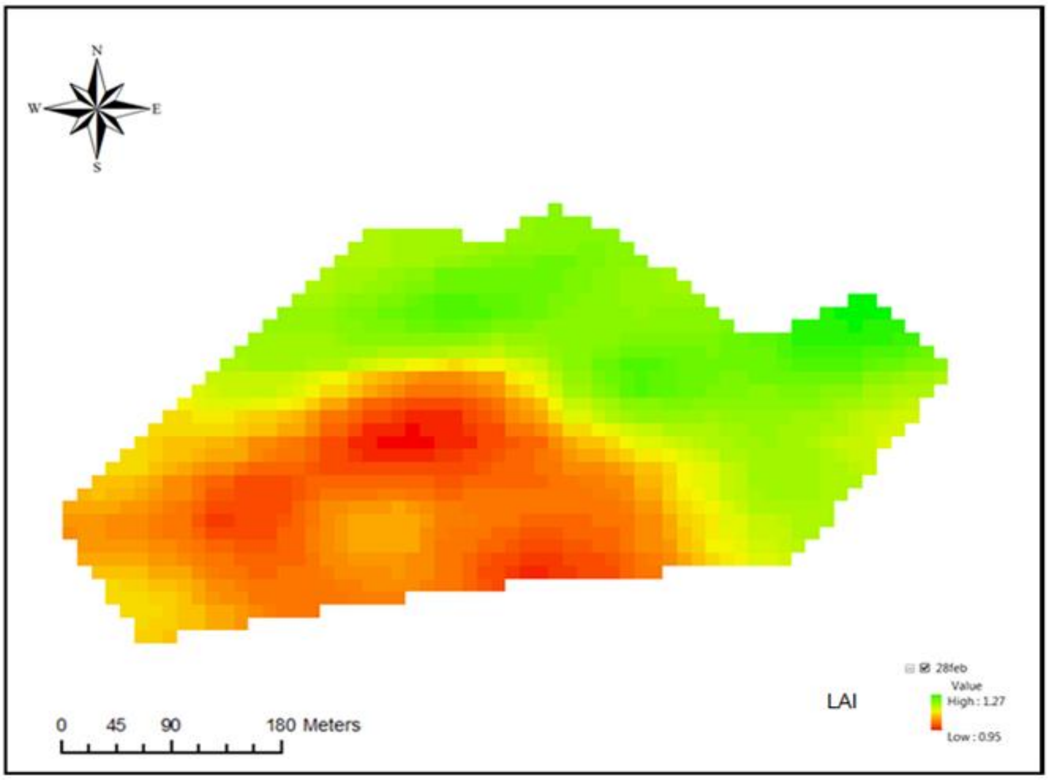


Figure 88. Home Farm LAI 28/02/14.

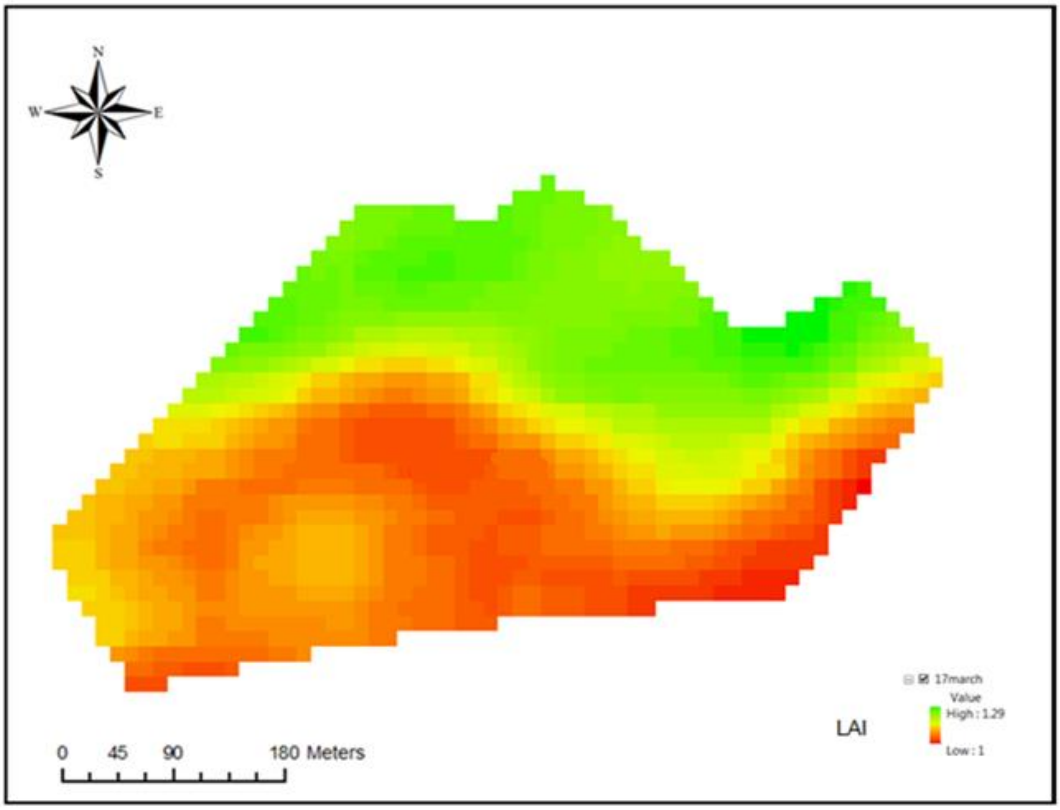


Figure 89. Home Farm LAI 17/03/14.

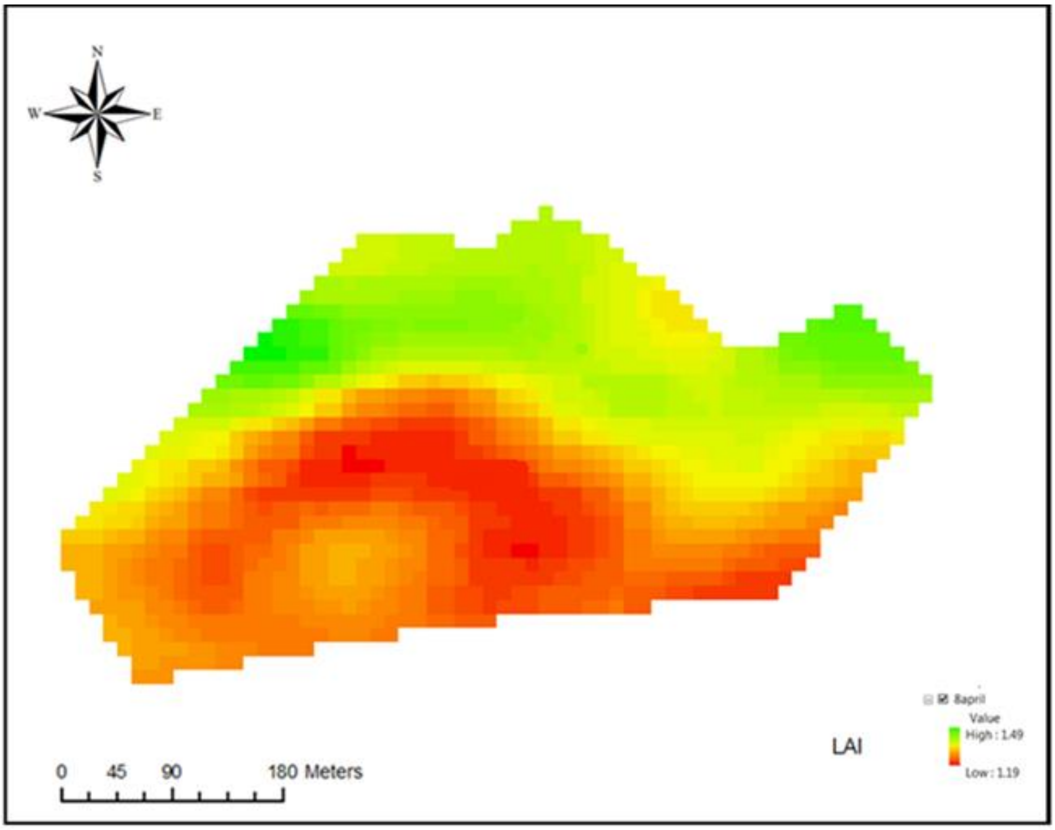


Figure 90. Home Farm LAI 08/04/14.

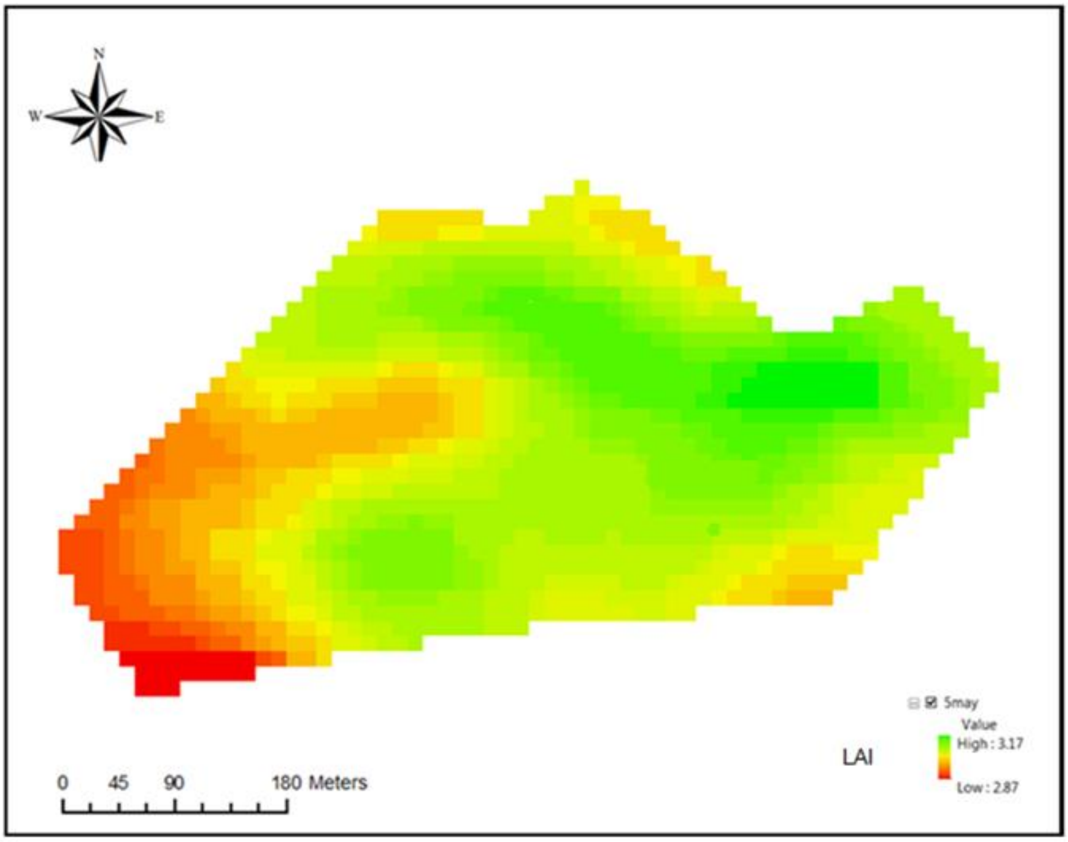


Figure 91. Home Farm LAI 05/05/14.

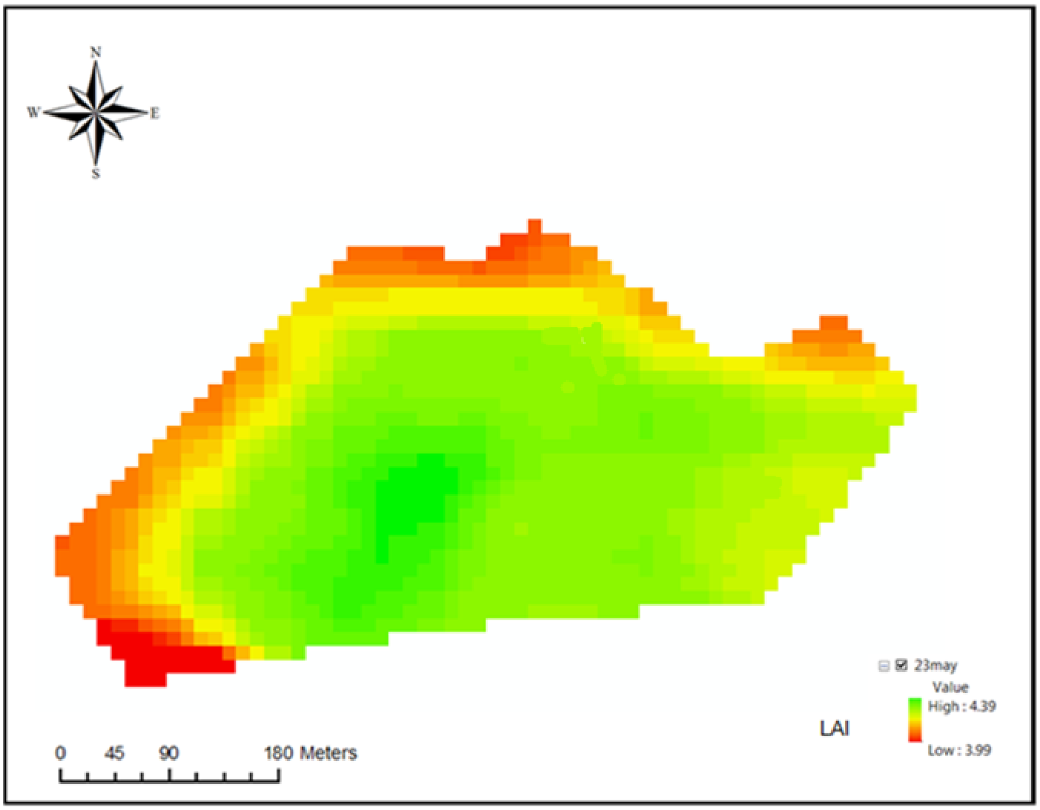


Figure 92. Home Farm LAI 23/05/14.

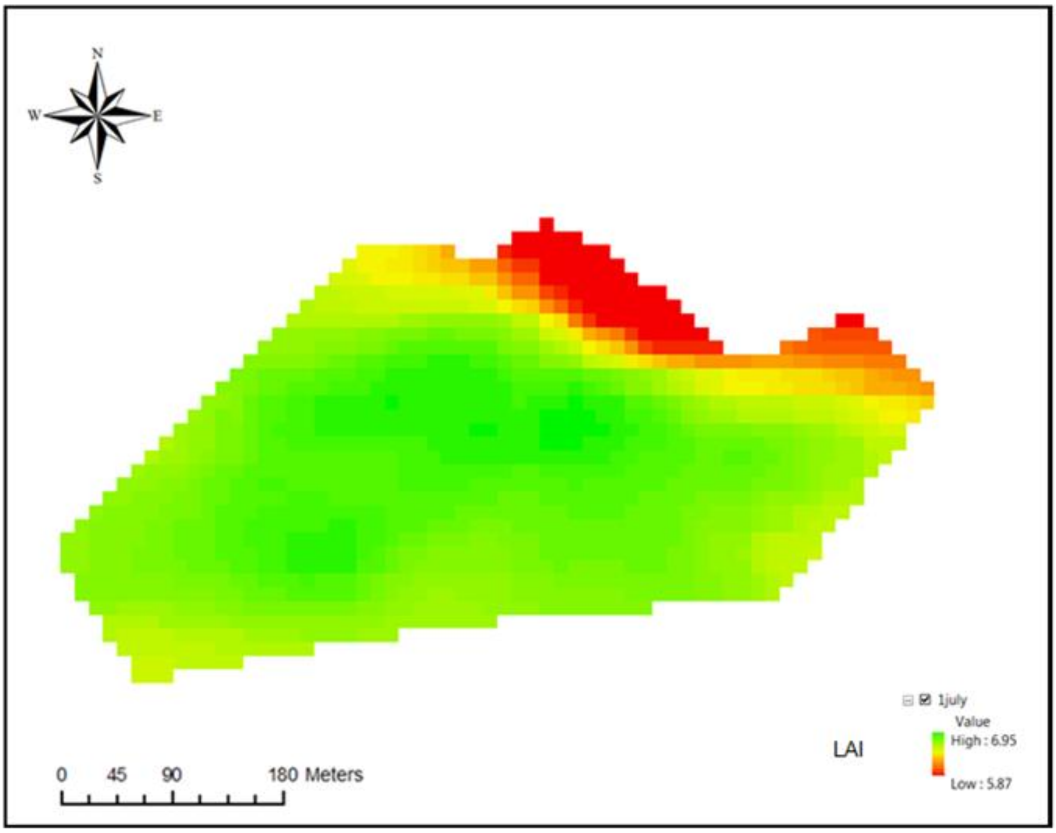


Figure 93. Home Farm LAI 01/07/14.

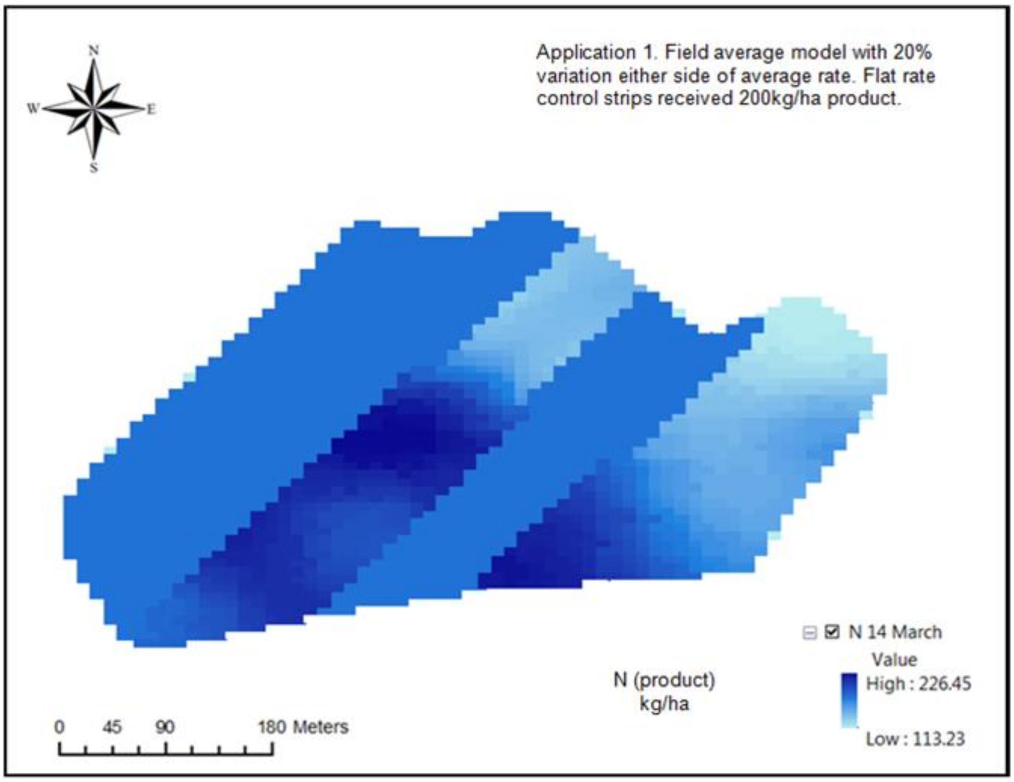


Figure 94. Home Farm N Application 14/03/14.

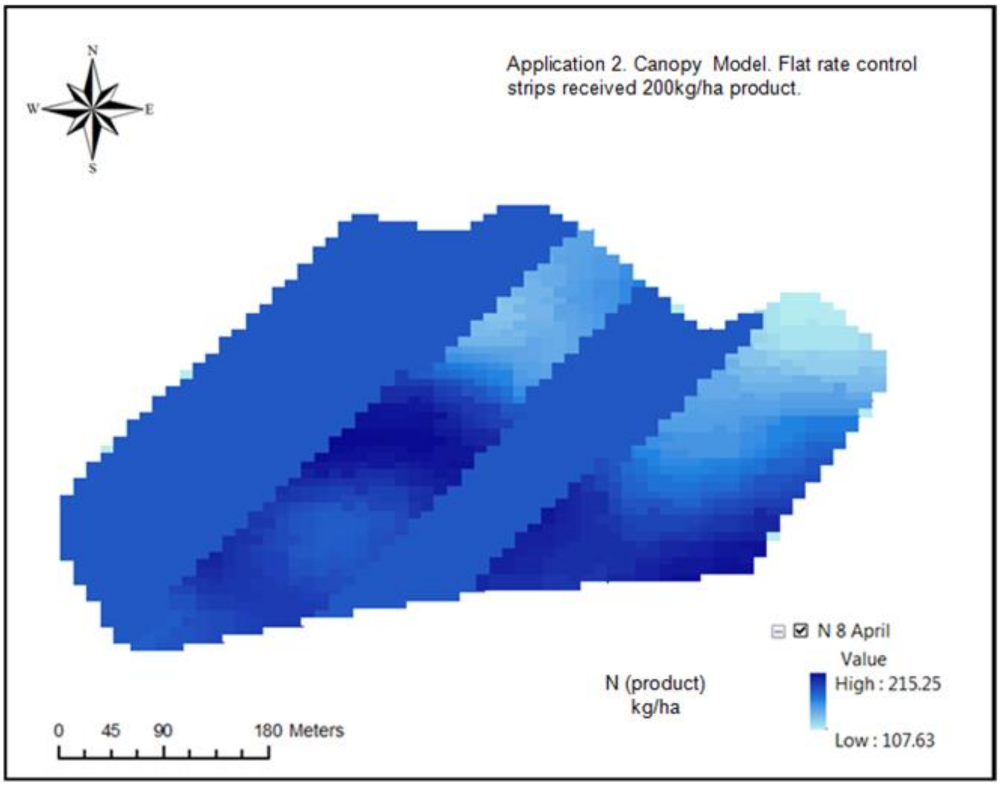


Figure 95. Home Farm N Application 08/04/14.

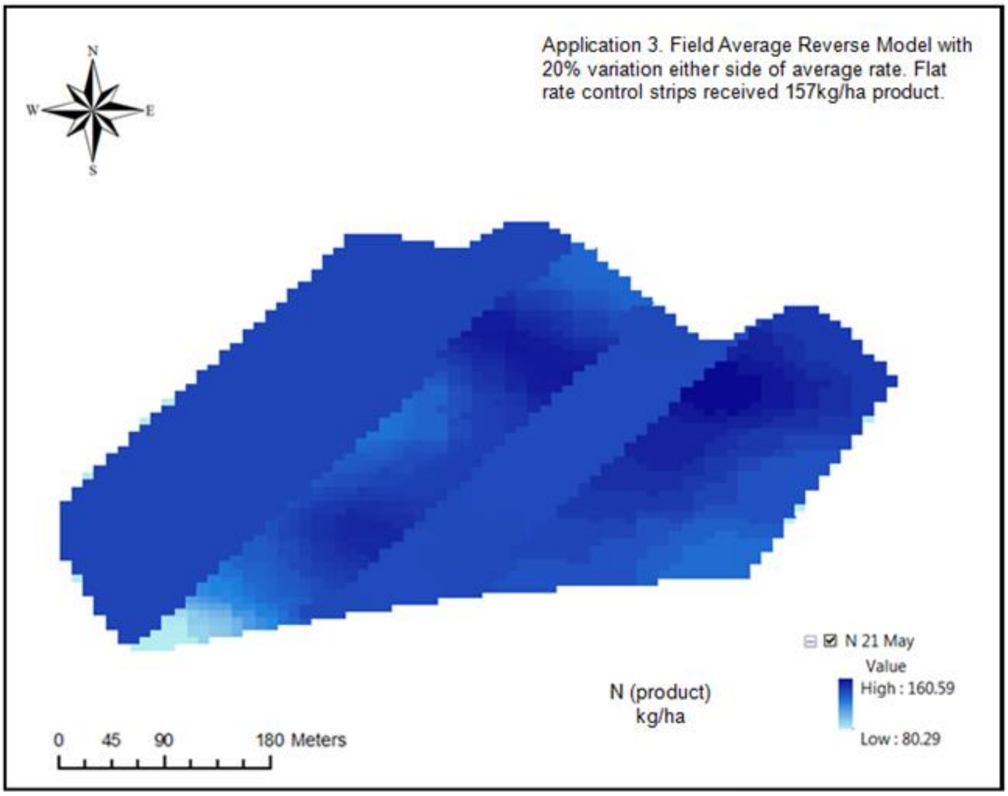

Application 3. Field Average Reverse Model with 20% variation either side of average rate. Flat rate control strips received 157kg/ha product.

