The application of land surveying and geophysical techniques to the study of within-field variation of soil properties in the upper catchment of the River Cober

Submitted by Andrew Beney to the University of Exeter as a dissertation towards the degree of Master of Science by advanced study in Surveying with Land and Environmental Management, 31st August 2017

I certify that all material in this dissertation which is not my own work has been identified and that no material is included for which a degree has previously been conferred on me.

Abstract

This study focussed on the River Cober catchment in Cornwall and considered whether soil erosion was taking place within arable fields in the north of the area. The combined methods of surveying, geophysical techniques (non-invasive electromagnetic induction and resistivity tomography) and soil sampling were used extensively, with a particular emphasis on using precision agriculture methods to improve nutrient management. It was found that overall levels of available phosphorus were low in the arable fields (6.1 – 22.0 mg/l) but significant differences were found between a more topographically stable zone compared with a steeply sloping area (20.4 mg/l and 13.4 mg/l). A zone where eroded soil was deposited was also identified and the depth of deposition was estimated using resistivity sections combined with soil profiles. The study offered valuable insights into within-field variation of soil chemistry, although electromagnetic induction could not accurately predict concentrations of available phosphorus.

Contents

List of Figures

List of Tables

Acknowledgements

I would like to acknowledge the help and support received from my project supervisor Neill Wood, who has always offered encouragement and advice. The staff of the Upstream Thinking Project have also been very supportive in setting-up the study, in particular Stuart Coleman who has offered much helpful advice throughout. Thanks are also due to the landowner who permitted regular access to the site during the project.

Introduction

The River Cober, in the Lizard Peninsula in Cornwall, receives water from urban and rural landscapes and flows into the English Channel at Loe Pool to the south of the town of Helston (Figure 1.1).

Figure 1.1 The River Cober and Loe Pool (to the south west), shown in a regional context. The orange circle approximates the centre of the study site (Ordnance Survey, 2017a, scale 1:50000, alongside an outline map courtesy of the OS)

Considerable attention has been given to the water quality status of both the River Cober and Loe Pool in the last decade and significant efforts have been made to improve the chemical and ecological conditions of the waterbody. This study focusses on water quality; particular attention will be paid to soil erosion and nutrient inputs from agricultural lands into the upper reaches of the river. The guiding principle of this study is controlling potential pollutants at their source, rather than attempting to mitigate their subsequent impacts.

The report begins by examining the study area and then considers the nature of the problem and reflects on some of the actions taken to date to mitigate the issue. The next section considers the challenge of phosphate leaching, how it arises and its ecological impacts. This complex issue is an important one as many aspects of water quality and soil condition are affected by it. Scientific methods of studying the issue will be examined. The combined approaches of surveying, geophysical techniques and soil sampling will be outlined, with a particular focus on using precision agriculture methods to improve nutrient targeting. The results of the investigations will be presented and discussed in relation to existing research on this subject.

The catchment of the River Cober extends from the uplands around Carthew and Porkellis to the north of Helston to Loe Pool, which is situated approximately midway between the town of Porthleven and the village of Gunwalloe on the south coast (Figure 1.1). The study site for this project is a mixed farm where beef cattle are raised and commercial flowers are grown on arable land (Figure 1.2, p7). There are estimated to be around 70 farms in the catchment of the River Cober (Walker, 2017, p.26), the majority of which are involved in beef or dairy production. In a broader context, agriculture is a vital element to the regional economy – around 75% of the land in Cornwall is classified as farmland (French, Murphy and Atkinson, 1999, p.10). The study farm is situated between the villages of Porkellis and Carnkie in the north east of the catchment and is within a Catchment Sensitive Farming area, where advice is given to landowners on how to improve water quality (Walker, 2017, p.31). The reasons why this location was chosen for the study will be outlined below and in the methodology section.

Small streams run to the east and south of the farm and the land drains towards these directions. To the southeast of the farm is an area of wet willow habitat, commonly known as willow carr. The streams feed into the River Cober, which becomes a more established river at Porkellis. At first sight the landscape around the north of the catchment appears to be a bucolic environment of rolling hills and streams. However, the entry of the river into Loe Pool reveals a more complex situation.

Water body status and the work of the Loe Pool Forum

The Environment Agency commenced monitoring of phosphorus levels in the River Cober and Loe Pool in 1995. This chemical was chosen because it is known to be implicated in eutrophication and also because it is targeted as a priority for control under the Water Framework Directive (WFD) and the monitoring of Loe Pool as a Site of Special Scientific Interest (SSSI). The current water body classifications are summarised in Table 1.1 below (Environment Agency, 2017). Chemical classifications are recorded as good or fail and are dependent on recorded levels of priority substances set by the Environmental Quality Standards framework. Ecological status ranges across five classes (high, good, moderate, poor and bad) and are measured according to biological quality indicators, physico-chemical quality and the presence of specific contaminants.

Water body	*Ecological classification*	*Chemical classification*
Upper River Cober	Moderate	Good
Lower River Cober	Moderate	Good
The Loe	Poor	Good

Table 1.1 Environment Agency water body classifications 2016

The ecological condition is only moderate at the upper reaches of the catchment and deteriorates when the river reaches the Loe. The recent Cober Management Plan (Walker, 2017, p.21) provides data and discussion about the reasons for this situation, these are outlined below. Monitoring of total phosphorus loadings from the river and its tributaries into Loe Pool showed that there has been a steady decline in concentrations since 1995 (from 8760 kg yr^{-1} to 1423.9 kg yr^{-1} in 2015/16). Of particular note are the reductions in phosphorus brought about by phosphate stripping that was installed in sewage treatment works in Helston and Culdrose. Further reductions are required if the target for the SSSI is to be met (a further 464.9 kg yr^{-1}). However, the recovery of the Pool is estimated to take many years and bioremediation works are being planned by the Loe Pool Forum to facilitate rehabilitation. Monitoring of phosphorus loading is taking place in the tributaries at several locations (Walker, 2017, p.64).

Many issues related to agriculture have been identified as contributing to the depleted condition of Loe Pool; these include ammonia from decomposing organic matter, nutrient enrichment from soil sediment deposited in the river and pesticide run-off (Walker, 2017, p.32). The river quality is also impacted by the presence of metal contaminants from earlier mine workings in the area (Walker, 2017, p.66). Study of sediment cores from Loe Pool has shown that total phosphorus, total organic matter and sedimentary chlorophyll have all significantly increased since 1938, largely owing to elevated nutrient inputs (Coard et al., 1983). Soil erosion prior to this date was predominantly influenced by mining activities.

Where water courses receive elevated concentrations of nutrients, particularly phosphate and nitrate, a notable increase in biological production results in eutrophication. During periods of low water flow (late spring and summer) the longer time for nutrients to accumulate and the raised temperatures promotes algal growth (Jarvie, Neal and Withers, 2006). The decay of organic matter leads to the development of algal blooms, increased oxygen demand, lower light availability and a reduction in the ecological health of the ecosystem (fewer key species and reduced growth). Loe Pool is in a state of advanced eutrophication (Walker, 2017, p.8) and the Forum is seeking means of reducing nutrient input at all stages of inflow.

In typical river catchments the nutrient levels are generally lower at the upper reaches than at the outflow areas; there is often a marked contrast in plant communities where the upper zones are characterised by plants suited to lower nutrient concentrations than at the outflow (Mainstone, Dils and Withers, 2008).

The work of the Loe Pool Forum encompasses an Integrated Catchment Approach to managing the Pool and the river along its entirety. This perspective means that the whole catchment area is studied and stakeholders are involved from many organisations in order to enhance water quality and manage flood risk. Specific aims have been set out in a Management Strategy Review and progress towards them is being evaluated.

Two of the stakeholders involved in the Loe Pool Forum are South West Water and the Cornwall Wildlife Trust, who together have instigated the Upstream Thinking Project to enhance the ecological condition of important catchments in Devon and Cornwall which provide drinking water. This project was established in order to bridge the gap between agricultural management and the quality of the freshwater environment. Specialist staff from Cornwall Wildlife Trust offer tailored advice and grants to farmers regarding methods of reducing agricultural run-off into water courses (Walker, 2017, p.31). Farms are identified in the zone where water quality issues have been noted. Typical strategies for improvement may include soil sampling and nutrient management planning to ensure that optimum nutrients are supplied to the crop without undue risk of run-off. Assistance with applications for Countryside Stewardship funding for ecological improvements is also offered. For instance, the installation of buffer strips, such as grasses and hedgerows, to mitigate against sediment transport is supported. This scheme commenced in July 2015 and since then several farms in the catchment have signed up to the programme (Walker, 2017, p.29).