Figure 96. Home Farm N Application 21/05/14.

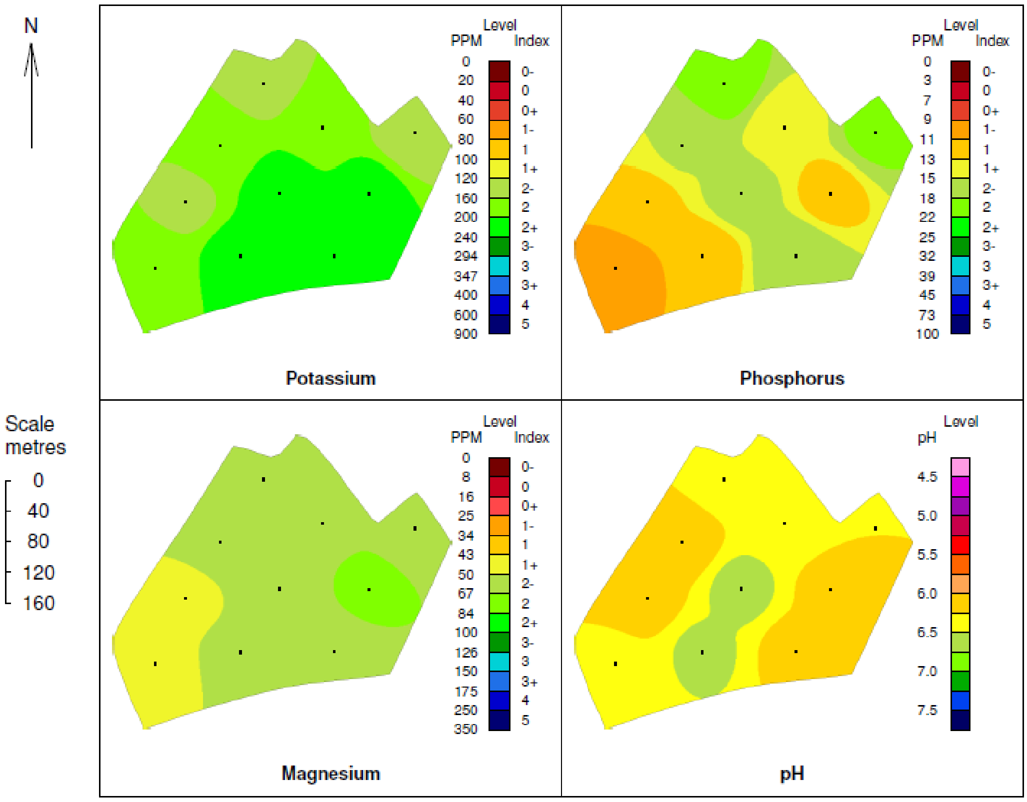


Figure 97. P, K, Mg and pH sampling results for Home Farm 18/10/2011.

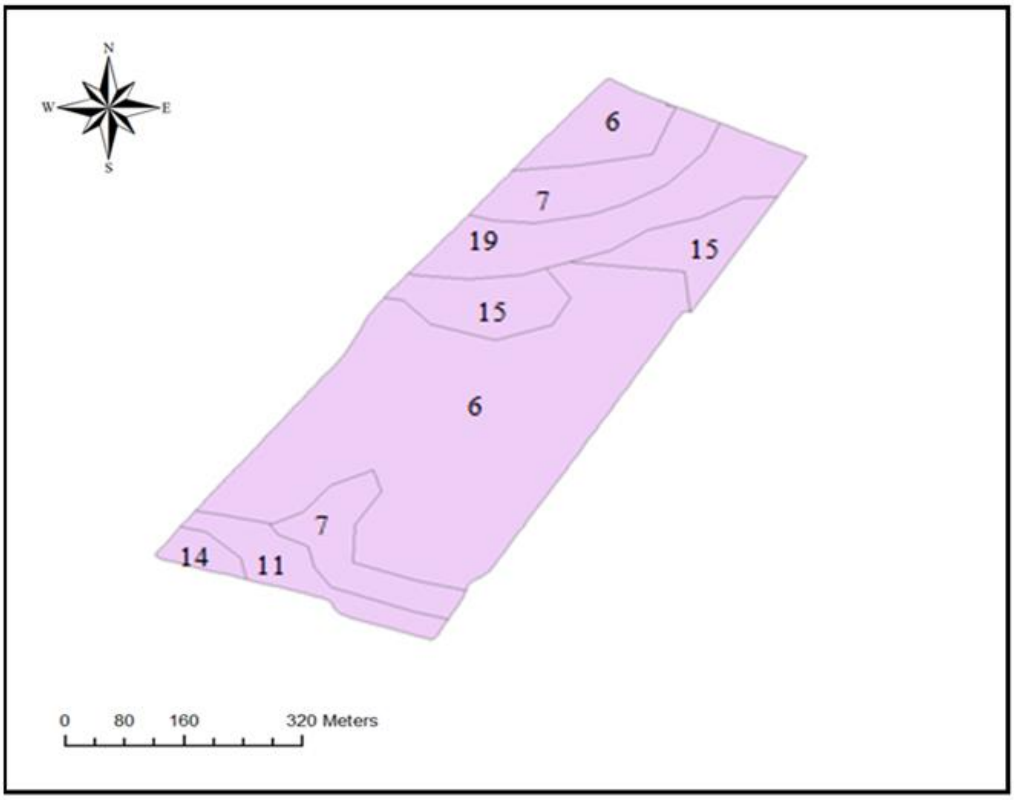


Figure 98. Soil Type for Singford (20.74 ha).

| | Topsoil | Stone Content (Topsoil) | Subsoil |
|---|---|---|---|
| **6** | Medium Clay Loam (Slightly Chalky) | Moderate | Chalky below 25-35cm |
| **7** | Medium Clay Loam, Calcareous | Moderate | Chalky below 30-50cm |
| **11** | Medium Heavy Silty Clay Loam | Moderate | Moderately Stony, Very Stony below 50-75cm |
| **14** | Medium-Heavy Silty Clay Loam | Moderate | Very Stony below 55-70cm |
| **15** | Heavy Silty Clay Loam | Moderate | Chalky below 30-50cm |
| **19** | Heavy Silty Clay Loam | Moderate | Silty Clay below 30cm, Chalky, or Very Stony below 60-80cm |

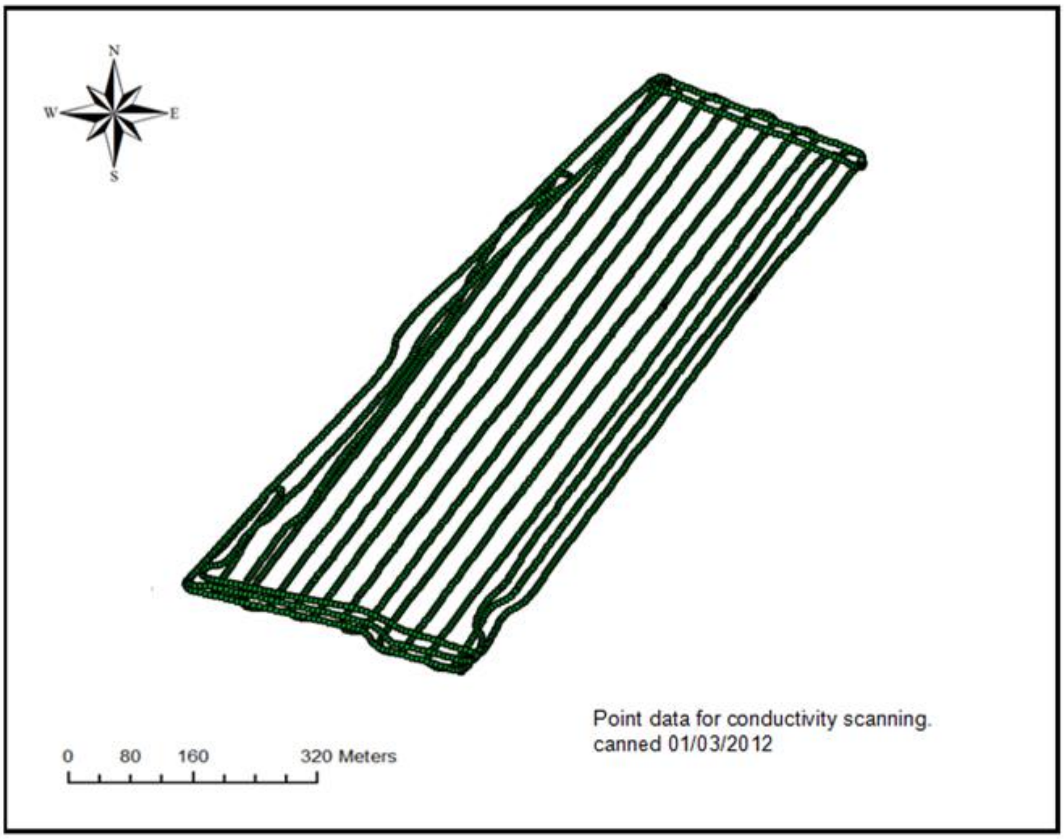


Figure 99. EC Point location for Singford.

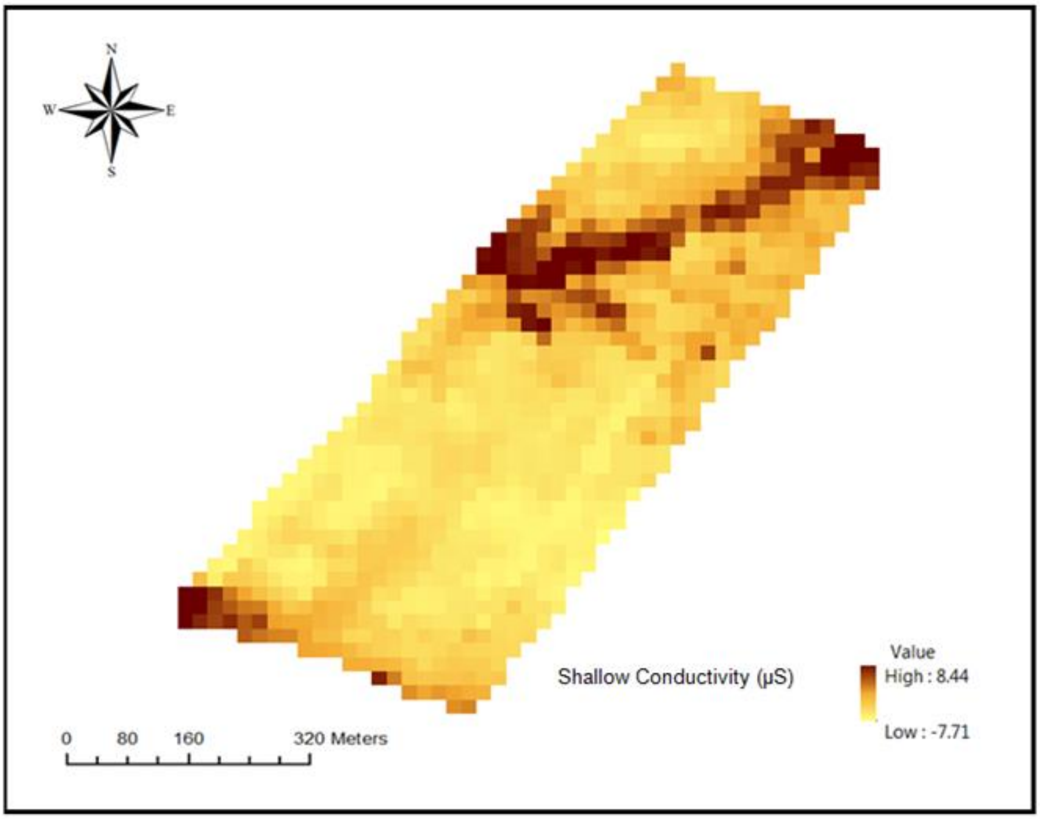


Figure 100. Shallow EC for Singford.

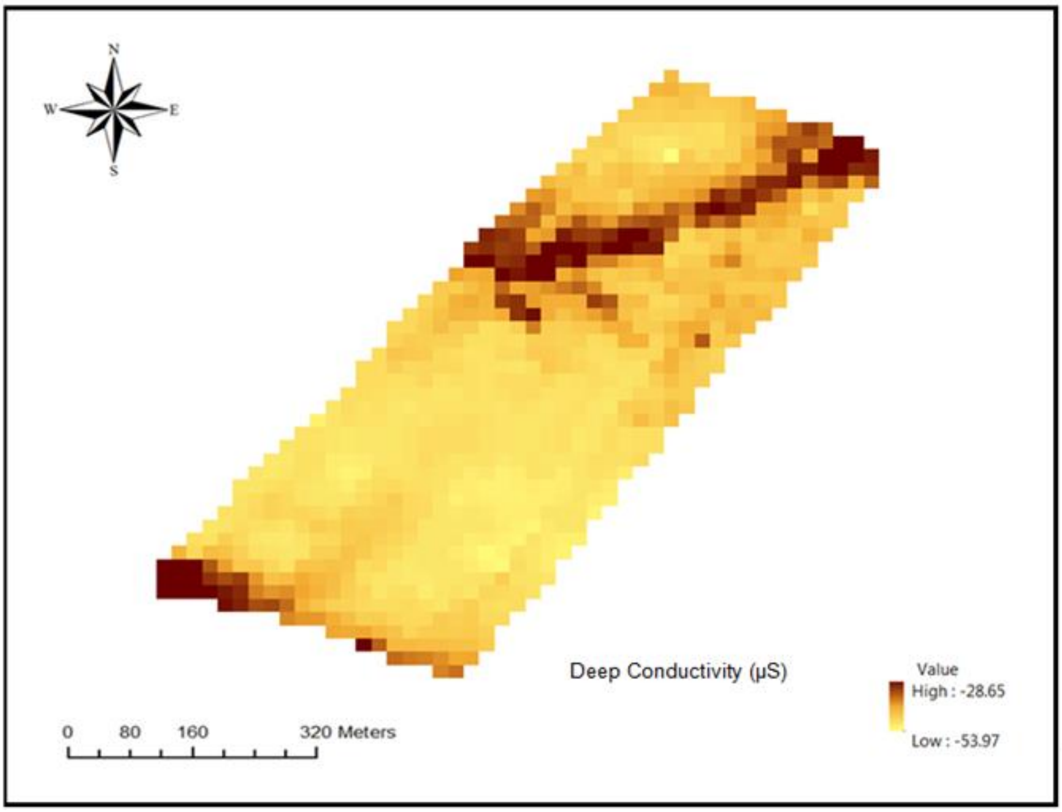


Figure 101. Deep EC for Singford.

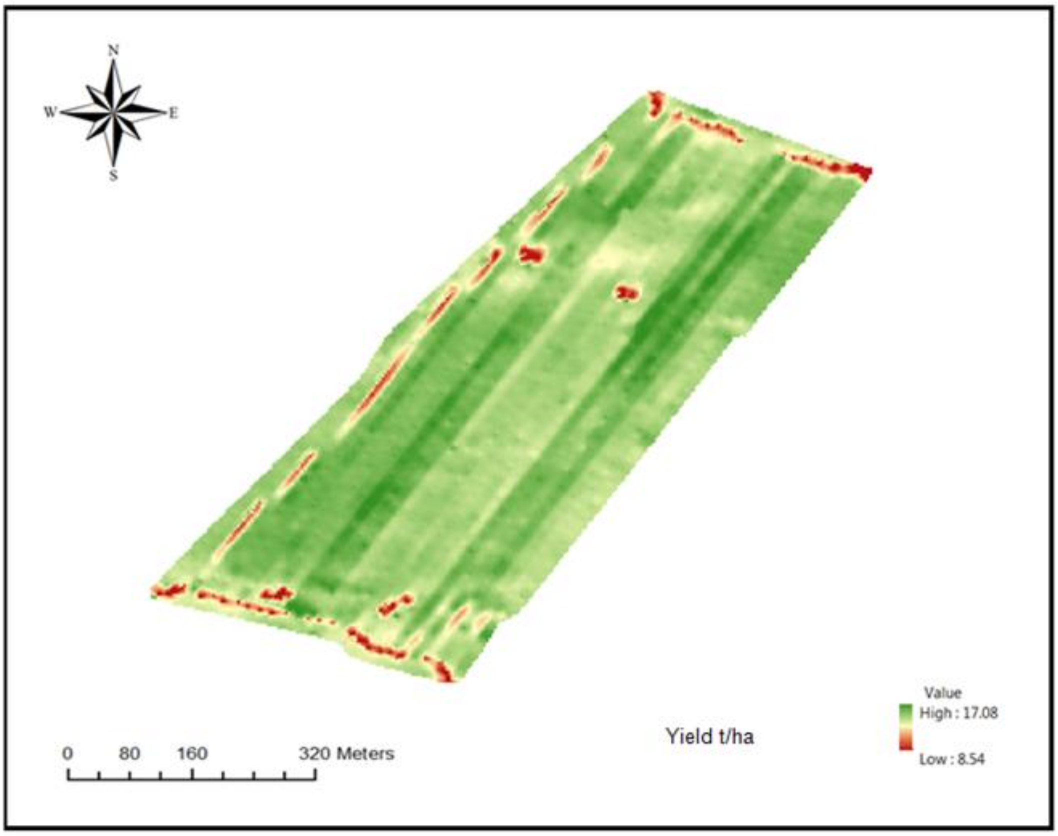


Figure 102. Singford Yield 2013.

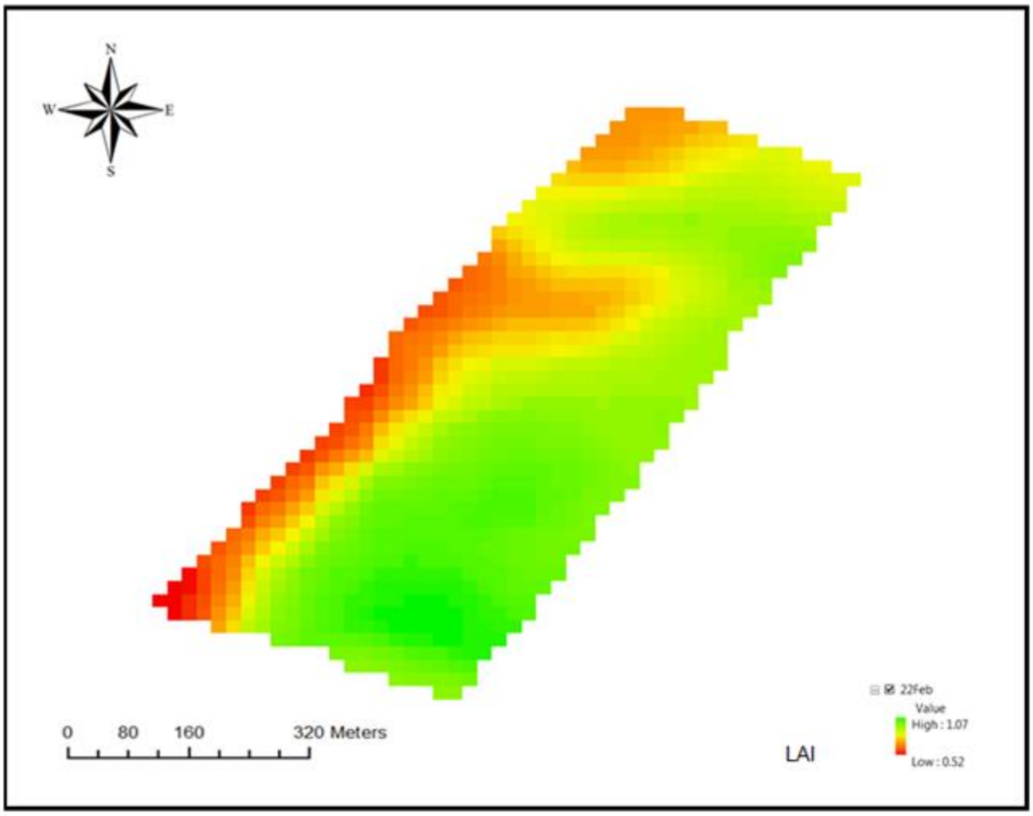


Figure 103. Singford LAI 22/02/13.

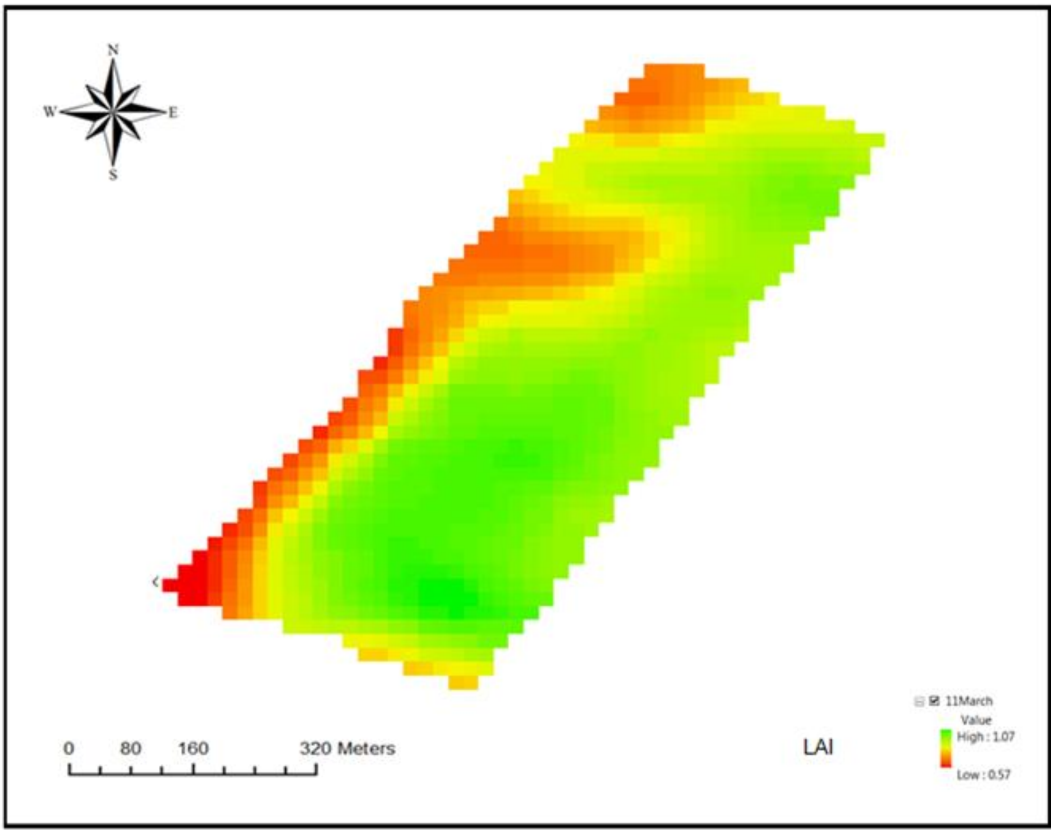


Figure 104. Singford LAI 11/03/13.

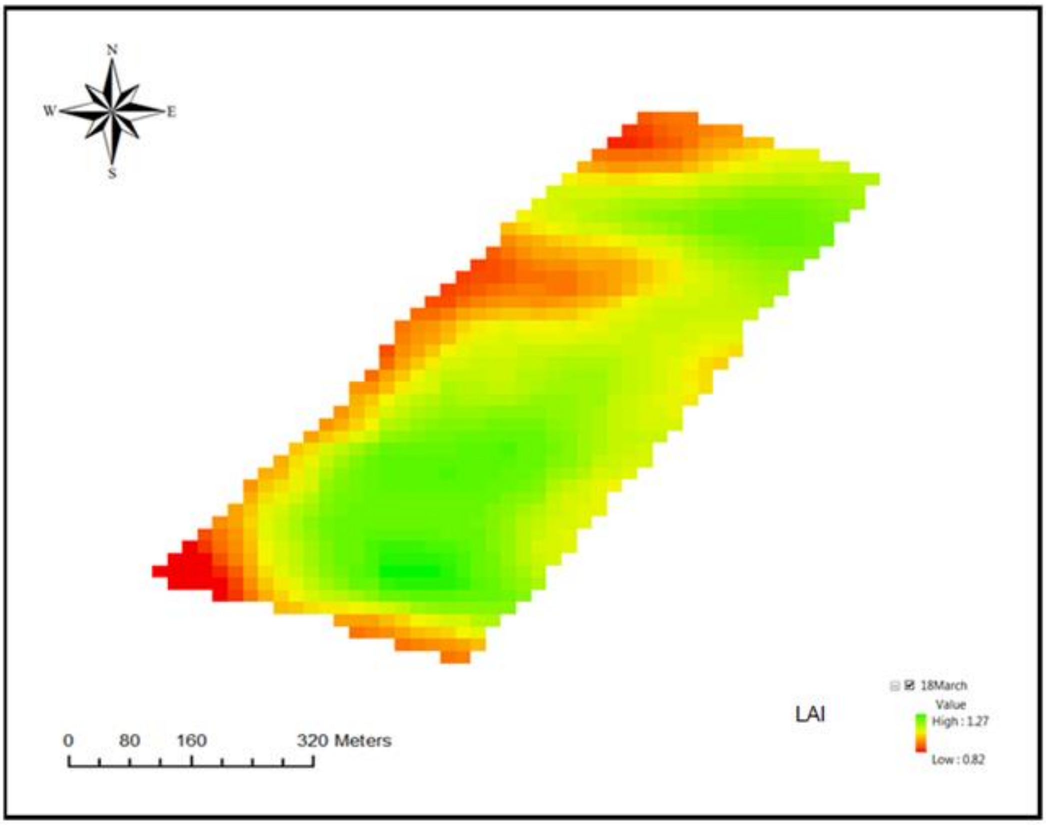


Figure 105. Singford LAI 18/03/13.

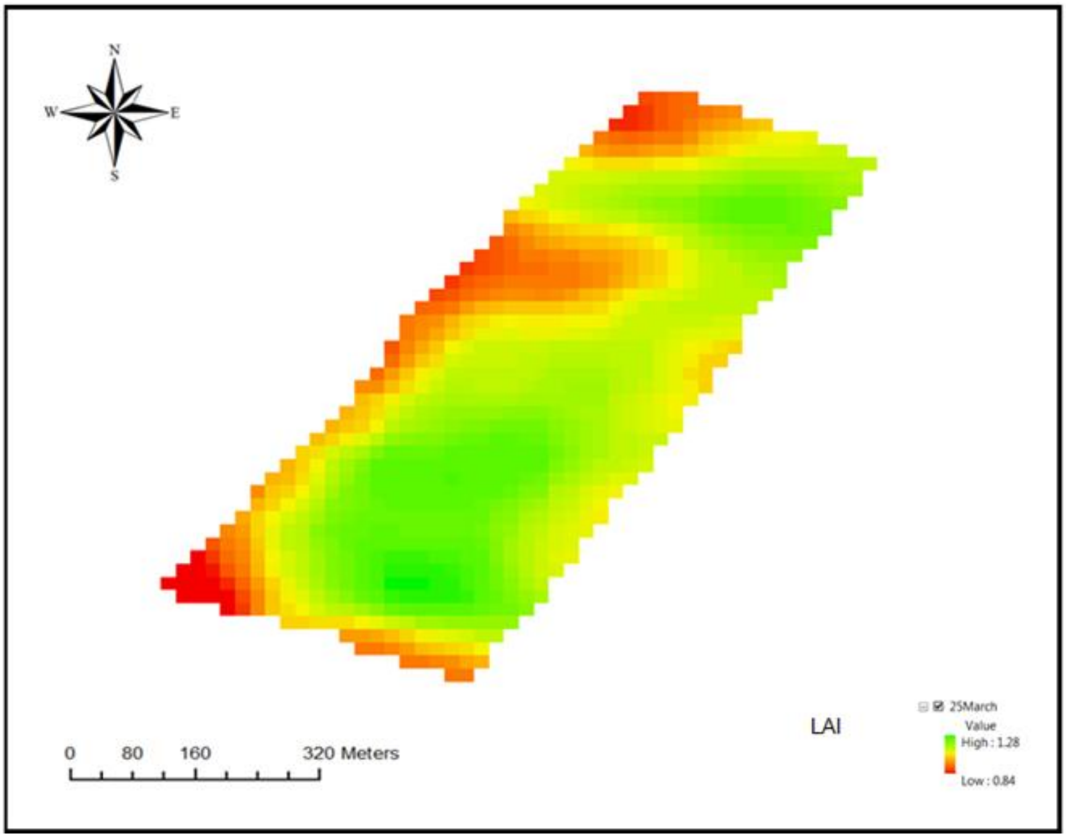


Figure 106. Singford LAI 25/03/13.

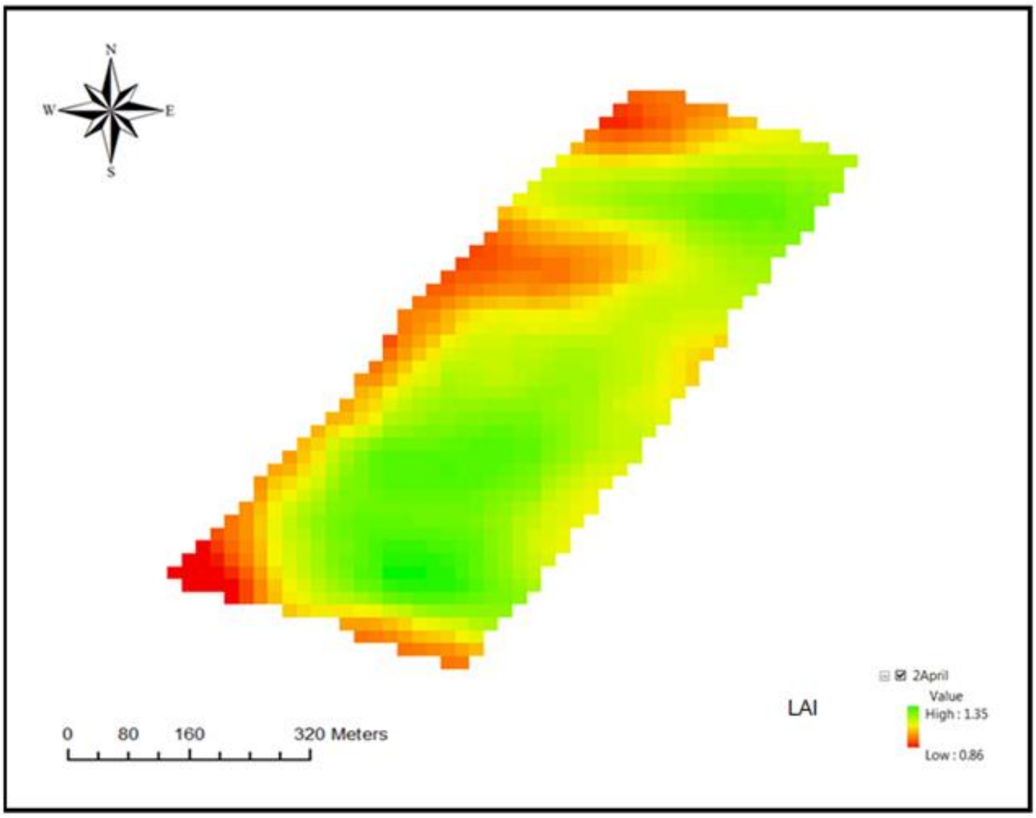


Figure 107. Singford LAI 02/04/13.

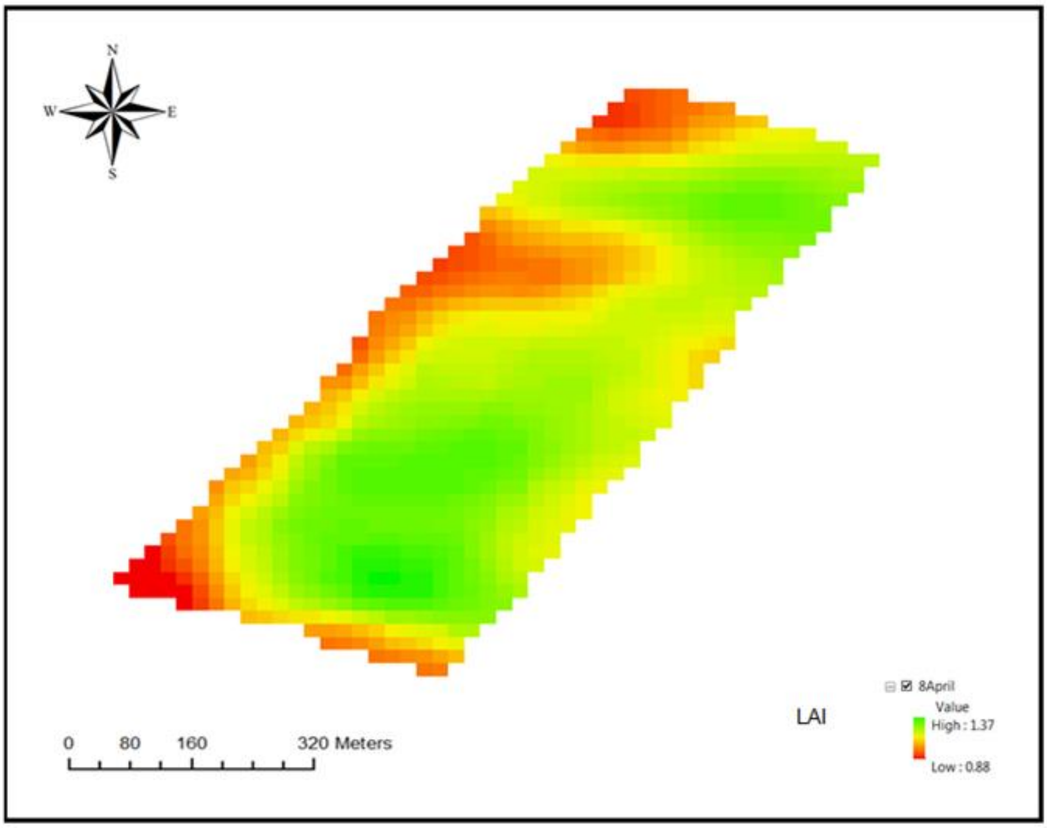


Figure 108. Singford LAI 08/04/13.

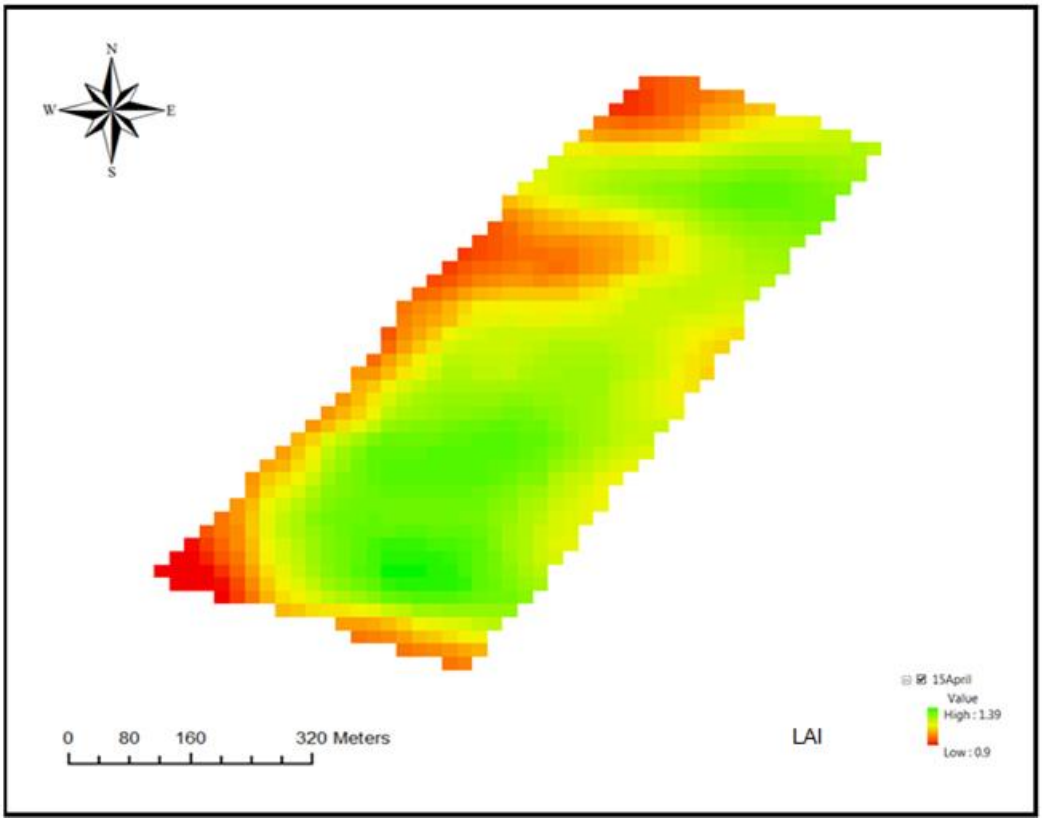


Figure 109. Singford LAI 15/04/13.

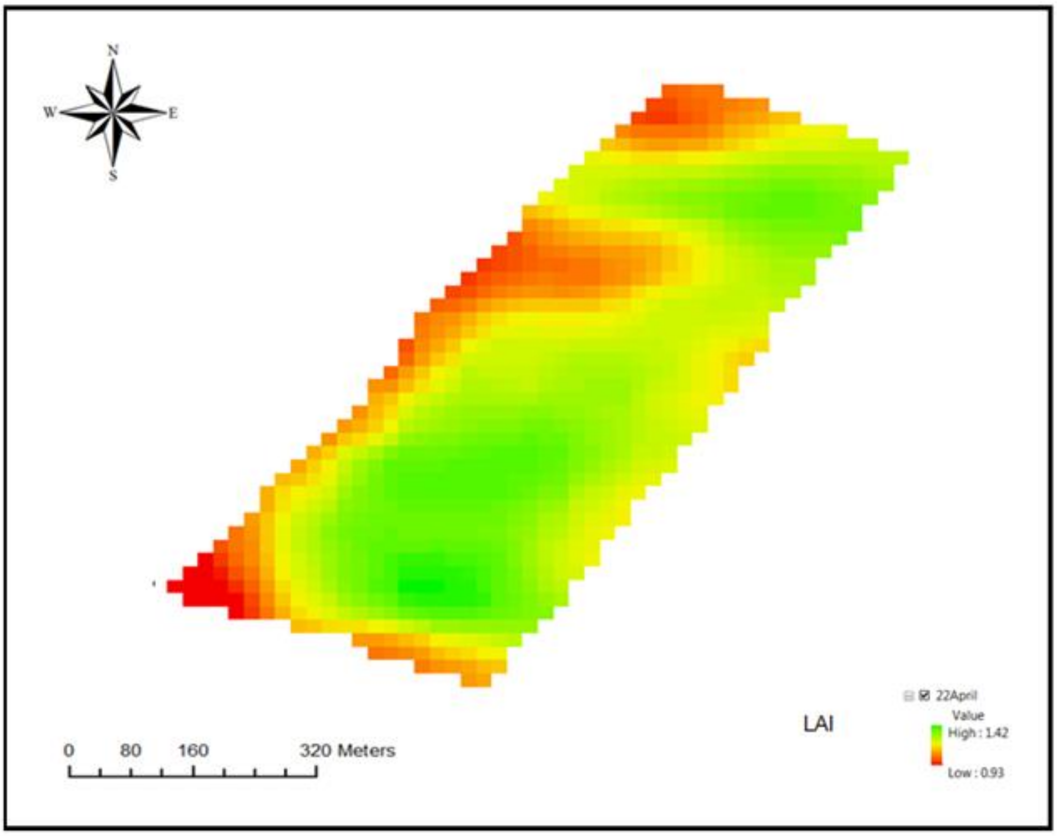


Figure 110. Singford LAI 22/04/13.

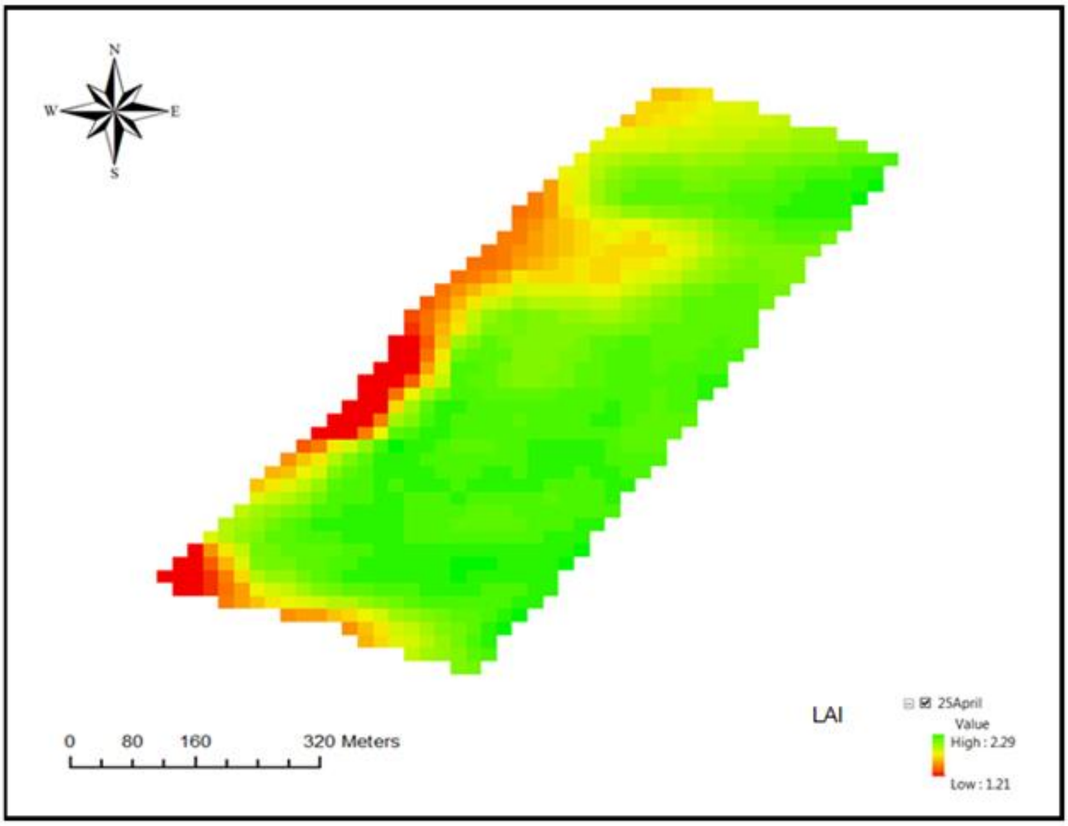


Figure 111. Singford LAI 25/04/13.

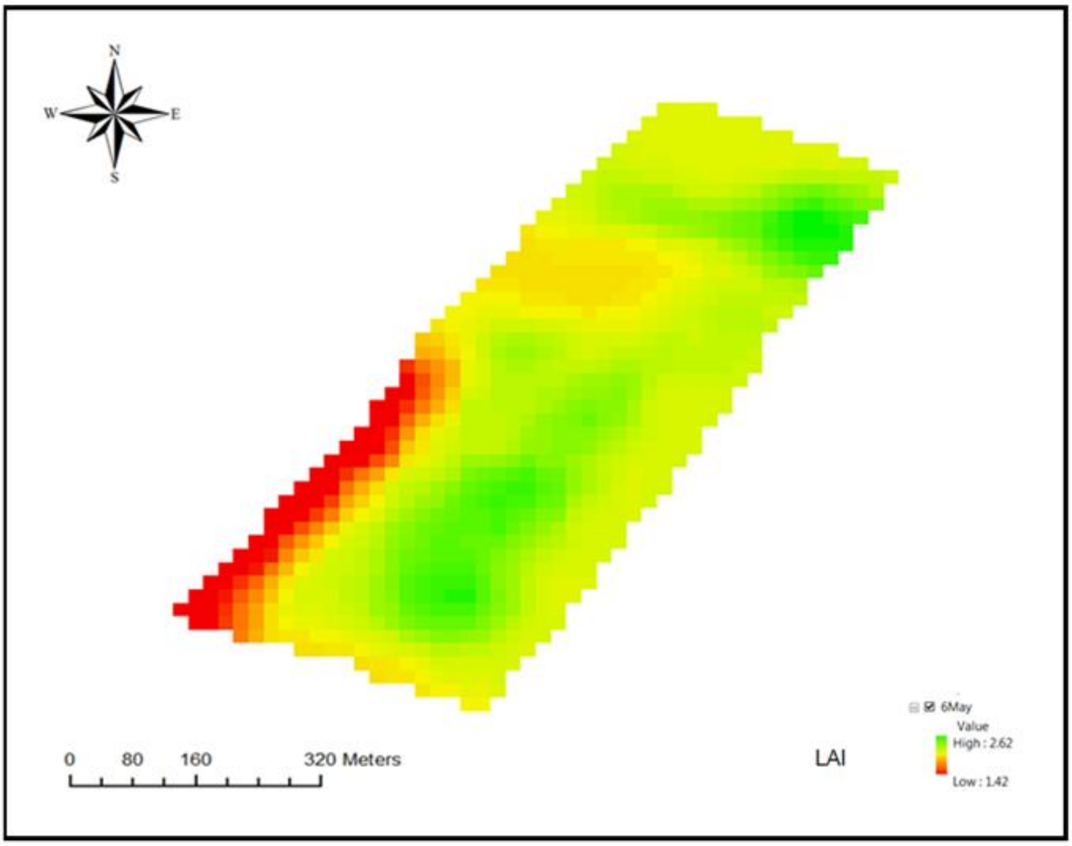


Figure 112. Singford LAI 06/05/13.

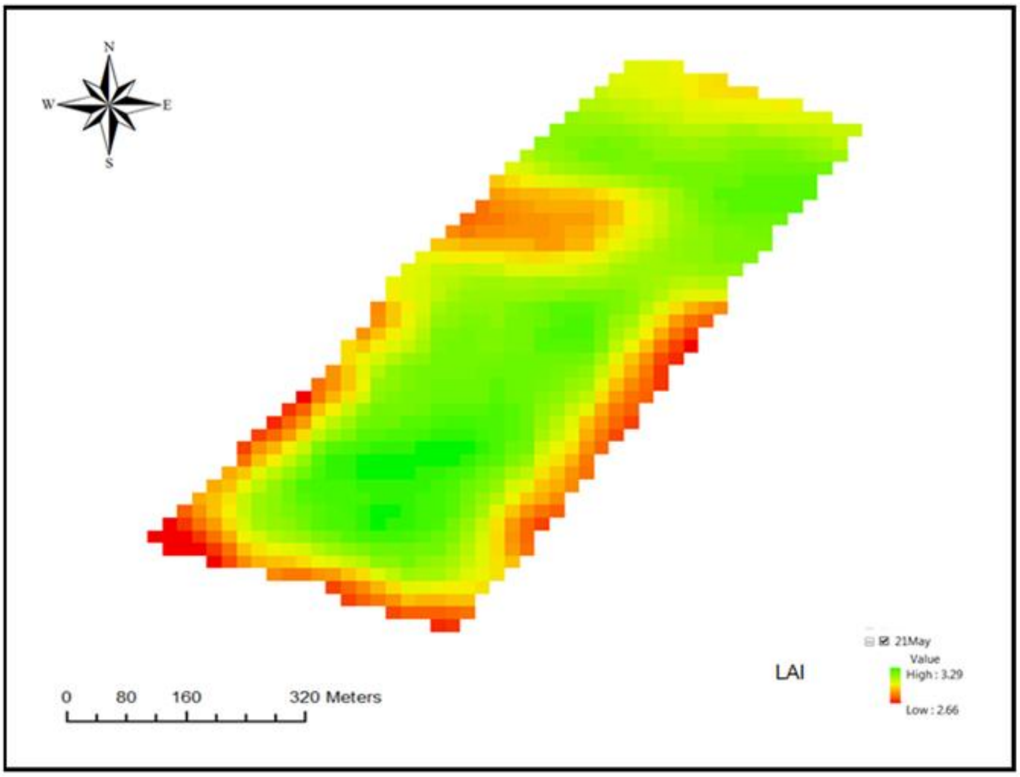
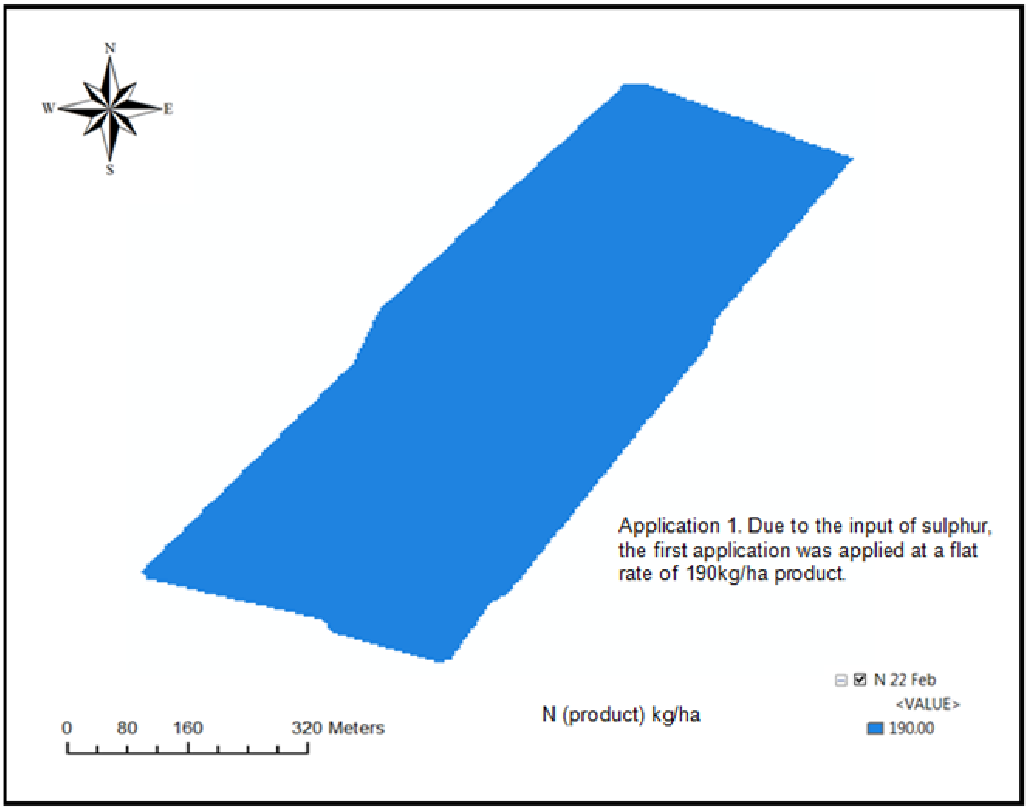


Figure 113. Singford LAI 21/05/13.