The regulation of environmental quality through the Cross Compliance process has also provided some degree of auditing of standards relating to ‘good agricultural and environmental condition’ of land (GAEC) and the EU Statutory Management Requirements; these have encouraged good practice relating to habitat and species protection (DEFRA, 2009, p.9). Where farming takes place in Nitrate Vulnerable Zones further rules apply concerning nitrogen application and manures. The farms in the Cober catchment are all within a NVZ (MAGIC, 2017).

The Upstream Thinking Project also includes regular water monitoring in collaboration with South West Water to correlate quality standards at the Wendron Water Treatment Works with sampling points across the catchment.

Timely and appropriate advice to landowners confers many benefits, with reduced nutrient inputs into rivers there is less requirement for water treatment by South West Water. On the River Cober the main drinking-water abstraction point is at Trenear (Figure 1.2) and South West Water have invested significantly in addressing pollution from ammonia and pesticides in the Cober Drinking Water Protection Area (Walker, 2017, p.32). Improved water quality also means that the lower stretches of the Cober are likely to improve in terms of nutrient and sediment loading, particularly Loe Pool. Of particular interest to this project is the issue of the loss of nutrients through soil erosion and methods of prevention.

Figure 1.2 The locality of the study area, showing the villages of Porkellis and Carnkie, along with the abstraction point at Trenear (south west corner), (Ordnance Survey 2017b, scale 1:25000)

Conserving soils

Soils are dynamic elements of ecological systems, natural erosion by water and wind is typically at a slower rate than soil formation (White, 2006, p.251). In the case of water erosion the physical nature of the impact is determined by the energy imparted by rainfall events and the soils susceptibility to erosion. High intensity rainfall imparts greater energy for soil detachment. Raindrops can detach particles from the surface which may become entrained in surface flow. The process may operate in a fairly uniform manner across the field or may become concentrated in channels (termed rill erosion). Where scouring takes place at sites of high velocity flow, deeper channels or gullies form. When the surface dries a hard crust forms that limits water infiltration and facilitates run-off (Environment Agency, 2007, p.34). During erosion the soil will have lost quantities of important organic nutrients and clay minerals. Furthermore the capacity for cation exchange and for biological processes will have reduced, limiting fertility, along with carbon sequestration (White, 2006, p.251). In more serious cases the material that remains in place is the more inert sand fraction. Root growth will also be hindered by the loss of soil porosity and change in structure.

Soil texture is a dominant influence on erosion potential, where a large fraction of clay is present the porosity is reduced resulting in higher runoff risk (White, 2006, p.254). Although high proportions of sand allow for water to infiltrate such conditions also result in less stable soil structure and greater susceptibility to wind and water erosion. Deposited sediments often collect in a fan-shape at the end of an inclined field (Figure 1.3) and also at the base of hedges (Environment Agency, 2007, p.35).

Figure 1.3 Deposition of soil at the base of a field in Cornwall

The impacts of soil erosion on ecological systems are well documented and include raised levels of sediment entering watercourses. This results in more turbid conditions that hinder the lifecycles of many aquatic organisms, such as salmon and trout eggs. Sediment deposits in reservoirs and navigational channels also require removal. Estimated costs of erosion in England and Wales per year amount to £139 and £187 million (Rickson, 2014). Anthropogenic influences can greatly exceed the natural rate of erosion in many locations. Rates of erosion have been reported in excess of 20 Mg ha yr^{-1} (Rickson, 2014). The most vulnerable soil types and land uses were found to be fine textured silt and peat soils supporting arable crops. The steepness of the field and length of incline are also important factors as they increase runoff velocity and volume- a Universal Soil Loss Equation has been developed to quantify losses (Morgan, 2005, p.57).

Certain crops are also more prone to erosion than others, primarily owing to exposure of the soil surface and limited root systems offering little binding action in the soil (potatoes and bulbs are noted in this regard; Environment Agency, 2007, p.28). For daffodil production the ground is prepared by cultivation methods (large stones are removed) and the soil tested for pH levels, which must be above 6.0 (Tompsett, 2006, p.26). Fertilisers including phosphate are often applied and bulbs are planted using a tractor and a hopper, usually in August. The bulbs are planted in ridges, tractors travel up and down the field rather than laterally, as they are susceptible to moving sideways and over-turning. Planting downslope increases the risk of soil erosion. Bulbs are usually lifted in June (Tompsett, 2006, p.31), although some stock is retained for replanting. Often some ground cover is left during winter and barley may be sown in autumn or a grass buffer strip planted at the bottom of the field. The daffodil crop may remain in the ground for up to three years.

It is important to note that economic and agricultural policy factors also play a major part in the issue, particularly in facilitating which types of crops are grown which can exacerbate the erosion problem (Evans, 2006). The rapid expansion in post-war agricultural output and intensification of production was enhanced by production subsidies.

The use of machinery in fields can readily create tramlines which may form into erosive channels. Planting crops in the autumn rather than the spring exposes the ground to machinery in wet conditions and may result in bare soil during the winter, increasing the risk of erosion (Rickson, 2014).

A well-structured soil facilitates water and air passage through pores, compacted soils limit the ability of water to infiltrate and are particularly problematic where poor structure occurs near the ground's surface. Soil structure is changed by tillage, dramatically reducing the coherence of soil aggregates (White, 2006, p.255). Tillage practices also result in translocation of soil particles. Research in Denmark (Heckrath et al., 2005) has shown that soil profiles can become reduced owing to tillage erosion at shoulder-slopes (high ground dipping in a convex manner) and on convex back-slopes. The study used soil samples and radio-nuclide techniques and found that deposition of soil nutrients occurred over time at concave features and at the foot of slopes. The researchers found a significant difference in total phosphorus concentrations between erosion and deposition areas. The combined influences of tillage and water erosion were thought to be responsible for this. However, soil parent material and varied application of fertilizers also impacted on the situation.

Solutions have been put forward to mitigate the situation, these include modifying tillage practices and in some cases stopping ploughing altogether and utilising in-situ drilling to minimise damage to soil structure (White, 2006, p.248). Other effective methods focus on working with the contours of the land and tilling across the incline to reduce the length of the slope; keeping crop residues either in the ground or on the soil surface throughout the year help to prevent perturbation from raindrops; inter-cropping of trees or grasses act as a barrier to surface run-off. Rickson (2014) reviewed findings across a number of approaches and found wide variability in the reported effectiveness, although the methods mentioned above showed substantial average reductions. The utilisation of these solutions will depend upon their cost effectiveness and the ease of adoption for landowners. Impetus may also arise from the Countryside Stewardship payment system for conservation practices. The Soils for Profit government initiative that ran until 2013 provided advice on soil management and promoted prudent use of fertilisers and the introduction of GPS to develop more precise farming systems (considered further below). Recent policy debates in the UK have focussed on the shift from growers' incentives for production towards payments for ecosystem services (House of Commons Environmental Audit Committee, 2016, p. 25). The protection of soil and water services provides a double benefit and enhances the likelihood of the mitigation methods being adopted.

The ecological impacts of sediment transfers can be significant particularly when contaminants become adsorbed onto the surfaces of small clay, silt and organic particles (Rickson, 2014). The pollutant pathway model provides a useful means of conceptualising how it can be managed (Figure 1.4). In this case the source of contamination is the sediment transfer from the field, which can be controlled using various geoengineering and crop management techniques. Pathways connect the field to the receptor, such as watercourses, and may be countered by the presence of barriers or site containment. The status of the receptor requires monitoring to gauge any detrimental impacts and methods can be instigated to reduce exposure. The primary aim is to limit the source of the contamination.