Application 1. Due to the input of sulphur, the first application was applied at a flat rate of 190kg/ha product.

Figure 114. Singford N Application 22/02/13.

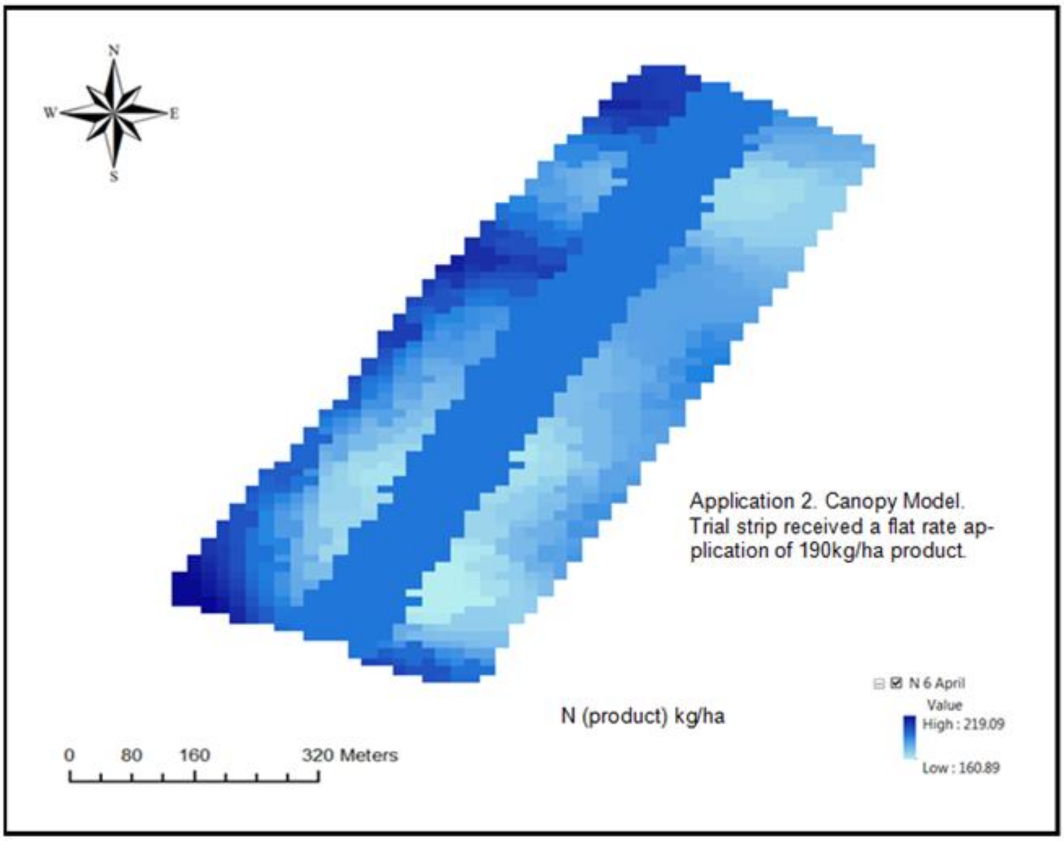


Figure 115. Singford N Application 06/04/13.

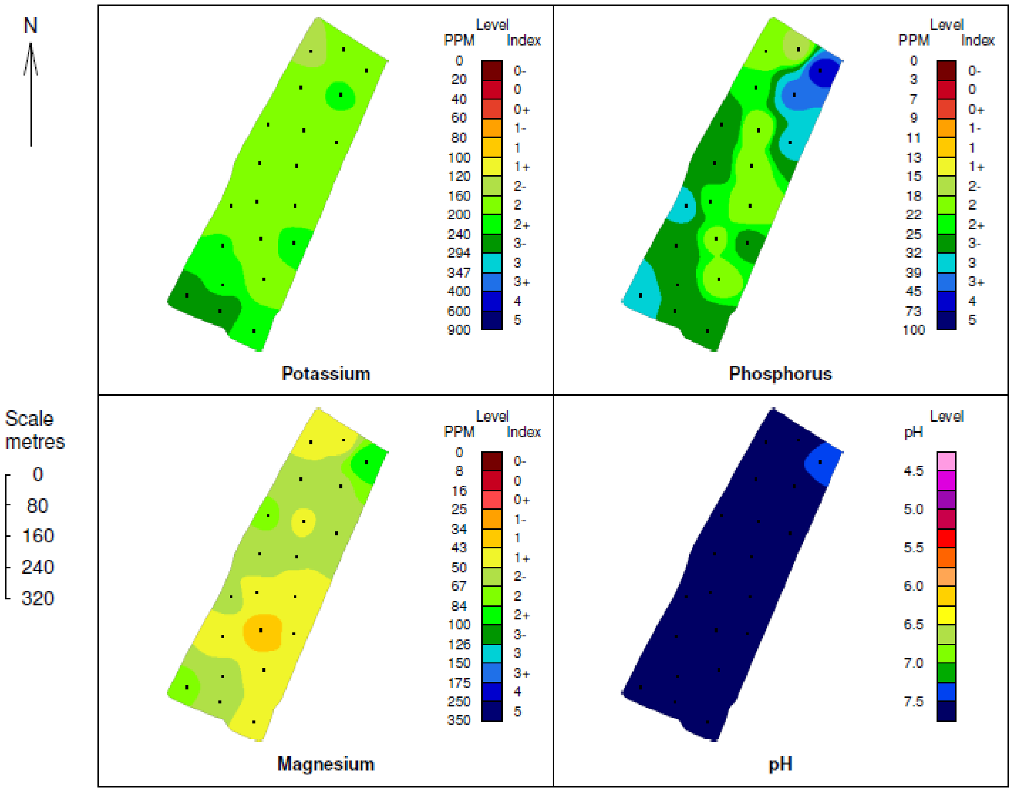


Figure 116. P, K, Mg and pH sampling results for Singford 05/08/2012.

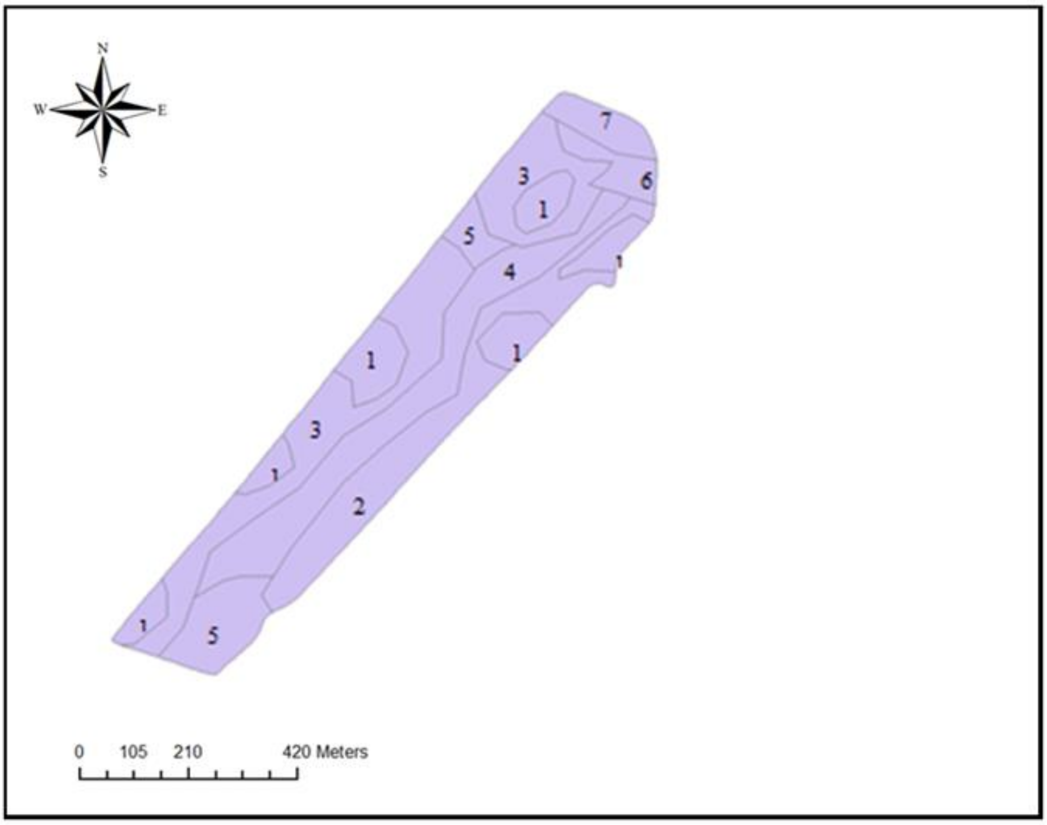


Figure 117. Soil Type for Weston Bottom (20.82 ha).

| | Topsoil | Stone Content (Topsoil) | Subsoil |
|---|---|---|---|
| **1** | Sandy Loam | Slight | Loamy Sand below 50cm |
| **2** | Medium Sandy Clay Loam | Very High | Very Stony below 20-25cm |
| **3** | Medium Silty Clay Loam, Chalky | Slight to Moderate | Chalky below 25-35cm |
| **4** | Medium Silty Clay Loam | High | Very Stony below 20-50cm |
| **5** | Medium Sandy Clay Loam | Very High | Very Stony below 50cm |
| **6** | Medium Clay Loam (Slightly chalky) | Moderate | Chalky below 25-35cm |
| **7** | Medium Clay Loam, Calcareous | Moderate | Chalky below 30-50cm |

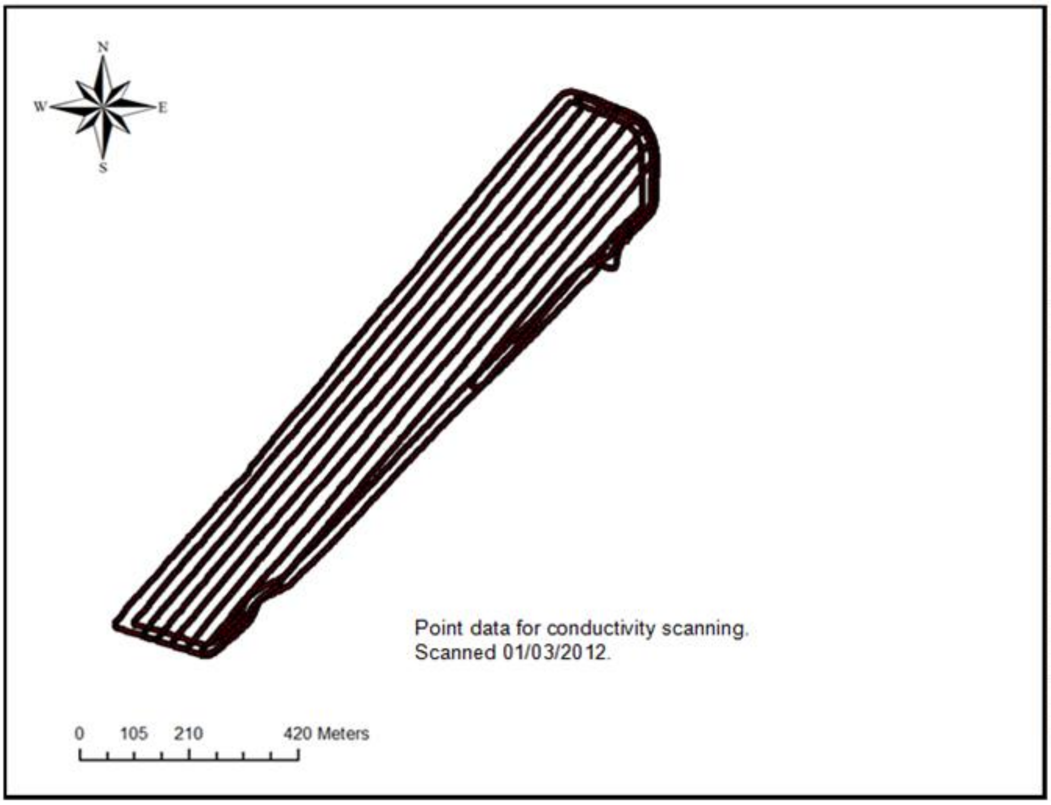


Figure 118. Point location for Weston Bottom.

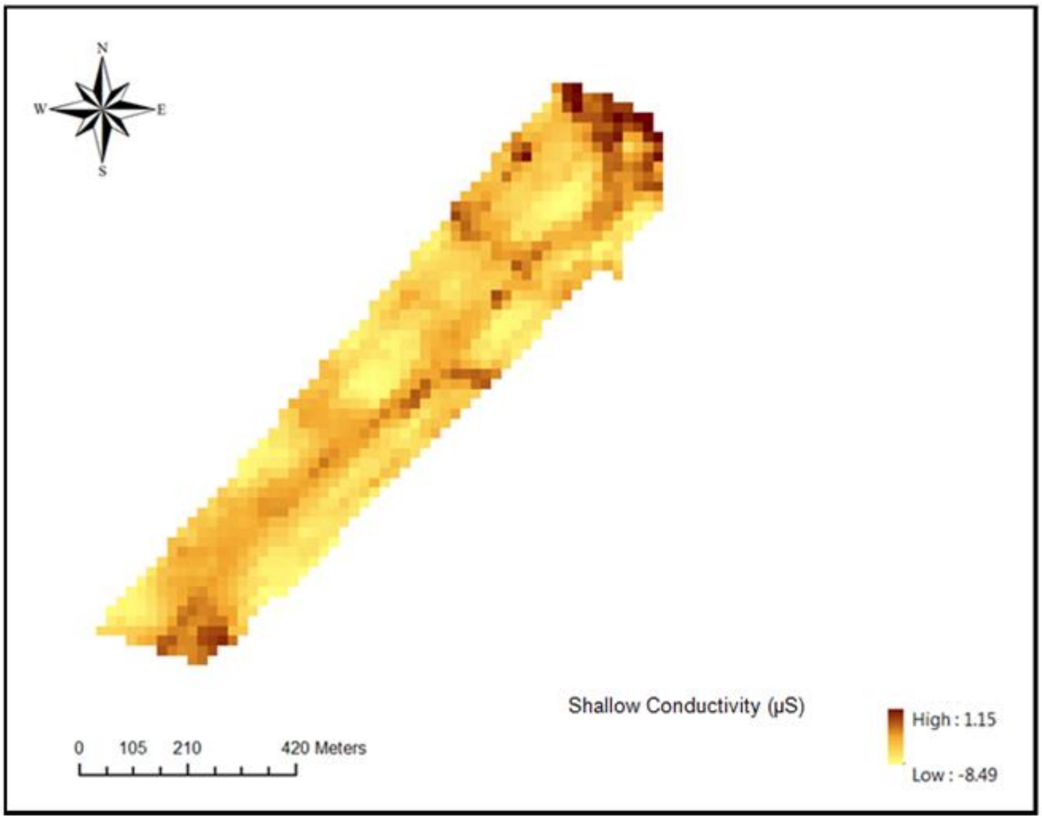


Figure 119. Shallow EC for Weston Bottom

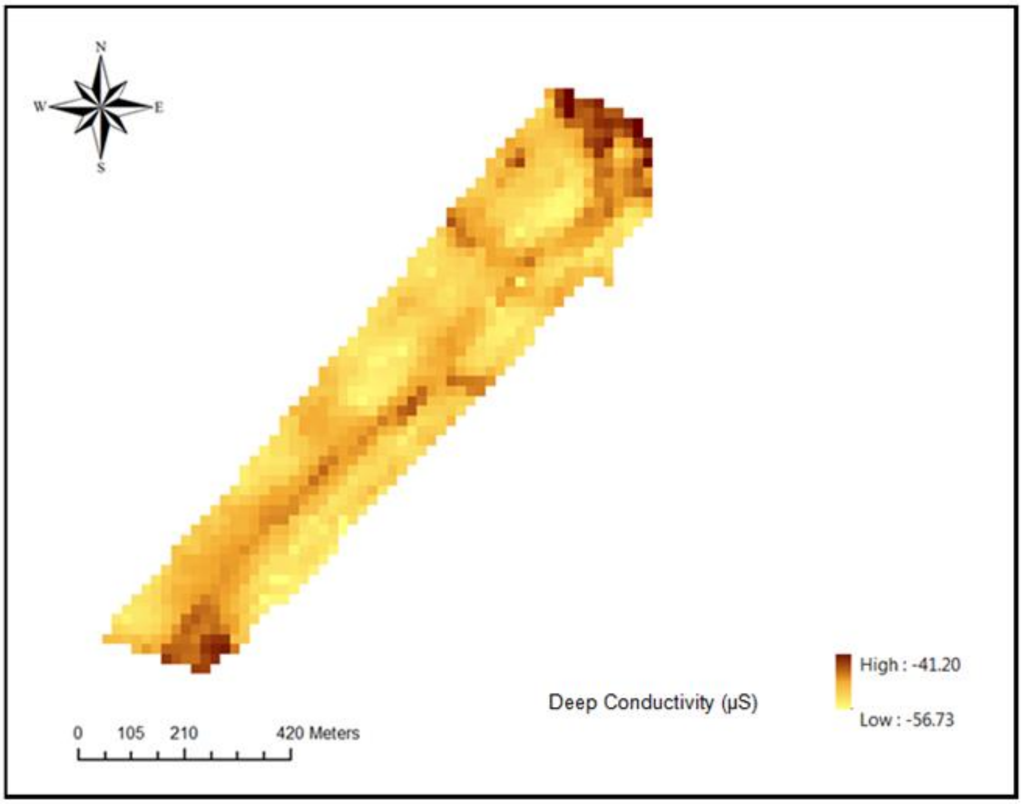


Figure 120. Deep EC for Weston Bottom.

Figure 121. Weston Bottom Yield 2013.

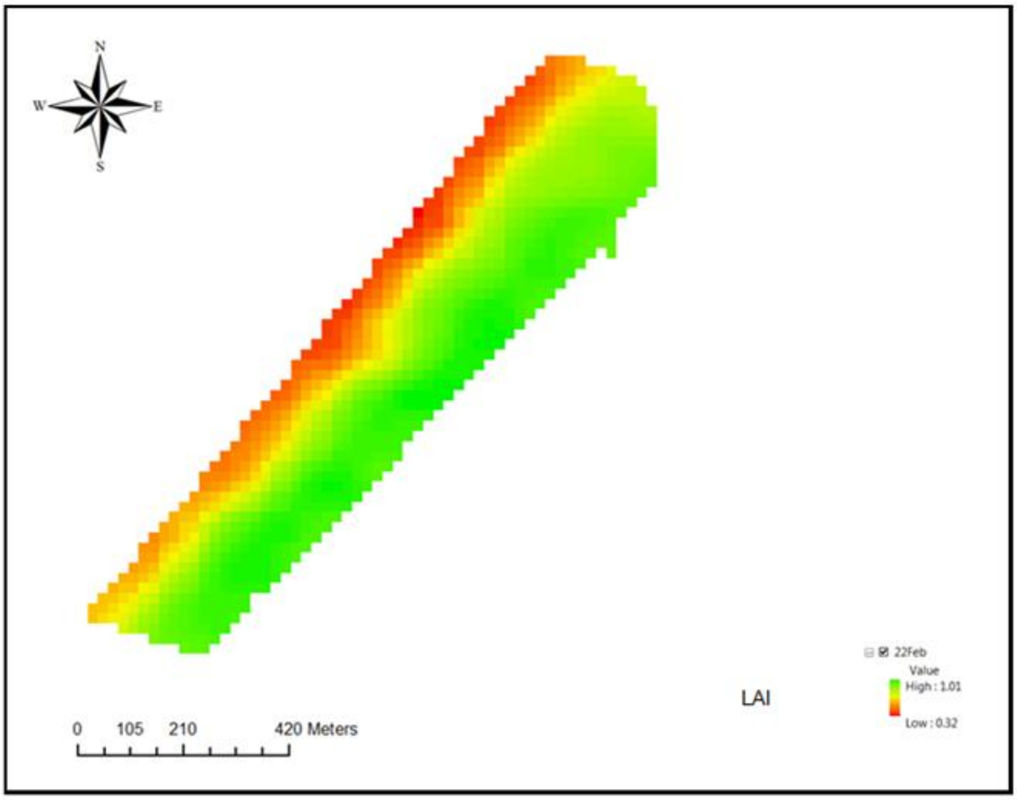


Figure 122. Weston Bottom LAI 22/02/13.

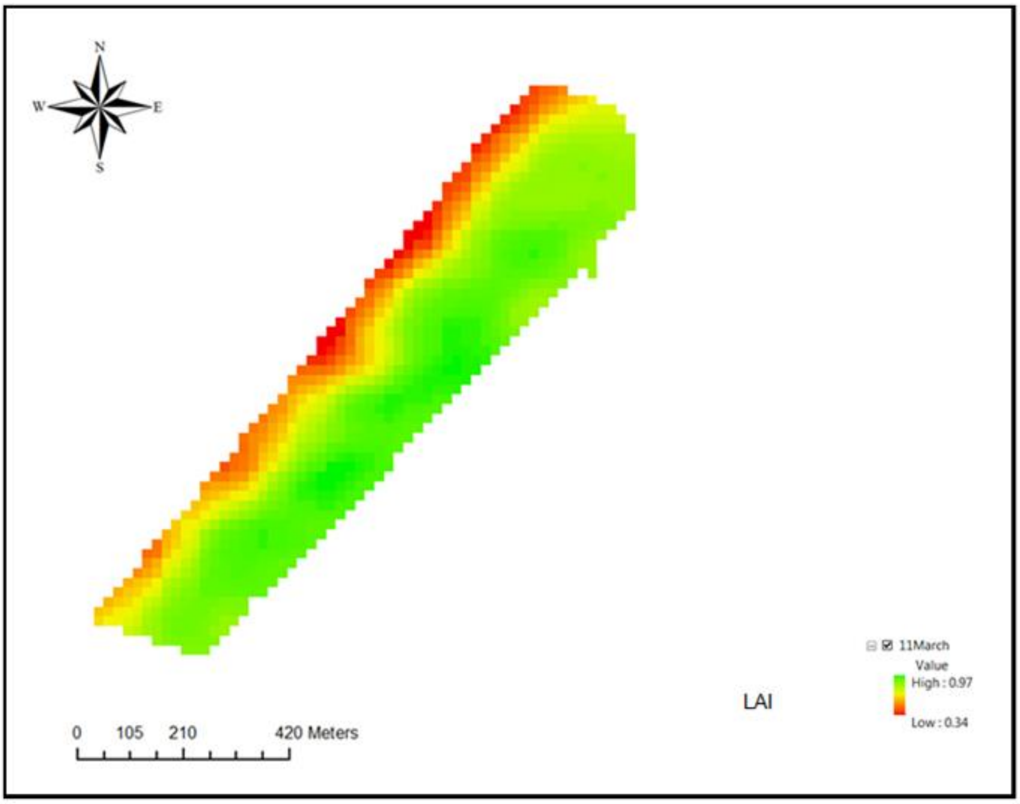


Figure 123. Weston Bottom LAI 11/03/14.