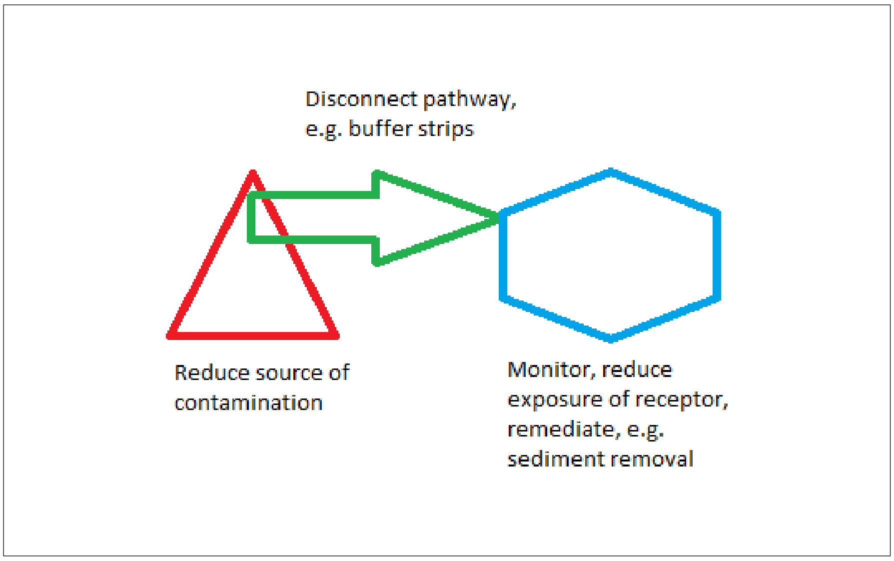


Figure 1.4 Conceptual model of pollution pathways and managing soil erosion

Nutrients such as phosphate can readily adsorb onto the small particles that represent a large surface area for adsorption, along with pesticides and metal contaminants. When these are entrained following water erosion the concentration in the sediment can be significantly higher than that in the remaining soil (discussed further below). For the contaminant to pose a risk to the surrounding ecology there has to be a pathway connecting the source to a receiving watercourse. Models have been developed that examine the dynamic interactions between field characteristics and delivery of sediment. Such models typically focus on the incline of the fields, along with soil type and land use. However, establishing precise cause and effect relationships is challenging (Mainstone, Dils and Withers, 2008). Often flood modelling also considers soil erosion probability, as localised flooding can occur from run-off. Flood modelling has been used in the Cober catchment, however this study is primarily concerned with erosion and water quality issues. The attempt to quantify sediment movements is helpful because it can pinpoint areas of surface erosion and how these connect with receiving watercourses (Walling et al 2002). More detailed understanding of within field erosive processes help to refine such models and this study aims to contribute towards this approach.

The methodology adopted by many researchers examining soil erosion is to collect data in the field over a period of time in order to identify trends in the soil conditions. Researchers have utilised simulated rainfall in the field to blend an experimental approach with a field-based method to enhance the validity of the findings (Morgan, 2005, p.112). More typically research has focused on measuring erosion in the field by delineating plots and collecting runoff in tanks or gutters where the sediment can be trapped and quantified (Morgan, 2005, p.100). Simple metal gauges have been used to measure the changes in soil elevation over time. However, this method requires an extensive network of gauges across the site and for data to be collected over a long period of time (Morgan, 2005, p.101). This variability in study methods has meant that comparing the effectiveness of erosion control measures is a complex process (Rickson, 2014). However, there is a considerable volume of evidence that highlights the effectiveness of geoengineering and ecological measures, such as crop residue management and minimum tillage systems, in limiting water pollution (Rickson, 2014).

Available phosphorus and soil erosion

Growers are aware of the requirement to maintain optimal soil nutrients in order to encourage plant growth and a bountiful yield. Assessments are made of soil fertility to identify which nutrients may be deficient, particularly nitrogen, phosphorus and potassium. Where phosphorus is the limiting nutrient plants will exhibit restricted growth (White, 2006, p.238). Simply applying fertiliser without first assessing the amount of nutrient available to the plants may result in toxicity. An optimal level of nutrient concentration has been identified for phosphorus in order to produce maximal plant yield (White, 2006, p.239). Adequate soil testing is required to assess nutrient availability, the labile pool of nutrients are available to be exchanged in solution whereas the stable pool consists of those that are released gradually via weathering and decomposition.

Because of the variability in soil characteristics across an area it is necessary to sample in sufficient quantity and distance (both temperature and moisture impact on the availability of nutrients to plants), (White, 2006, p.240).

Modelling the inputs of soil nutrients, the processes within the soil that modify these nutrients and losses by erosion, leaching and other means, allows for a detailed calculation of fertiliser applications. Estimating the fertiliser requirements of a crop may include measures of yield from the previous season (White, 2006, p.242). This may provide detailed information of within-field variation at the metre level. Such data can be collected and mapped over several years to indicate particular areas showing high or low fertility. Consequently fertiliser inputs can be adjusted to account for this variability. The increase in yield per hectare does not increase in a linear manner with fertiliser input, usually a maximum yield can be observed for a particular level of input.