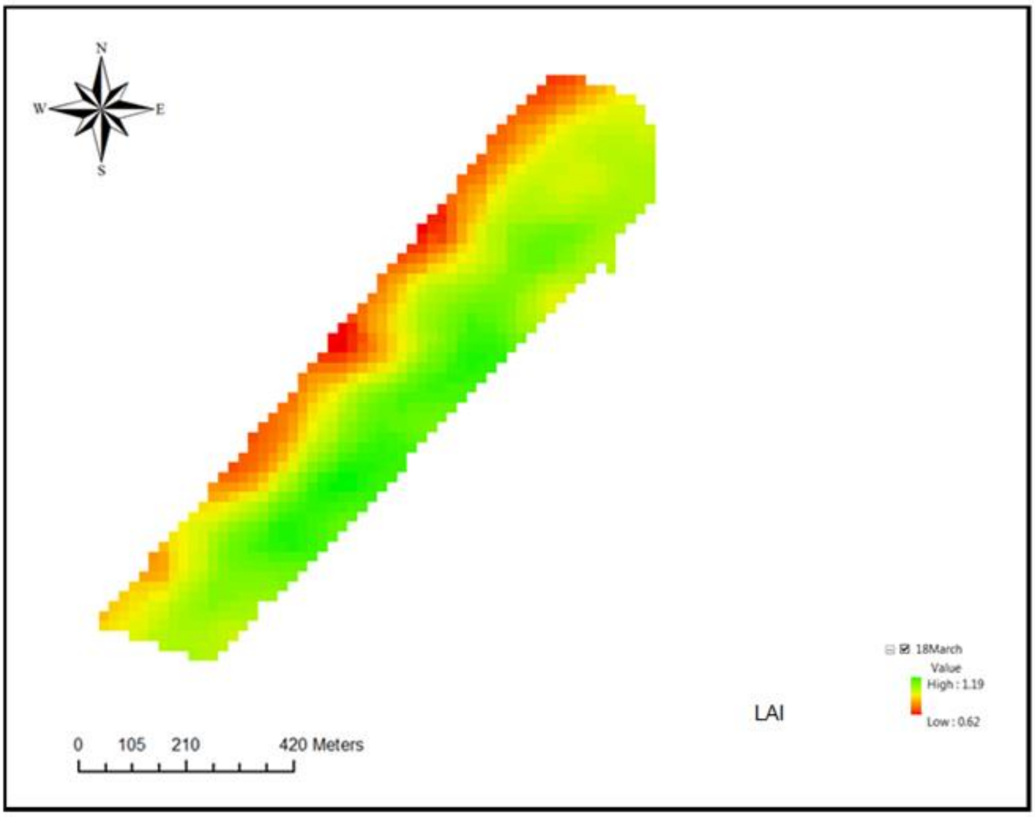


Figure 124. Weston Bottom LAI 18/03/13.

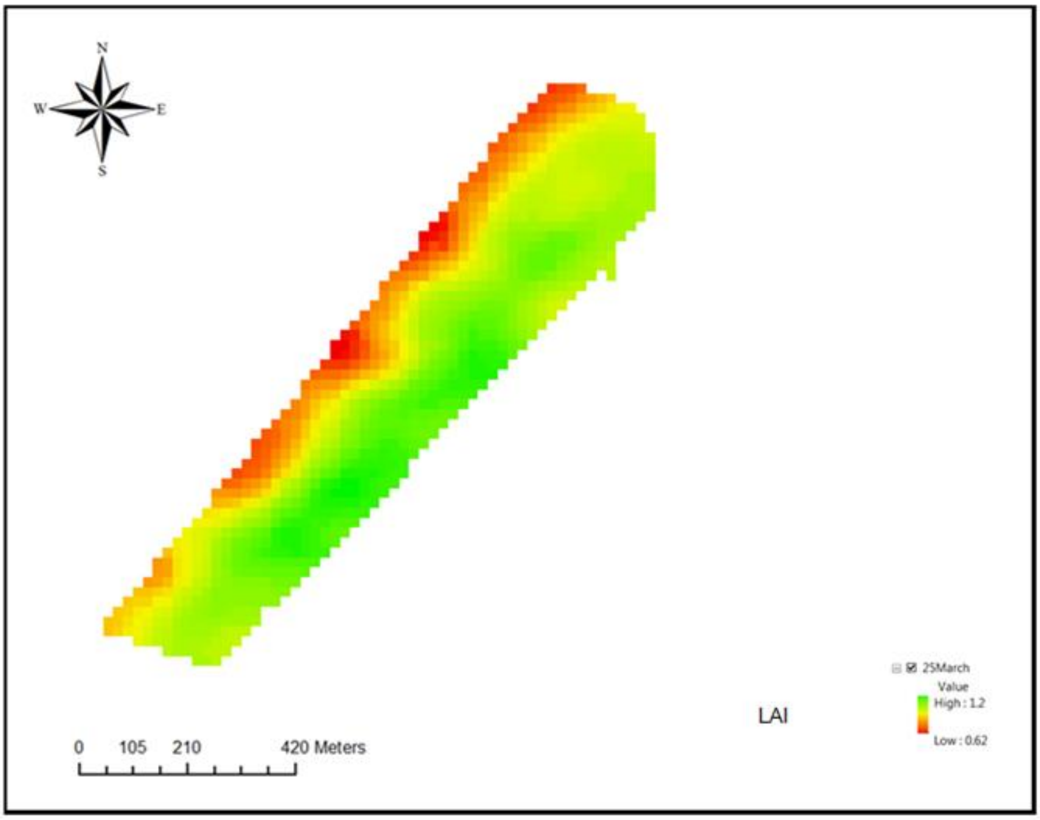


Figure 125. Weston Bottom LAI 25/03/13.

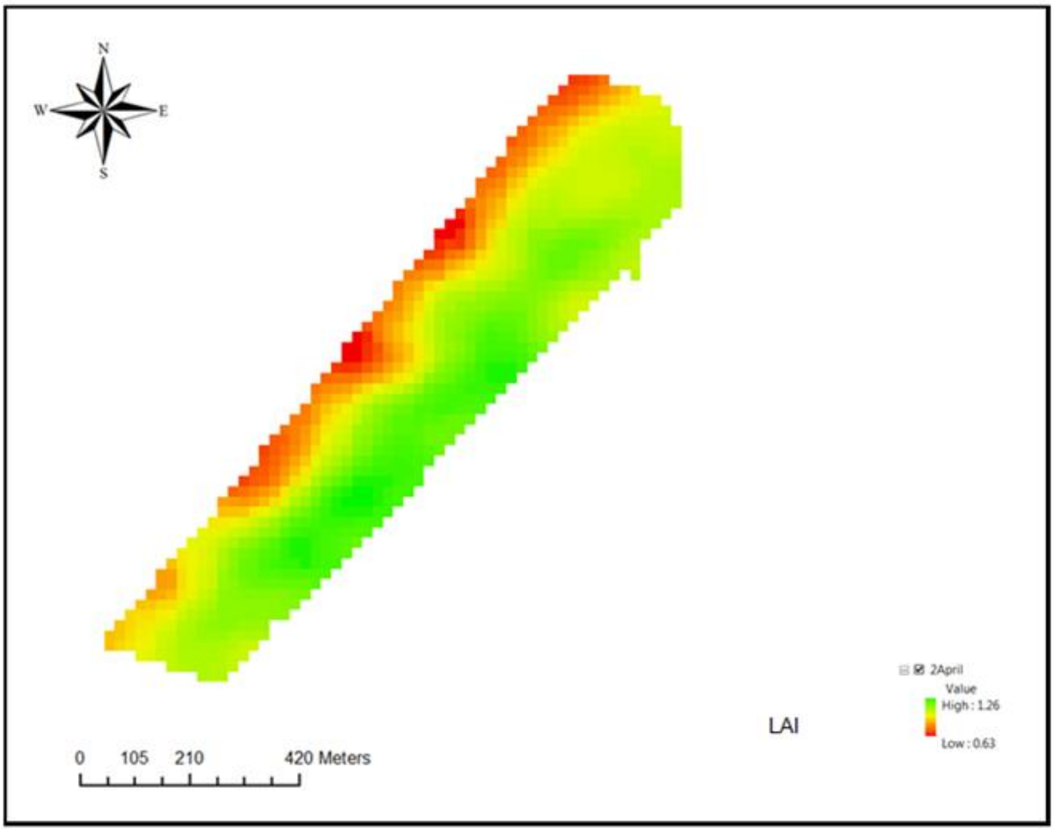


Figure 126. Weston Bottom LAI 02/04/13.

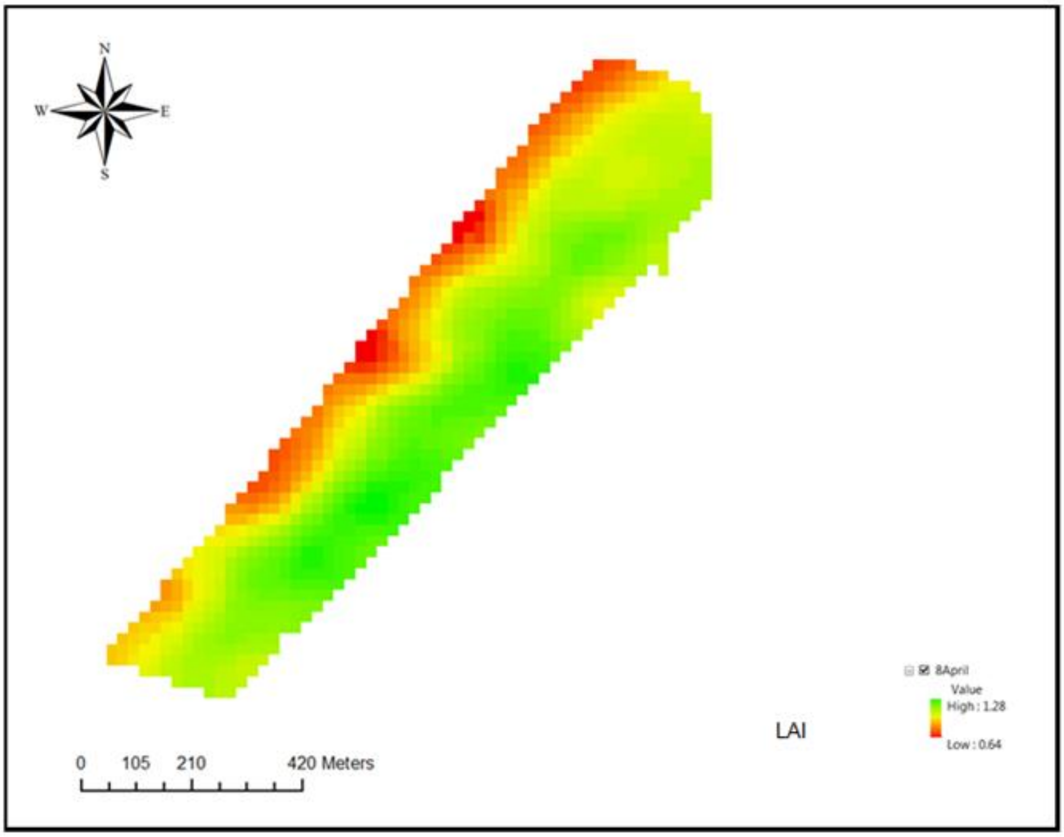


Figure 127. Weston Bottom LAI 08/04/13.

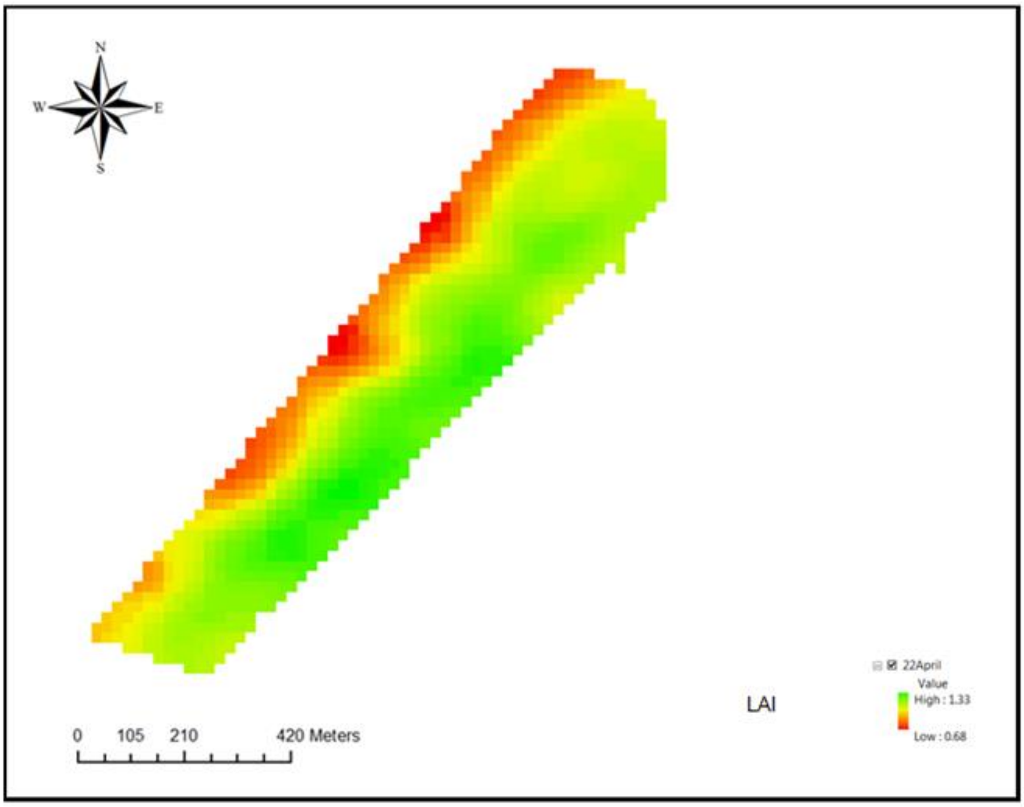
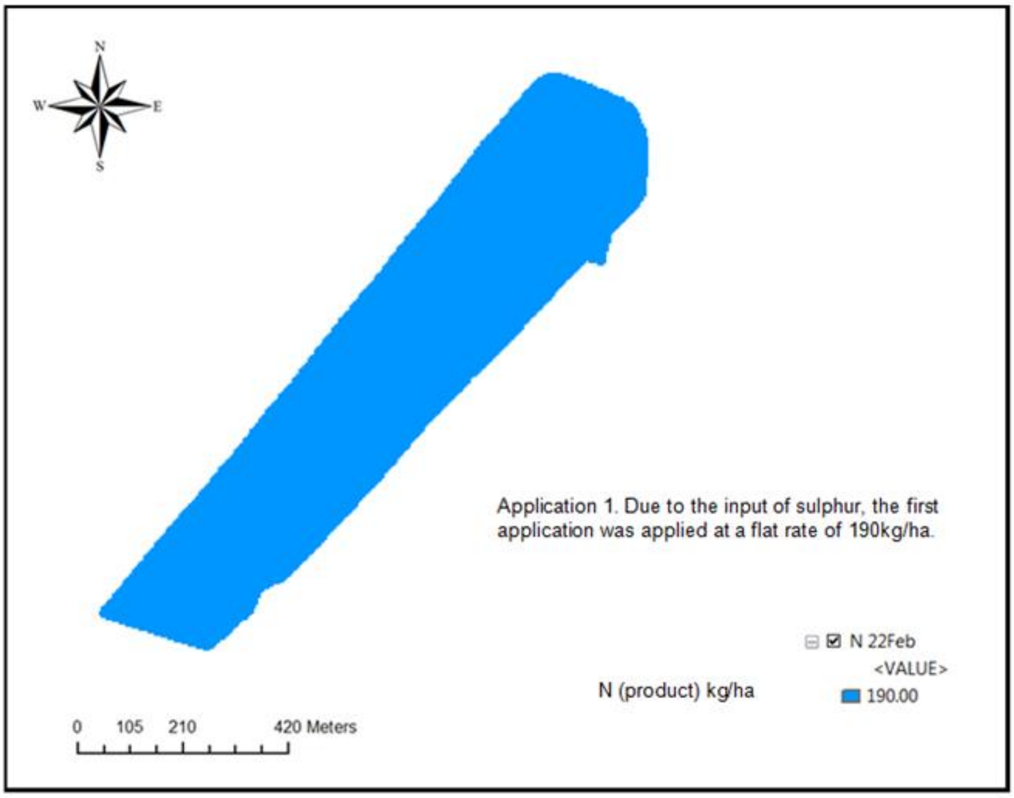


Figure 128. Weston Bottom LAI 22/04/13.



Application 1. Due to the input of sulphur, the first application was applied at a flat rate of 190kg/ha.

Figure 129. Weston Bottom N Application 22/02/13.

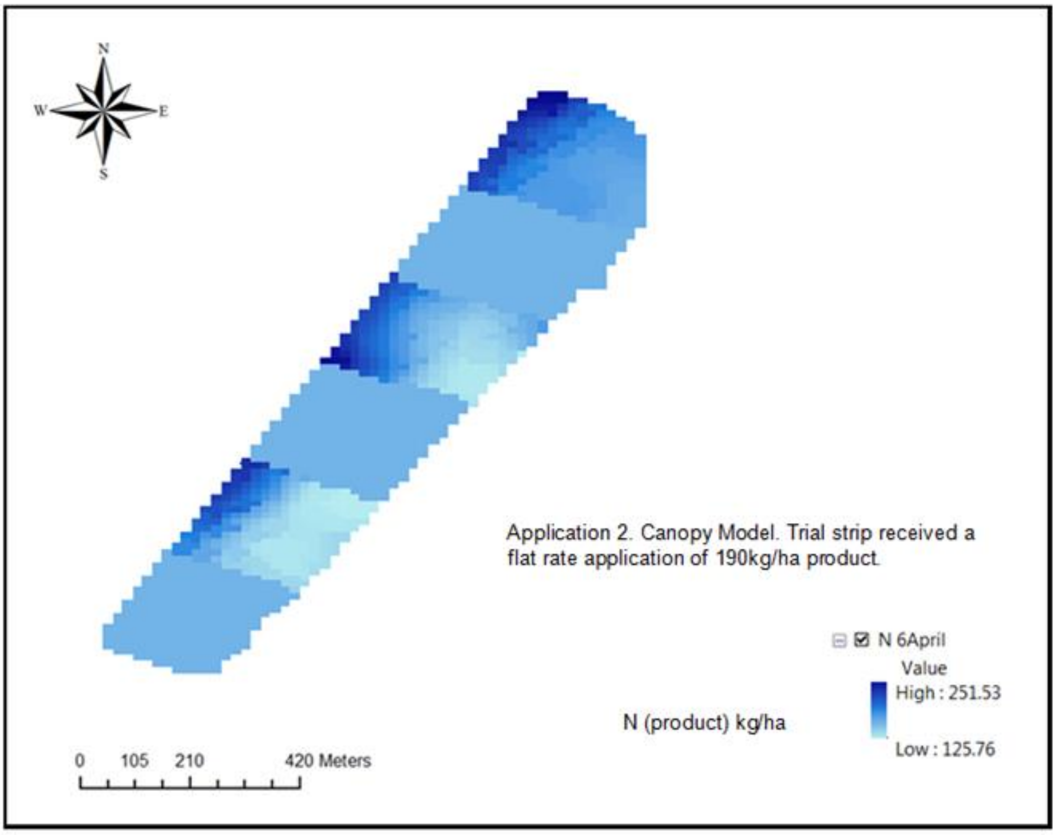


Figure 130. Weston Bottom N Application 06/04/13.

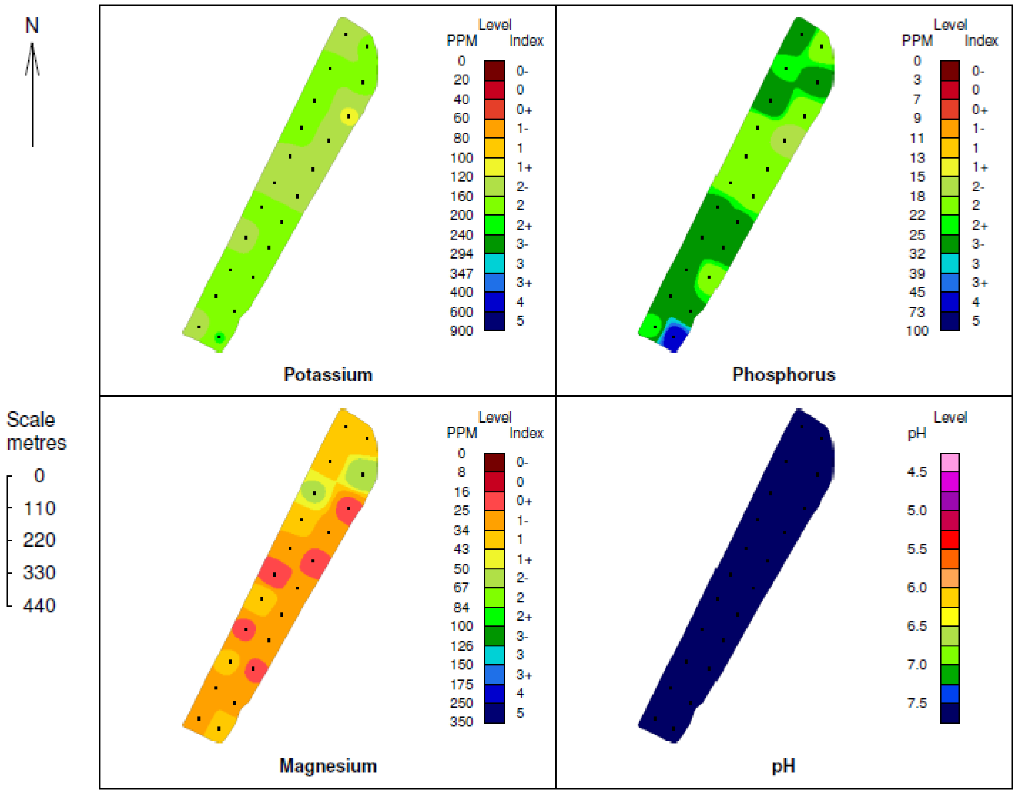


Figure 131. P, K, Mg and pH sampling results for Weston Bottom 12/11/2008.