Contamination from agricultural activities, such as the organic form of phosphorus - phosphate, is one of the primary contributors to phosphate levels in nutrient-enriched watercourses. There is ongoing debate regarding the levels of input from diffuse agricultural sources compared with point sources, such as sewage treatment works. An estimate of 50% contribution to overall load in rivers from the former source has been given (Jarvie, Neal and Withers, 2006). Soluble reactive phosphorus is the most bioavailable form and is widely regarded as posing a significant challenge to river water quality, with 80% of rivers in England and Wales exhibiting levels greater than 100 µG P l^{-1} (a definitive level has not been set but this figure has been proposed as a criteria for ecological assessment; Jarvie, Neal and Withers, 2006). Phosphate can be utilised by crops, but it can also be incorporated in sediment transport following storm events. The contaminants may originate from fertilisers and manures applied to the crops, from the biomass, as adsorbed particles on soil sediments or dissolved in solution (Mainstone, Dils and Withers, 2008). The sediments may function to trap the contaminants within the watercourse during times of low water flow, providing they are not disturbed which will result in their mobilisation (Carpenter and Bennett, 2011). The presence of sediment on its own also represents a deterioration in ecological condition, creating turbid conditions (Jarvie, Neal and Withers, 2006).

On a broader scale, the natural rate of influx of phosphorus into the oceans is being exceeded by approximately eight times by anthropogenic influences (Rockstrom, 2009), with consequences including eutrophication and ocean anoxia. Researchers have also highlighted that the supply of mined phosphorus may be reaching peak production by around 2030 and that effective recycling of manures and nutrient management are required to ensure continued soil fertility (Carpenter and Bennett, 2011).

Nutrient management and precision agriculture

From the twin perspectives of farm business efficiency and ecological management there is growing interest in the implementation of precision agriculture. This approach involves a more detailed assessment of within-field nutrient variation and soil conditions, where farming practices are adjusted accordingly (King et al., 2005). Precision agriculture utilises technology, such as differential global positioning systems (DGPS; Figure 1.5) and electronic monitoring, to measure variability in soil properties or crop yield (Corwin and Lesch, 2005a). Further benefits may also accrue, including the reduction of ecological impacts of practices such as excessive fertiliser application, and the enhancement of yields and crop quality. A recent study by McCormick, Jordan and Bailey (2009) in Northern Ireland found that index values for soil phosphorus varied between 1 (second lowest level) and 4 (highest level) within individual grassland fields. The authors cautioned that applying fertilizer across the field without taking this variation into account would enhance the probability of nutrient enrichment runoff.

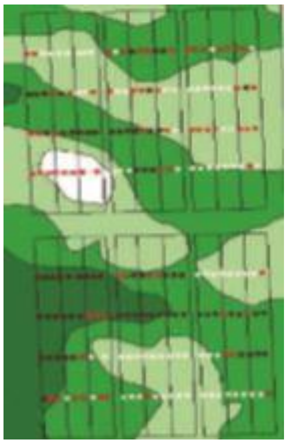


Figure 1.5 The versatility of the Trimble AgGPS 542 GNSS Receiver allows it to be used as a standalone receiver or alternatively integrated into vehicle operating equipment, *left* (image courtesy of Trimble Inc., 2017). Researchers have used these devices to map experimental layouts across fields, *right* (see Omonode and Vyn, 2006).

Evidence-based decision making is dependent upon identifying discrete and stable management zones within fields. One established approach is to study yield maps for variations in crop quality over time (King et al., 2005). The factors which influence crop yield can also be examined, typically by soil sampling across the field. However, this method is labour and resource intensive and for newly planted crops is unlikely to be of practical benefit.

Geophysics and precision agriculture

The innovative approach of mobile electromagnetic induction mapping provides an economical and adaptable method of measuring variation in soil conditions across an area of land in a non-intrusive manner (Corwin and Lesch, 2005a). This approach can also reveal variations in soil properties concerning non-point sources of pollution and other dimensions. Electromagnetic induction and electrical resistivity tomography are two established geophysical methods for field studies. The electromagnetic instrument used for this study was a moving-source type (a GSSI Profiler EMP-400) which comprised a transmitter and receiver coils connected by a reference cable; the latter detected the electromagnetic field that emanated from the ground (Figure 1.6 and discussed further in the methods section).