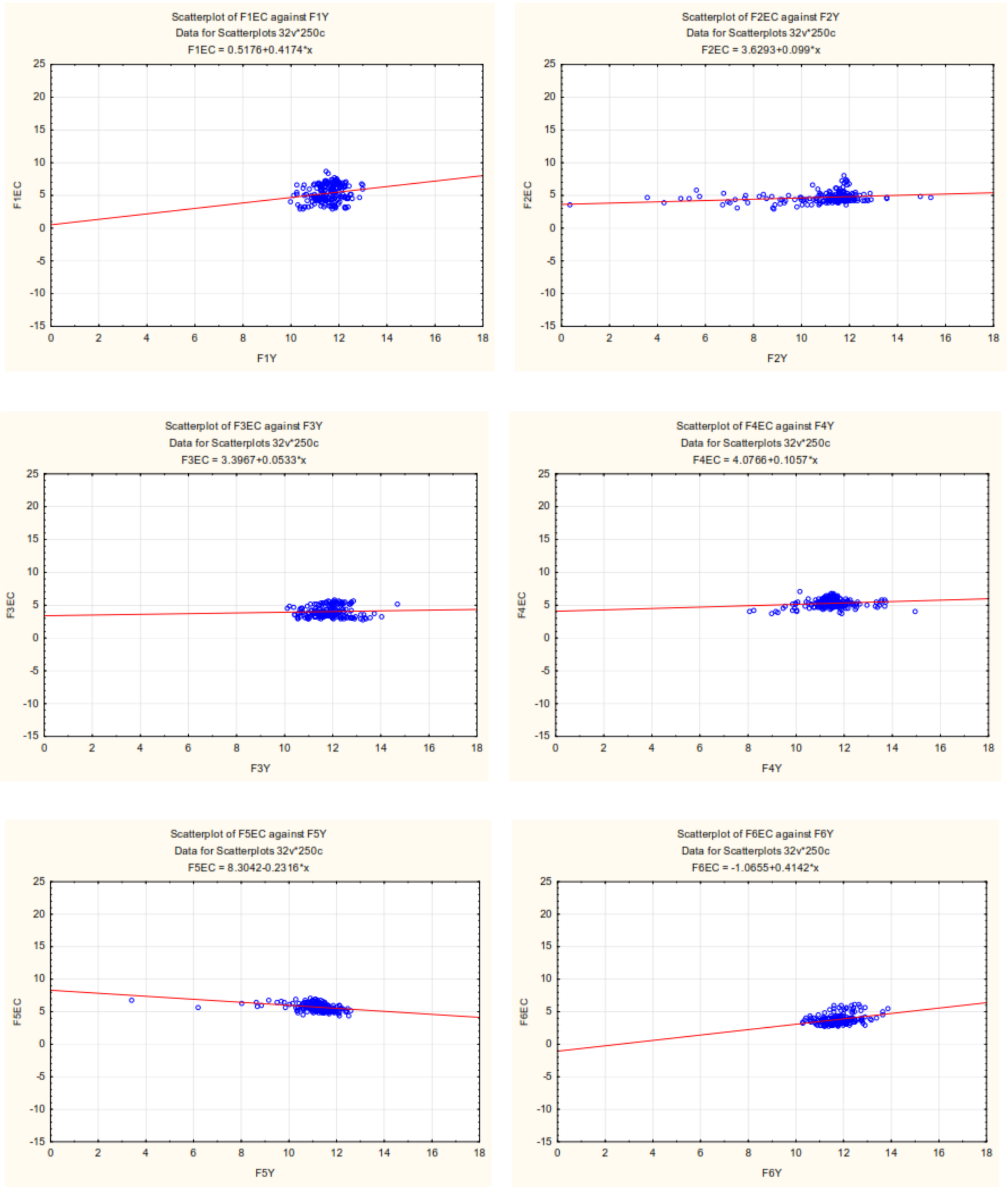
Table 10. Descriptive Statistics for all Sub-sample plots.

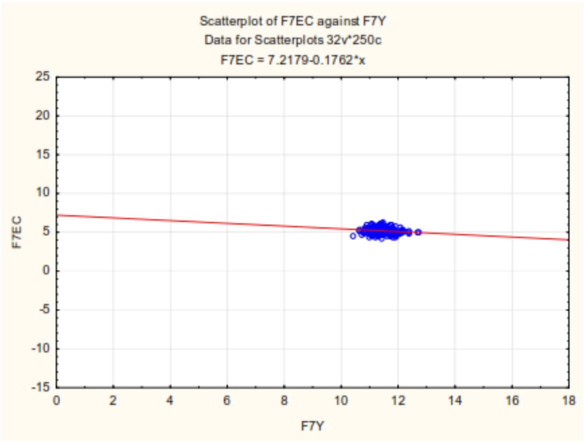
| **Plot** | **Mean Yield (t/ha)** | **Yield SD (t/ha)** | **Mean Shallow EC (µS)** | **Shallow ECSD (µS)** | **Mean Deep EC (µS)** | **Deep EC SD (µS)** |
|---|---|---|---|---|---|---|
| Bugmore F1 | 11.54 | 0.56 | 5.34 | 1.29 | 16.95 | 1.37 |
| Bugmore F2 | 10.95 | 1.86 | 4.71 | 0.78 | 16.37 | 0.69 |
| Bugmore F3 | 11.84 | 0.72 | 4.03 | 0.80 | 15.16 | 0.79 |
| Bugmore F4 | 11.47 | 0.88 | 5.29 | 0.63 | 17.39 | 0.57 |
| Bugmore F5 | 11.16 | 0.87 | 5.72 | 0.55 | 18.75 | 0.85 |
| Bugmore F6 | 11.74 | 0.62 | 3.80 | 0.74 | 14.11 | 0.44 |
| Bugmore F7 | 11.48 | 0.39 | 5.20 | 0.40 | 17.61 | 0.40 |
| Bugmore F8 | 11.04 | 0.64 | 3.97 | 0.82 | 16.22 | 1.02 |
| Bugmore V1 | 11.61 | 0.91 | 5.15 | 1.38 | 16.39 | 1.25 |
| Bugmore V2 | 10.99 | 1.30 | 4.46 | 0.82 | 17.09 | 1.03 |
| Bugmore V3 | 11.79 | 0.55 | 4.63 | 0.65 | 15.16 | 0.70 |
| Bugmore V4 | 11.46 | 0.42 | 5.33 | 0.31 | 17.75 | 0.28 |
| Bugmore V5 | 10.61 | 1.21 | 5.40 | 0.40 | 17.66 | 0.63 |
| Bugmore V6 | 10.65 | 2.28 | 3.36 | 0.81 | 13.94 | 0.69 |
| Bugmore V7 | 11.46 | 0.41 | 4.14 | 0.94 | 15.70 | 1.20 |
| Bugmore V8 | 10.81 | 0.67 | 3.89 | 1.37 | 16.14 | 1.68 |
| Chalk Churn F1 | 11.33 | 1.04 | -3.49 | 2.43 | -46.39 | 3.94 |
| Chalk Churn F2 | 11.83 | 0.74 | -2.42 | 1.54 | -44.03 | 2.85 |
| Chalk Churn F3 | 11.10 | 0.77 | -2.90 | 2.94 | -44.57 | 4.28 |
| Chalk Churn F4 | 10.64 | 1.69 | -7.40 | 1.23 | -52.92 | 2.08 |
| Chalk Churn V1 | 10.93 | 0.86 | -0.75 | 3.41 | -39.58 | 6.56 |
| Chalk Churn V2 | 10.90 | 1.41 | -4.46 | 1.85 | -46.07 | 2.96 |

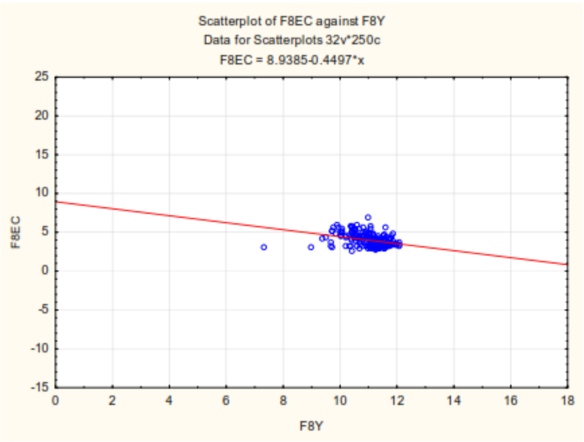
| Plot | Mean Yield (t/ha) | Yield SD (t/ha) | Mean Shallow EC (µS) | Shallow ECSD (µS) | Mean Deep EC (µS) | Deep EC SD (µS) |
|---|---|---|---|---|---|---|
| Chalk Churn V3 | 11.42 | 1.03 | -2.63 | 2.08 | -42.04 | 3.30 |
| Chalk Churn V4 | 11.31 | 0.65 | -6.55 | 2.25 | -50.87 | 3.79 |
| Hamstyles F1 | 5.93 | 1.73 | 18.21 | 1.39 | -56.37 | 2.02 |
| Hamstyles F2 | 7.22 | 2.58 | 13.50 | 2.75 | -60.83 | 3.28 |
| Hamstyles F3 | 11.01 | 1.07 | 1.84 | 4.31 | -78.41 | 8.92 |
| Hamstyles F4 | 7.87 | 2.61 | 14.04 | 3.16 | -62.26 | 3.12 |
| Hamstyles F5 | 11.20 | 0.75 | 6.73 | 1.94 | -73.56 | 2.99 |
| Hamstyles F6 | 10.00 | 1.31 | 5.27 | 1.12 | -78.06 | 2.28 |
| Hamstyles V1 | 6.67 | 1.70 | 13.22 | 1.59 | -62.66 | 2.86 |
| Hamstyles V2 | 6.54 | 1.47 | 14.81 | 3.96 | -57.60 | 10.35 |
| Hamstyles V3 | 11.97 | 1.15 | 3.67 | 1.29 | -75.15 | 2.12 |
| Hamstyles V4 | 9.22 | 1.29 | 10.20 | 1.66 | -67.71 | 1.97 |
| Hamstyles V5 | 9.45 | 2.22 | 11.29 | 3.62 | -66.03 | 3.61 |
| Hamstyles V6 | 12.59 | 0.93 | 2.50 | 0.89 | -83.78 | 1.35 |
| High Street Lane F1 | 10.98 | 2.54 | 4.92 | 2.67 | 11.35 | 4.45 |
| High Street Lane F2 | 11.48 | 1.71 | -1.75 | 3.07 | 7.07 | 4.22 |
| High Street Lane F3 | 11.26 | 1.54 | 1.10 | 1.69 | 4.99 | 2.87 |
| High Street Lane V1 | 10.94 | 1.42 | 8.11 | 3.09 | 17.40 | 5.76 |
| High Street Lane V2 | 11.57 | 1.28 | 3.91 | 2.85 | 8.22 | 4.27 |
| High Street Lane V3 | 10.78 | 1.89 | 0.35 | 1.81 | 3.28 | 2.37 |
| Home F1 | 12.24 | 1.23 | -7.79 | 1.24 | -51.55 | 2.32 |
| Home F2 | 12.69 | 0.94 | -6.42 | 1.22 | -49.48 | 1.68 |
| Home F3 | 11.23 | 0.60 | -6.75 | 1.59 | -50.31 | 2.22 |
| Home V1 | 11.01 | 1.34 | -8.19 | 0.46 | -52.55 | 0.97 |

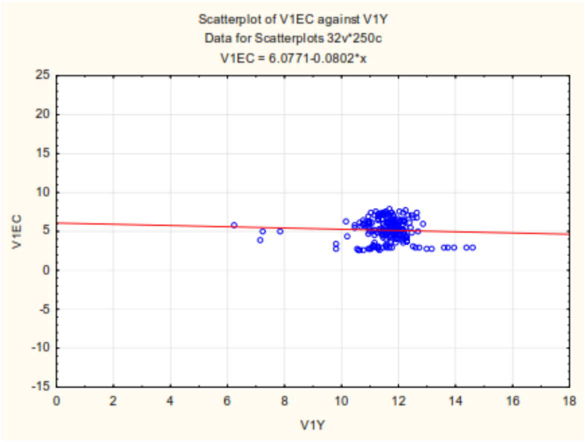
| Plot | Mean Yield (t/ha) | Yield SD (t/ha) | Mean Shallow EC (µS) | Shallow EC SD (µS) | Mean Deep EC (µS) | Deep EC SD (µS) |
|---|---|---|---|---|---|---|
| Home V2 | 11.51 | 1.03 | -5.65 | 1.31 | -48.87 | 1.66 |
| Home V3 | 10.89 | 1.40 | -4.17 | 0.73 | -46.64 | 0.94 |
| Singford F1 | 12.29 | 1.45 | -5.90 | 0.76 | -51.20 | 0.98 |
| Singford F2 | 11.96 | 1.31 | -2.28 | 3.14 | -46.25 | 4.43 |
| Singford V1 | 12.90 | 1.92 | -5.90 | 1.23 | -50.78 | 1.93 |
| Singford V2 | 13.67 | 1.23 | -3.02 | 2.11 | -47.47 | 3.01 |
| Weston Bottom F1 | 11.76 | 1.83 | -4.46 | 1.00 | -47.95 | 1.61 |
| Weston Bottom F2 | 13.05 | 1.36 | -5.58 | 1.24 | -49.73 | 1.71 |
| Weston Bottom F3 | 12.37 | 1.08 | -5.72 | 1.24 | -50.29 | 1.47 |
| Weston Bottom V1 | 12.86 | 1.46 | -5.92 | 1.08 | -50.25 | 1.82 |
| Weston Bottom V2 | 12.23 | 1.68 | -6.12 | 1.07 | -50.65 | 1.30 |
| Weston Bottom V3 | 11.98 | 1.37 | -4.85 | 1.45 | -49.13 | 1.96 |

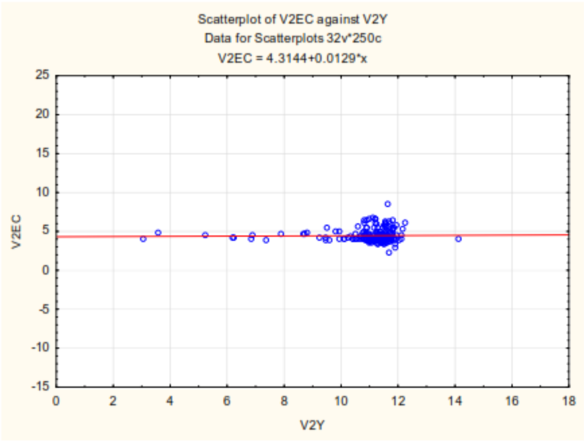
Figure 132. Shallow EC vs. Yield scatter plot for Bugmore sub-sample plots.

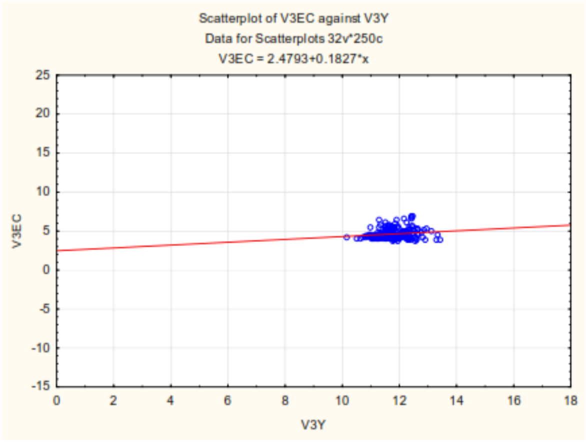


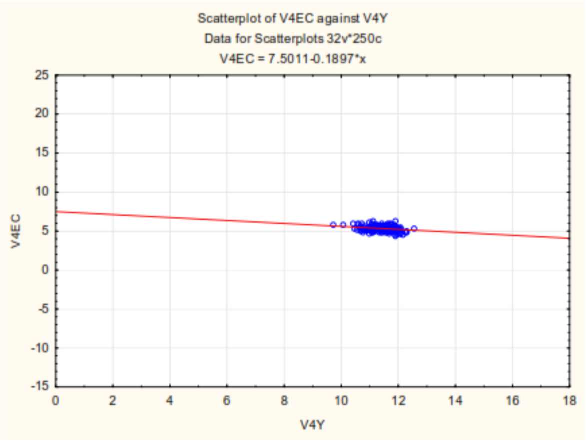

Scatterplot of F7EC against F7Y
Data for Scatterplots 32v*250c
F7EC = 7.2179-0.1762*x

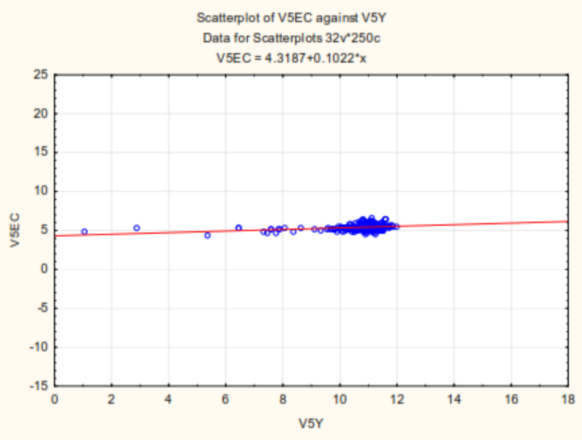

Scatterplot of F8EC against F8Y
Data for Scatterplots 32v*250c
F8EC = 8.9385-0.4497*x

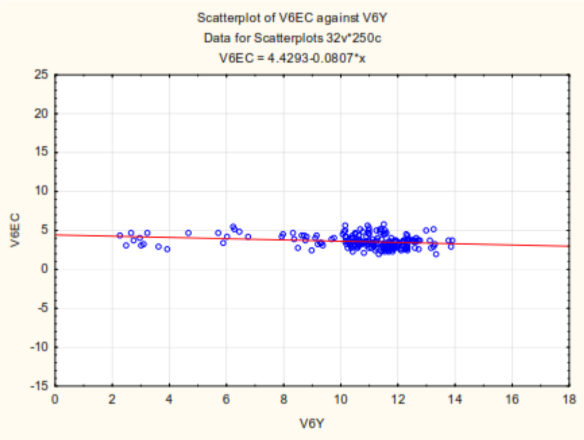

Scatterplot of V1EC against V1Y
Data for Scatterplots 32v*250c
V1EC = 6.0771-0.0802*x

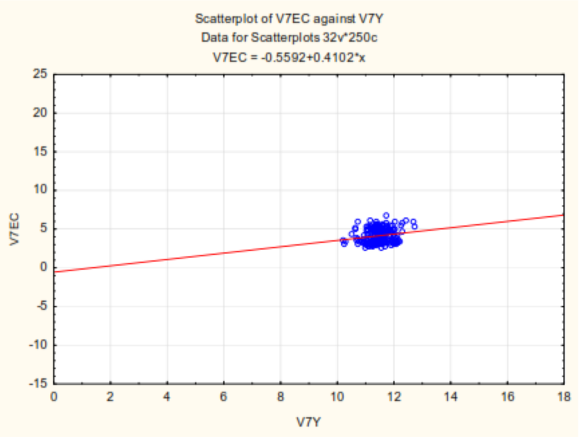

Scatterplot of V2EC against V2Y
Data for Scatterplots 32v*250c
V2EC = 4.3144+0.0129*x


Scatterplot of V3EC against V3Y
Data for Scatterplots 32v*250c
V3EC = 2.4793+0.1827*x


Scatterplot of V4EC against V4Y
Data for Scatterplots 32v*250c
V4EC = 7.5011-0.1897*x


Scatterplot of V5EC against V5Y
Data for Scatterplots 32v*250c
V5EC = 4.3187+0.1022*x
V5EC
V5Y
25
20
15
10
5
0
-5
-10
-15
0
2
4
6
8
10
12
14
16
18


Scatterplot of V6EC against V6Y
Data for Scatterplots 32v*250c
V6EC = 4.4293-0.0807*x
V6EC
V6Y
25
20
15
10
5
0
-5
-10
-15
0
2
4
6
8
10
12
14
16
18


Scatterplot of V7EC against V7Y
Data for Scatterplots 32v*250c
V7EC = -0.5592+0.4102*x
V7EC
V7Y
25
20
15
10
5
0
-5
-10
-15
0
2
4
6
8
10
12
14
16
18

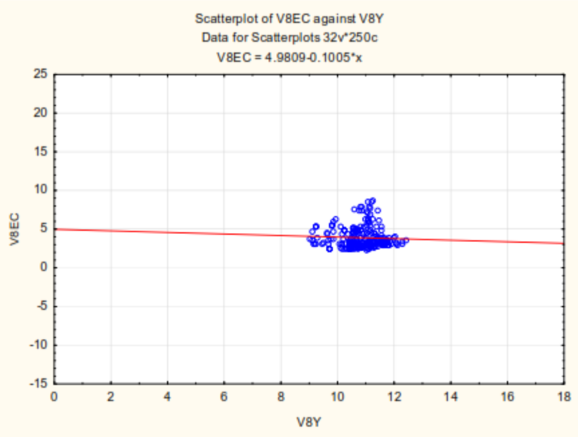
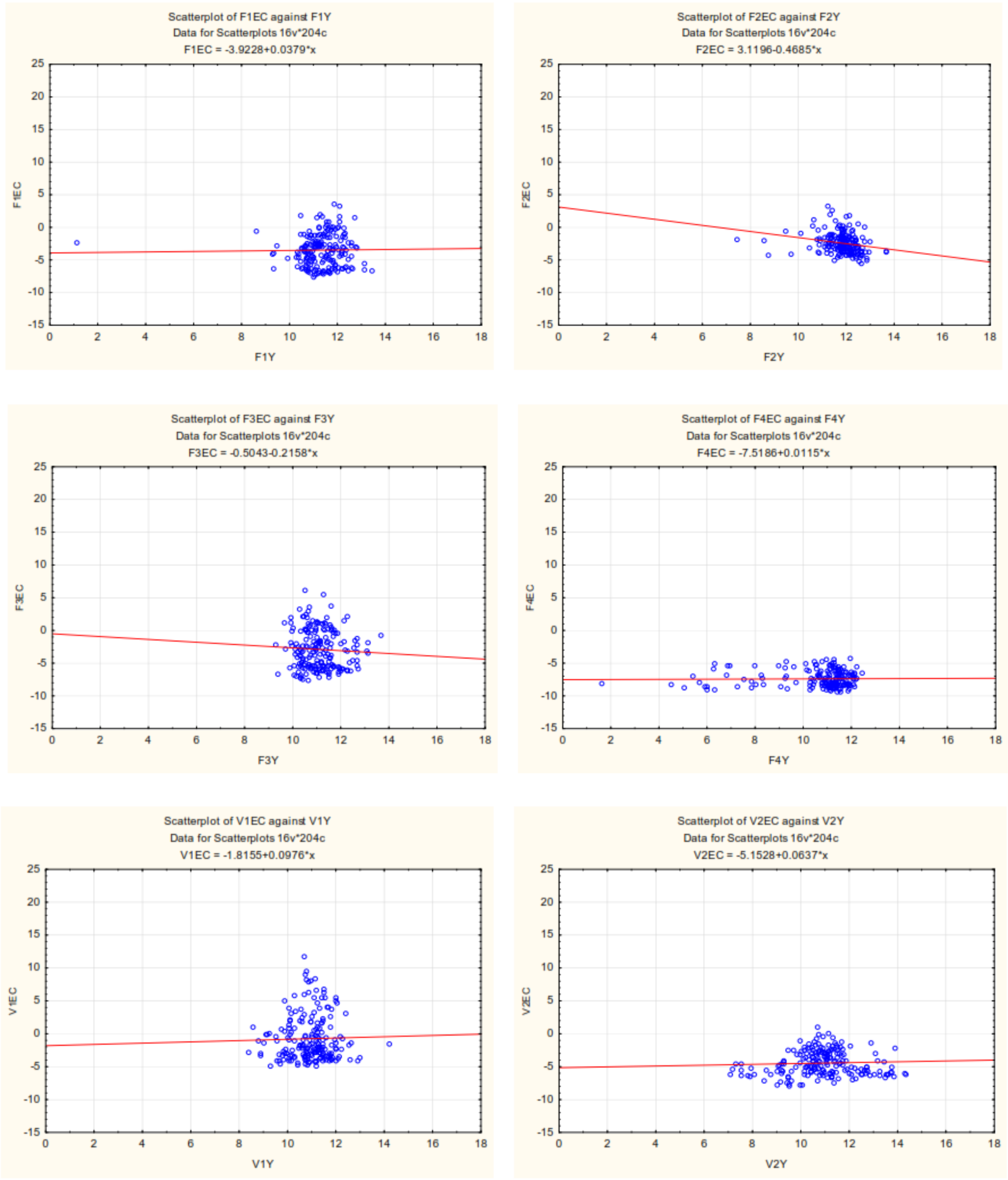
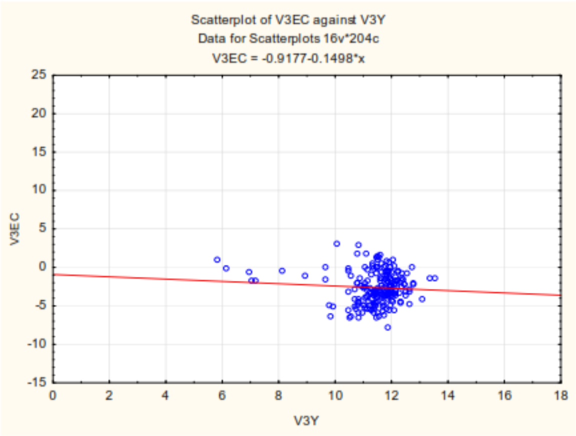
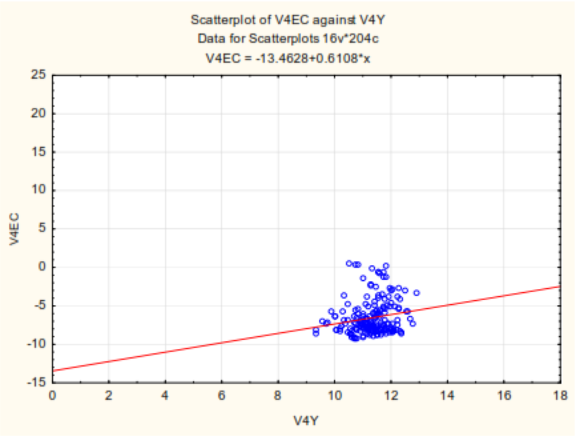

Scatterplot of V8EC against V8Y
Data for Scatterplots 32v*250c
V8EC = 4.9809-0.1005*x
V8EC
V8Y
25
20
15
10
5
0
-5
-10
-15
0
2
4
6
8
10
12
14
16
18

Figure 133.Shallow EC vs. Yield scatter plot for ChalkChurn sub-sample plots.



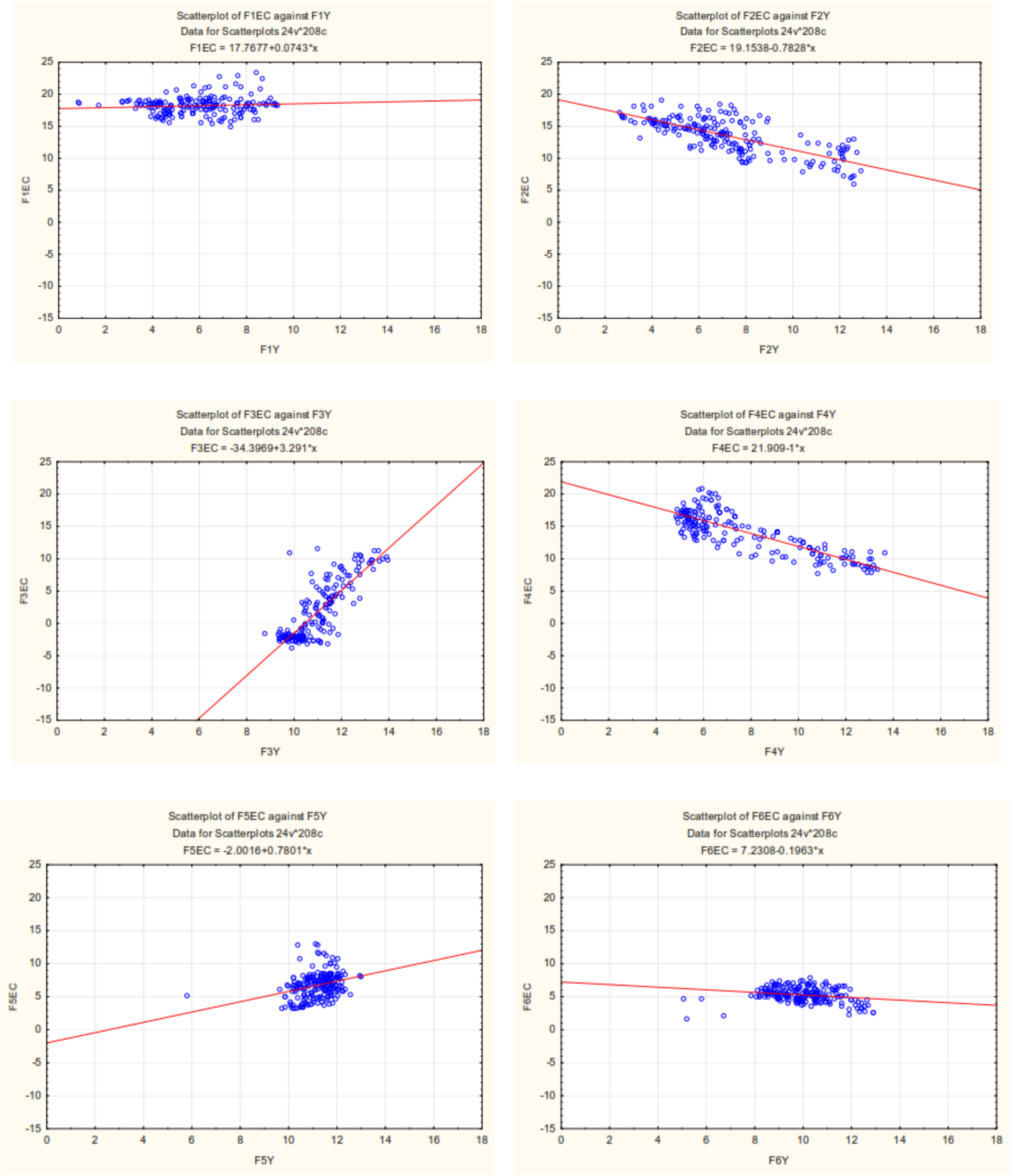


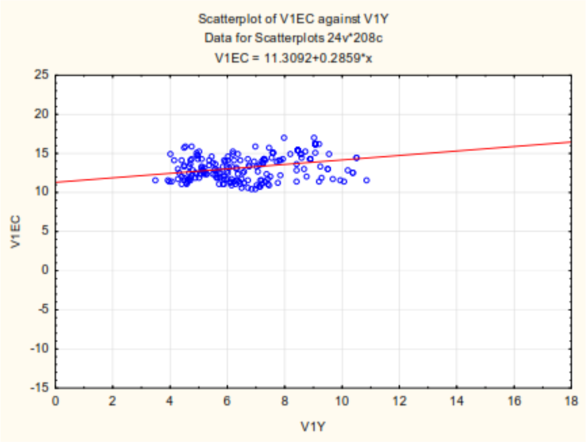
Scatterplot of V3EC against V3Y
Data for Scatterplots 16v*204c
V3EC = -0.9177-0.1498*x
V3EC
V3Y
25
20
15
10
5
0
-5
-10
-15
0
2
4
6
8
10
12
14
16
18

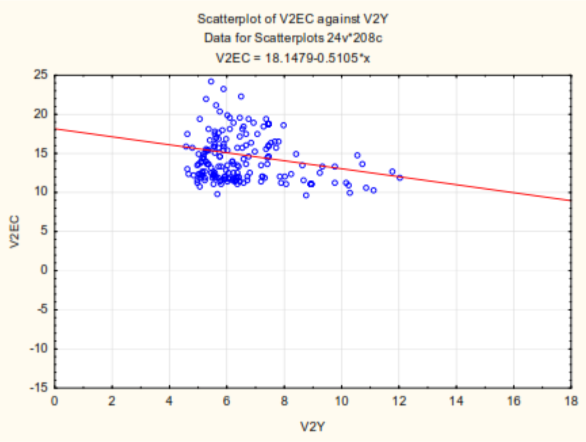


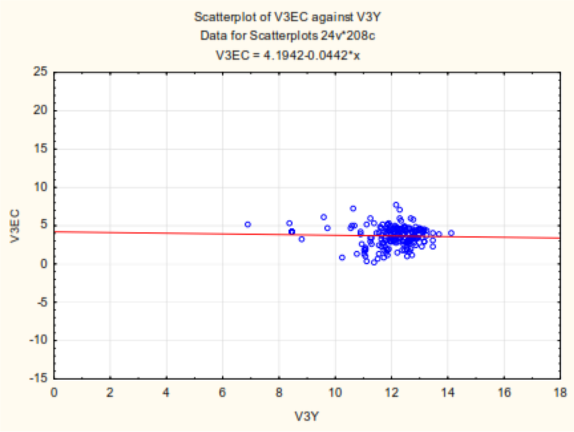
Scatterplot of V4EC against V4Y
Data for Scatterplots 16v*204c
V4EC = -13.4628+0.6108*x
V4EC
V4Y
25
20
15
10
5
0
-5
-10
-15
0
2
4
6
8
10
12
14
16
18

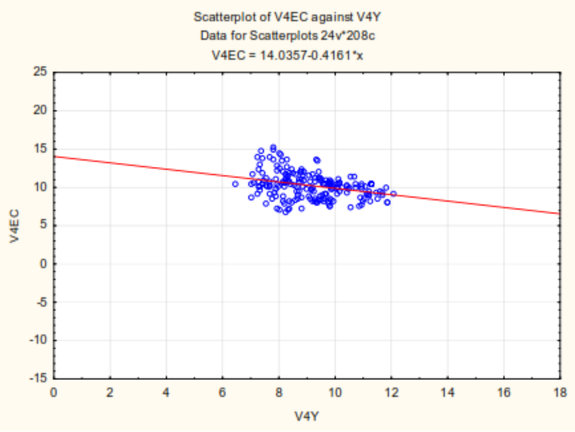
Figure 134. Shallow EC vs. Yield scatter plot for Hamstyles sub-sample plots.

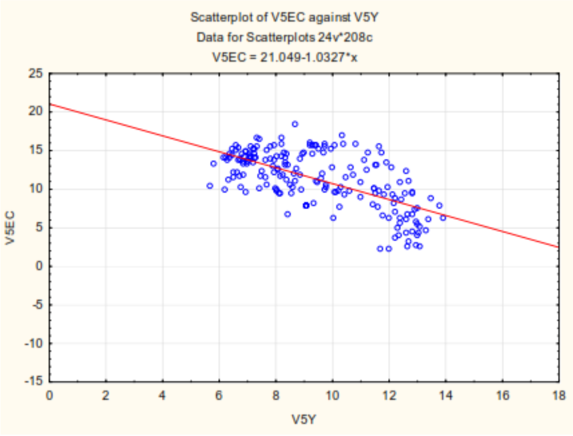



Scatterplot of V1EC against V1Y
Data for Scatterplots 24v*208c
V1EC = 11.3092+0.2859*x
V1EC
V1Y
25
20
15
10
5
0
-5
-10
-15
0
2
4
6
8
10
12
14
16
18


Scatterplot of V2EC against V2Y
Data for Scatterplots 24v*208c
V2EC = 18.1479-0.5105*x
V2EC
V2Y
25
20
15
10
5
0
-5
-10
-15
0
2
4
6
8
10
12
14
16
18


Scatterplot of V3EC against V3Y
Data for Scatterplots 24v*208c
V3EC = 4.1942-0.0442*x
V3EC
V3Y
25
20
15
10
5
0
-5
-10
-15
0
2
4
6
8
10
12
14
16
18


Scatterplot of V4EC against V4Y
Data for Scatterplots 24v*208c
V4EC = 14.0357-0.4161*x
V4EC
V4Y
25
20
15
10
5
0
-5
-10
-15
0
2
4
6
8
10
12
14
16
18


Scatterplot of V5EC against V5Y
Data for Scatterplots 24v*208c
V5EC = 21.049-1.0327*x
V5EC
V5Y
25
20
15
10
5
0
-5
-10
-15
0
2
4
6
8
10
12
14
16
18

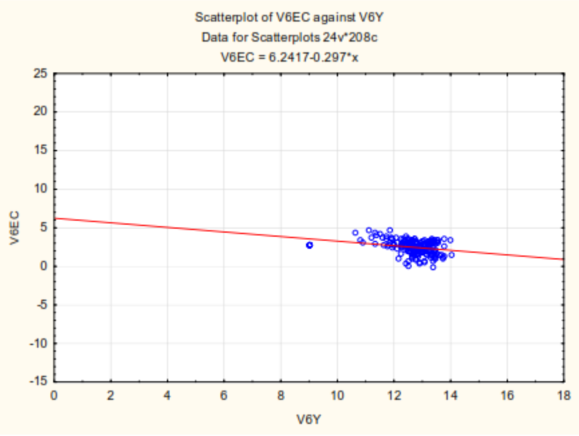

Scatterplot of V6EC against V6Y
Data for Scatterplots 24v*208c
V6EC = 6.2417-0.297*x
V6EC
V6Y
25
20
15
10
5
0
-5
-10
-15
0
2
4
6
8
10
12
14
16
18

Figure 135. Shallow EC vs. Yield scatter plot for High Street Lane sub-sample plots.

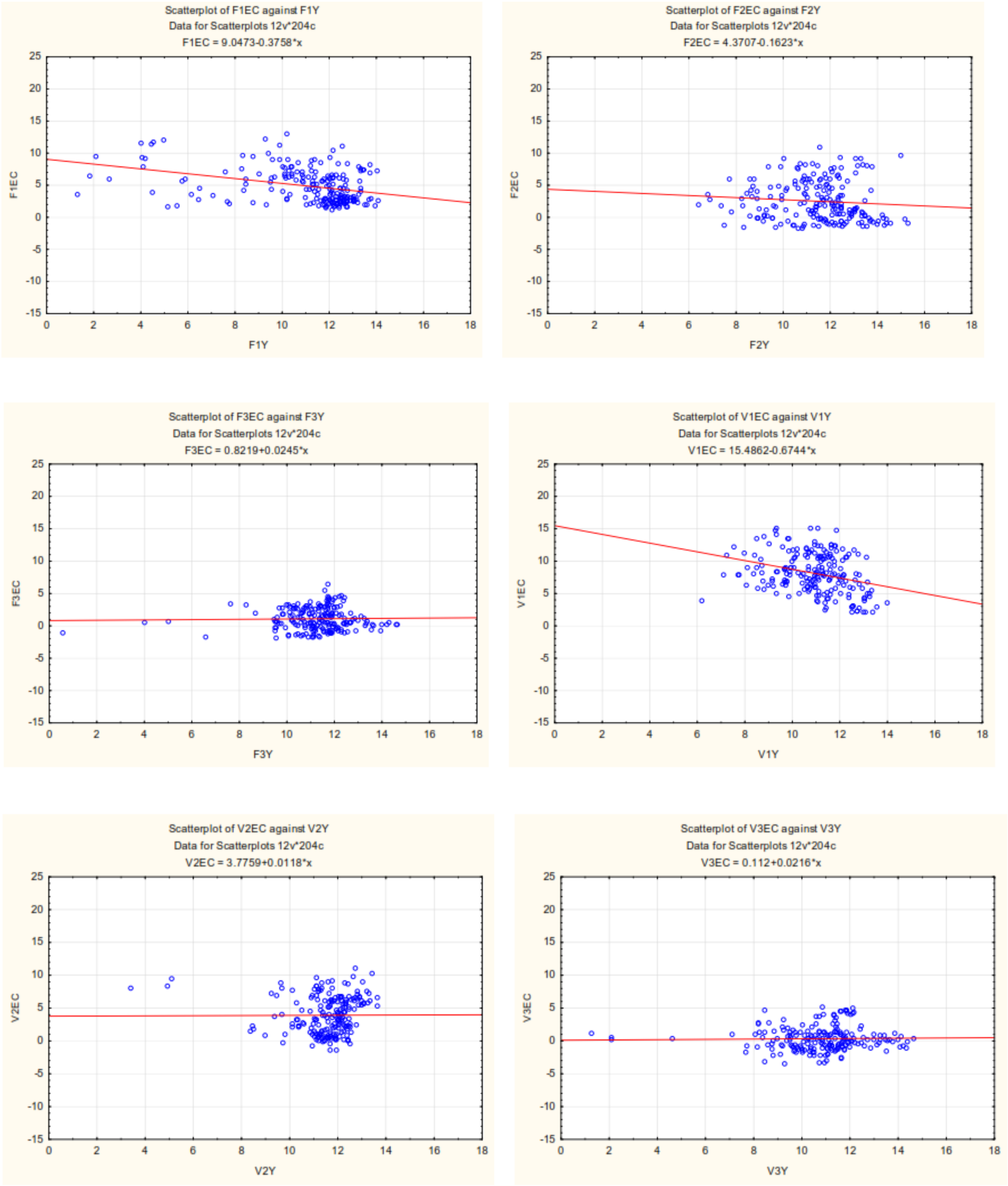


Figure 136. Shallow EC vs. Yield scatter plot for Home Field sub-sample plots.

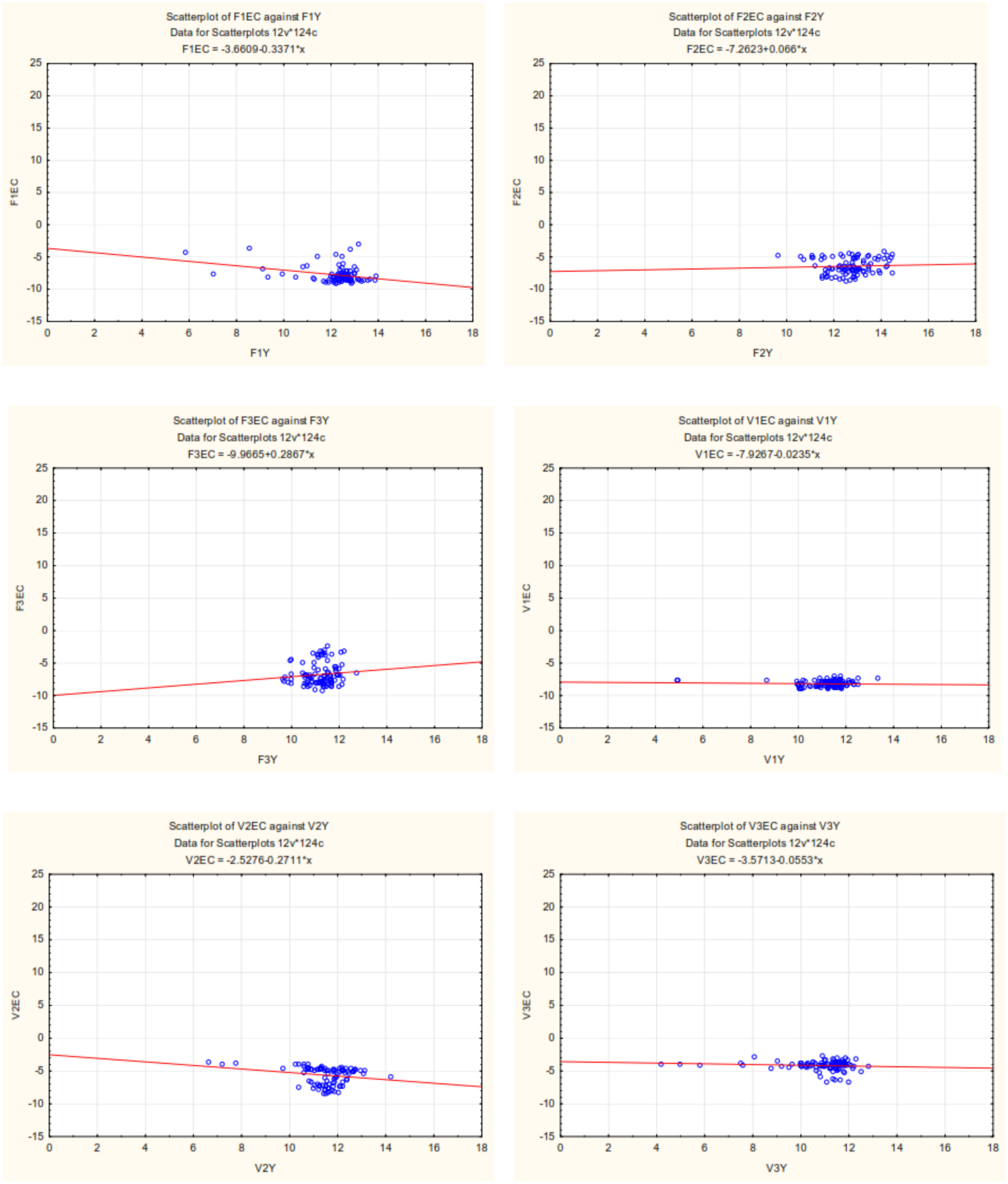


Figure 137. Shallow EC vs. Yield scatter plot for Singford sub-sample plots.

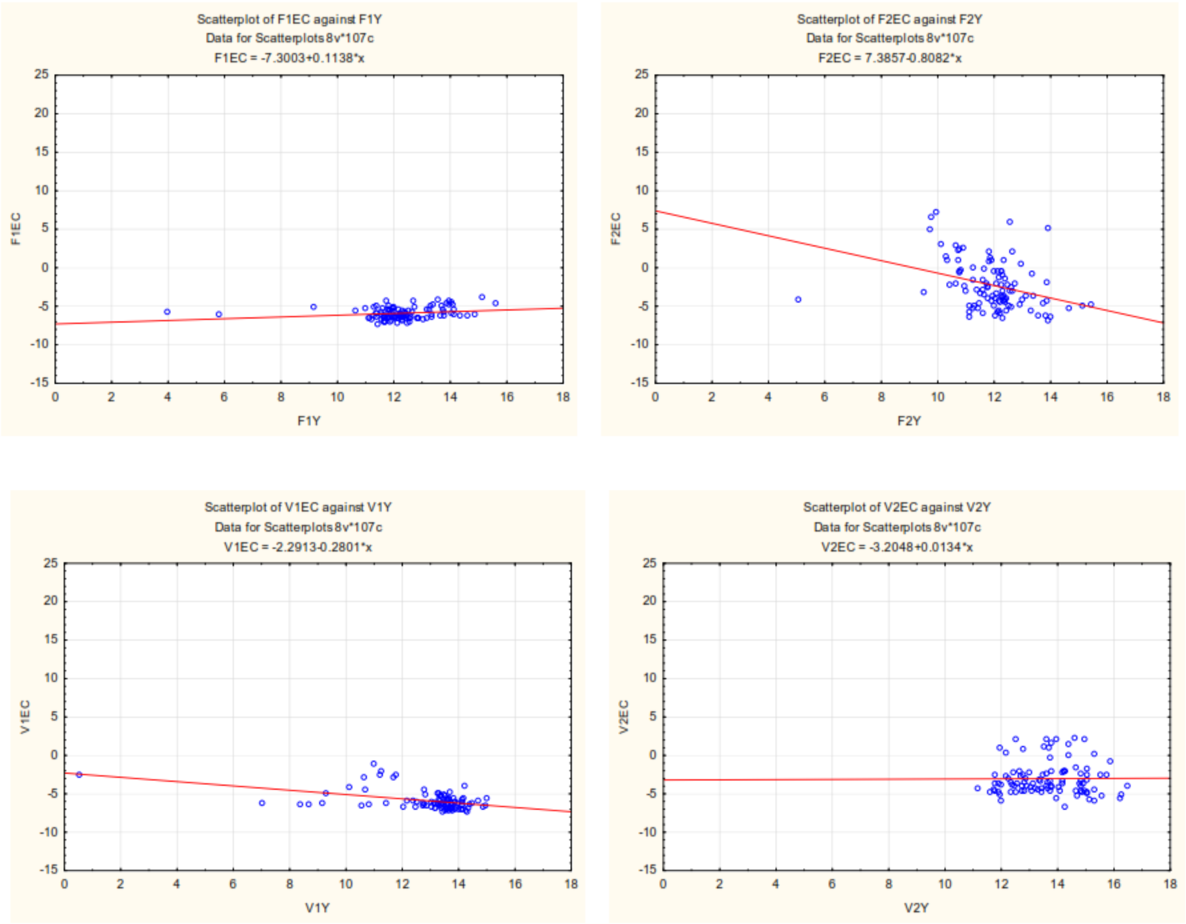
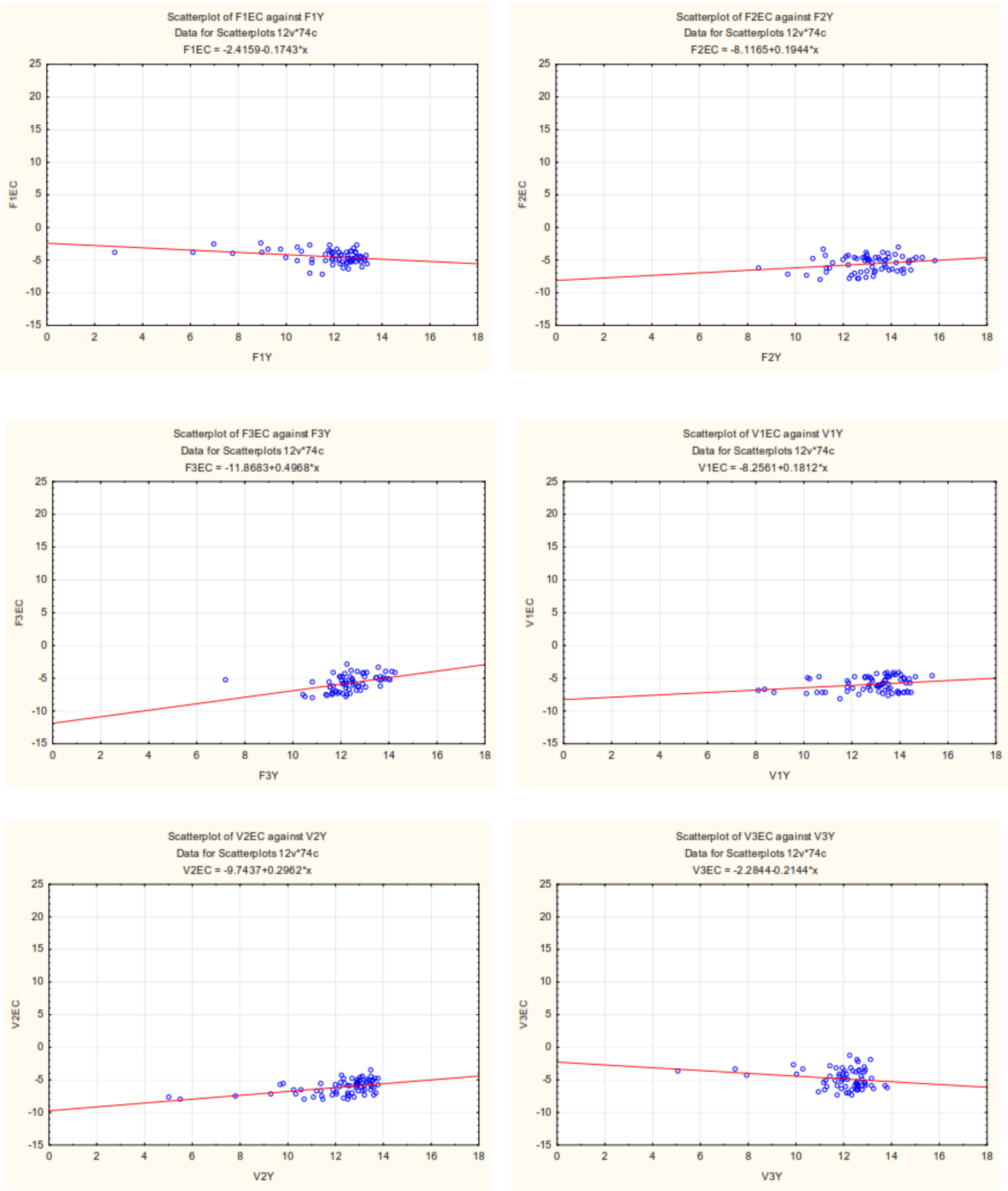


Figure 138. Shallow EC vs. Yield scatter plot for Weston Bottom sub-sample plots.



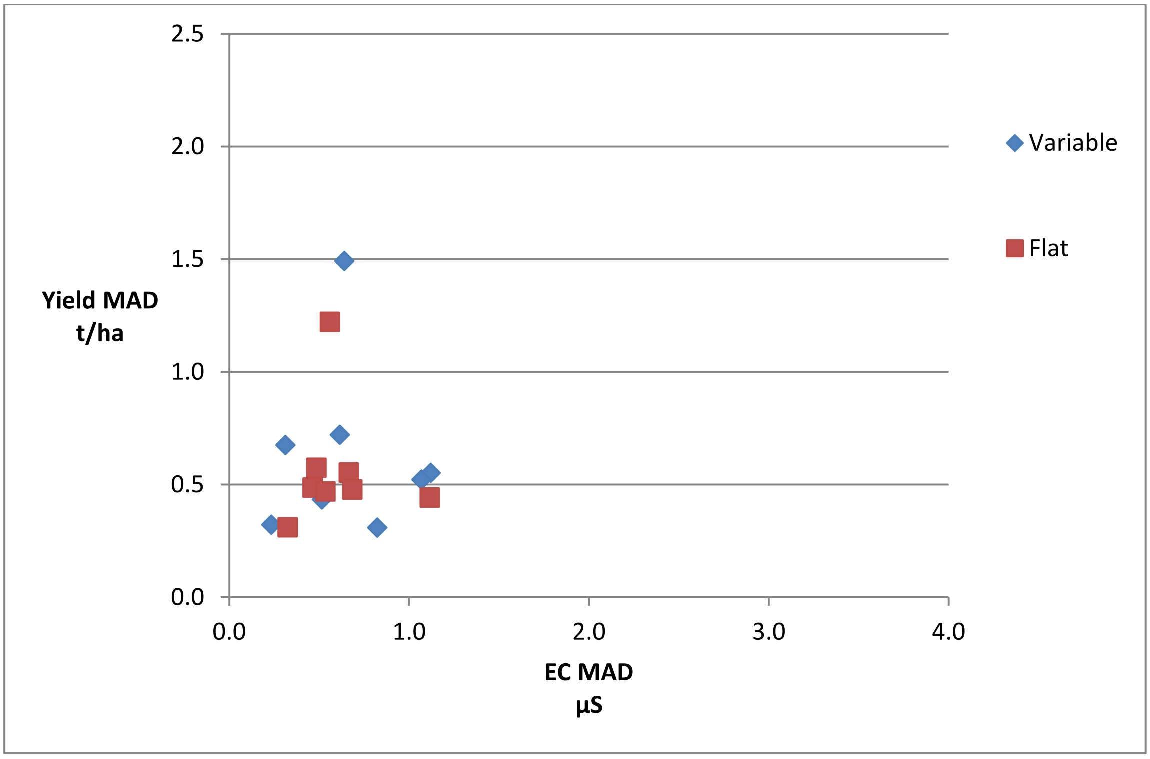


Figure 139. Scatter plot of Yield MAD vs. Shallow EC MAD for Bugmore.

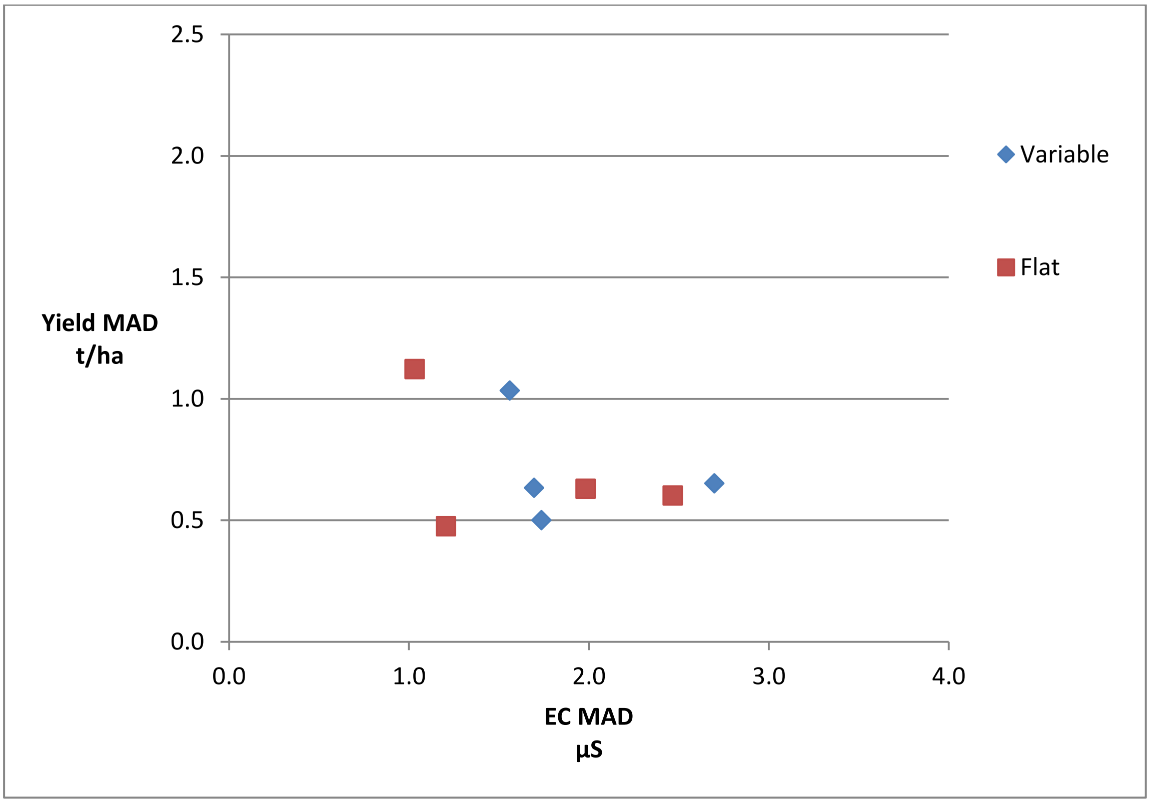


Figure 140. Scatter plot of Yield MAD vs. Shallow EC MAD for Chalk Churn.

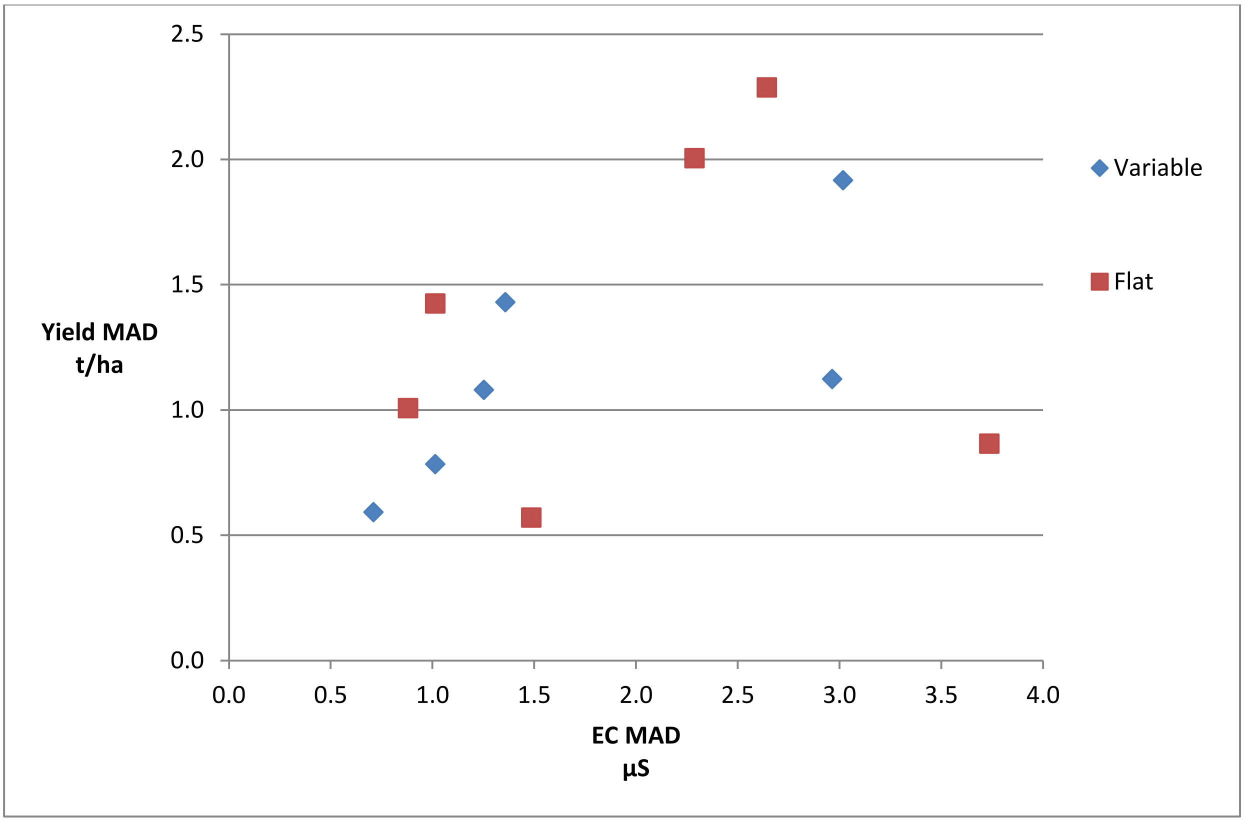


Figure 141. Scatter plot of Yield MAD vs. Shallow EC MAD for Hamstyles.

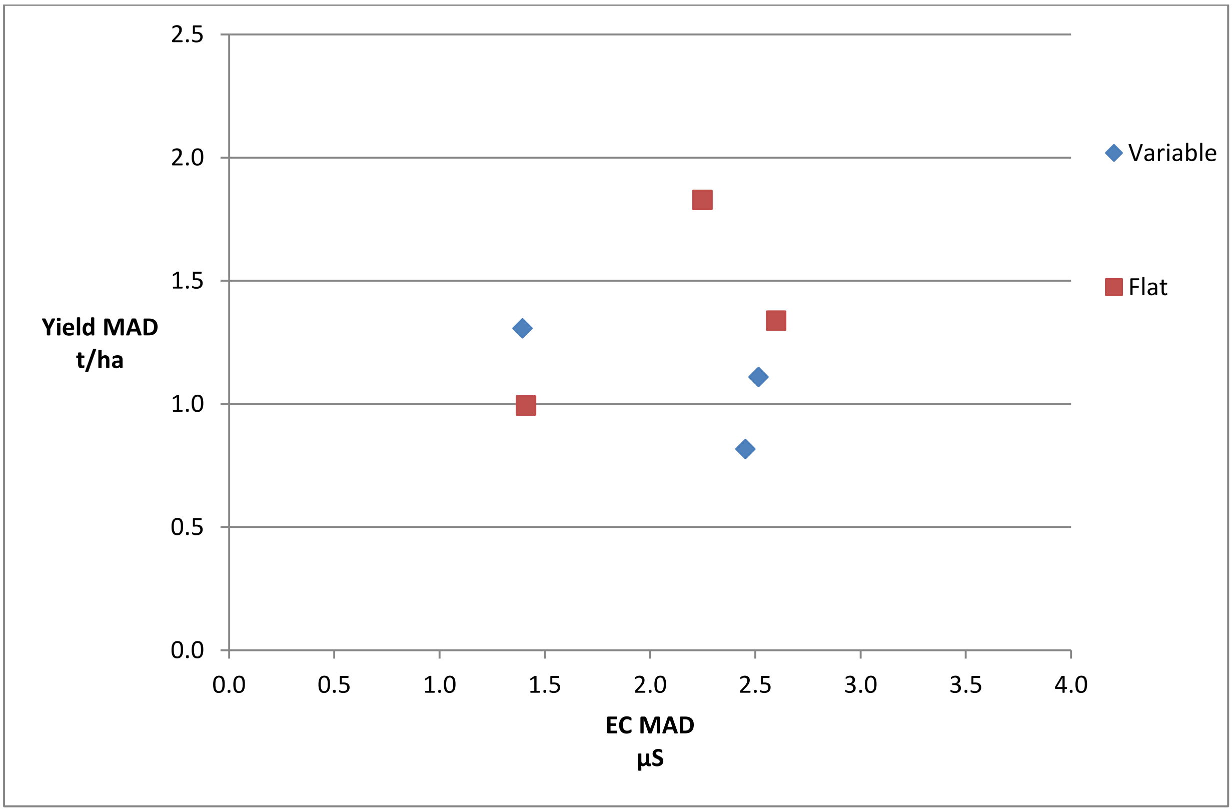


Figure 142. Scatter plot of Yield MAD vs. Shallow EC MAD for High Street Lane.

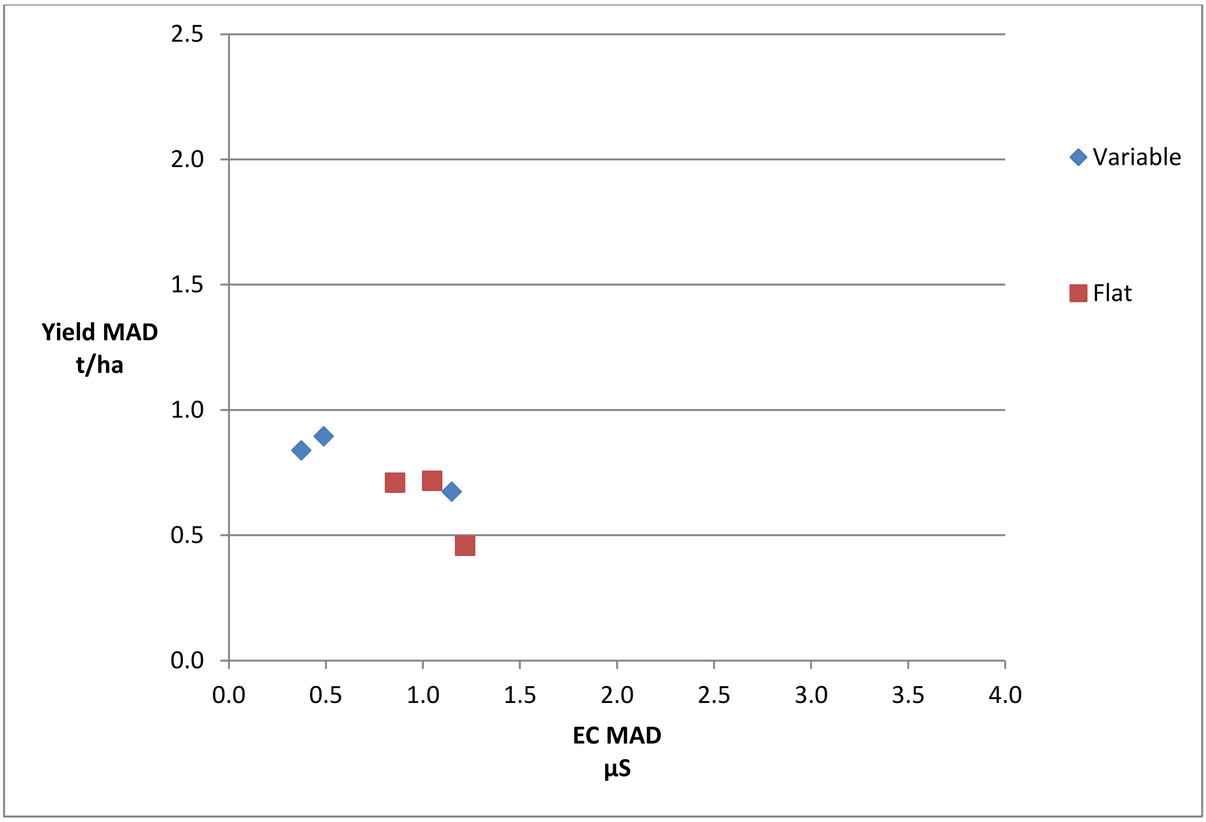


Figure 143. Scatter plot of Yield MAD vs. Shallow EC MAD for Home Field.

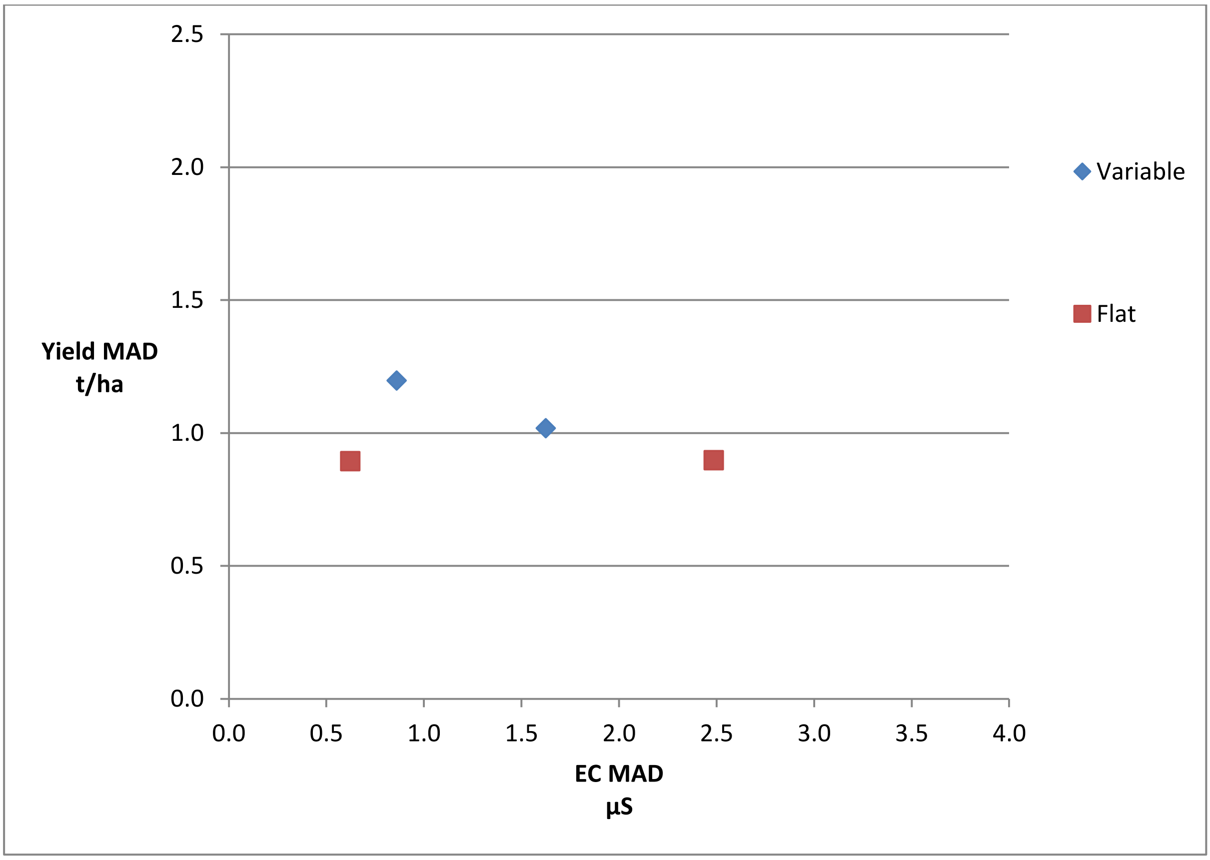


Figure 144. Scatter plot of Yield MAD vs. Shallow EC MAD for Singford.

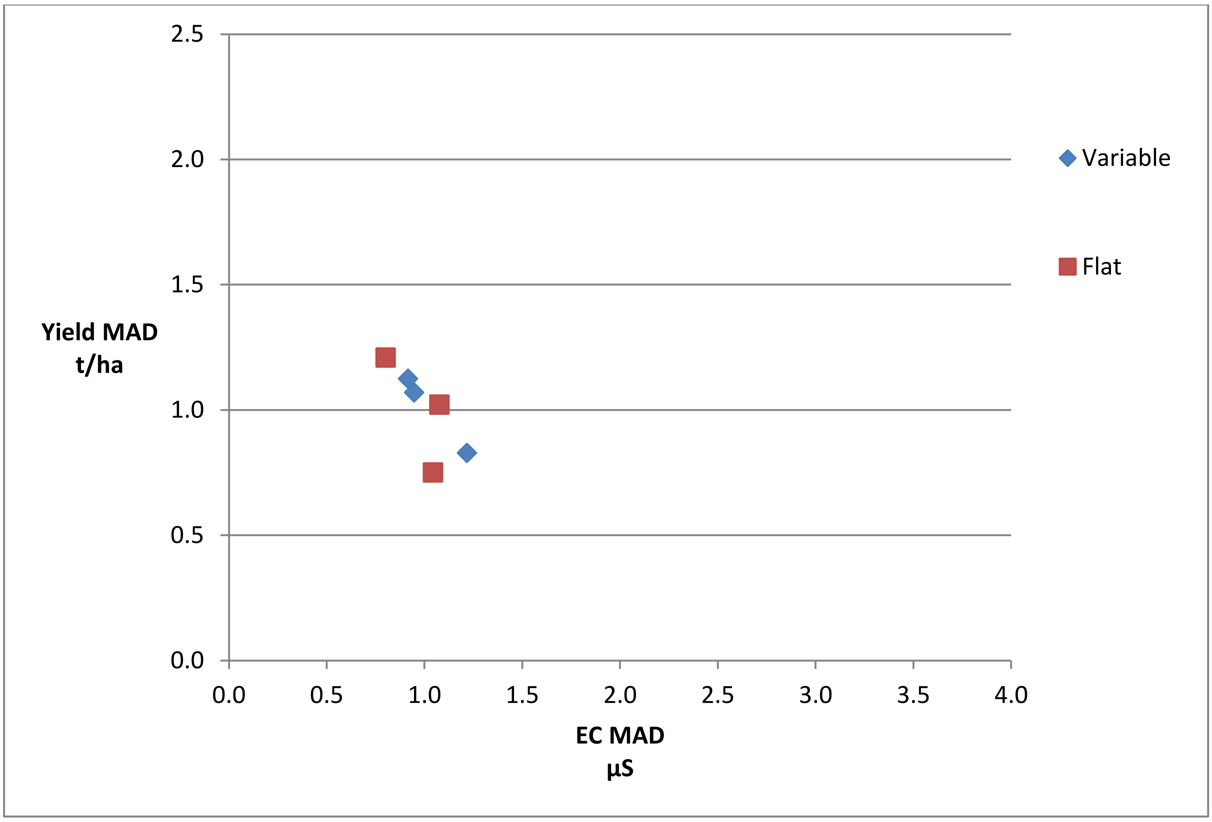


Figure 145. Scatter plot of Yield MAD vs. Shallow EC MAD for Weston Bottom.