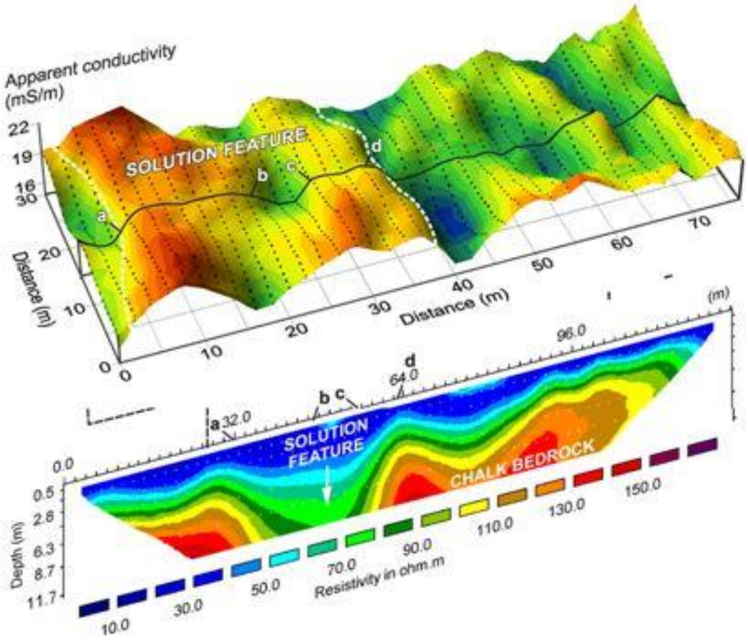


Figure 1.6 The GSSI Profiler EMP-400 is a multi-frequency electromagnetic induction device, *left*. Data gathered using the Profiler can be transformed using GIS and displayed as a conductivity map as in this example of gravel layers over chalk, *top right*, the lower figure is of a resistivity profile from across the centre of the grid (charts from Reynolds, 2011, p.456)

A two-dimensional map of electrical conductivity is produced which highlights contrasts in ground conditions. The interpretation of such maps requires an understanding of the properties of the soil that most influence the observed conductivity and these factors will be site specific. At a general level the dominant influences are water content, bulk density, soil texture (especially clay) and cation exchange capacity (Corwin and Lesch, 2005a). Other factors such as organic matter content, salinity and temperature also influence conductivity (an increase of 1 °C results, in a rise in electrolytic conductivity of 1.9 % (Corwin and Lesch, 2005a)).

Three pathways for the induced current to flow through the soil have been identified (Corwin and Lesch, 2005a):

- The liquid phase, where current travels via dissolved solids in soil pore water
- The solid-liquid phase, regulated by the exchange of cations in association with clays and organic matter
- The solid pathway, where soil particles are adjoining each other

A digital probe can be used to passively measure conductivity, where an electric current is passed between two contacts whilst the probe is inserted into a soil and water solution (the conductivity is measured in micro Siemens per cm (µS/cm). A conversion process also provides measurements of salinity, which is of considerable benefit to farmers who wish to understand the health of crops, as many organisms are sensitive to elevated concentrations of salt. More precise laboratory methods are also available to measure salinity and conductivity (White, 2006, p.298). Higher conductivity readings are typically associated with greater concentrations of ions such as Mg^{2+}, K^{+}, Na^{+} and NO_{3-} (Corwin and Lesch, 2005a).

In contrast to measurement of conductivity using a handheld meter that analyses soil solution for passive conductivity, the mobile EM Profiler combines both the solid and liquid phases in one conductivity measurement. Two further dimensions of ground properties can be measured using this approach. The resultant electromagnetic waves can be analysed as two vectors representing electrical intensity (the quadrature component) and magnetic susceptibility (the in-phase component), these are discussed further in the methodology section.

The pattern of electromagnetic conductivity observed across the grids indicates variation in soil conditions, however of itself does not provide direct evidence of which soil properties are primarily responsible for the effects. Researchers recommend that soil sampling is required in order to ground-truth the findings (Corwin and Lesch, 2005b). The identification of the sample locations can be made by using statistical methods and computer software developed by a team at the United States Department for Agriculture (USDA) defines sampling points based upon conductivity data gathered by electromagnetic induction (Corwin and Lesch, 2005b). The software package ESAP (EC Sampling, Assessment and Prediction), has been successfully utilised in a number of soil studies, particularly concerning field variations in salinity (Heilig, et al., 2011; discussed further in the methodology section).

A recent study by Lardo et al. (2016) measured apparent electrical conductivity using electromagnetic induction and soil CO_2 emissions, in relation to organic carbon content. A strong negative correlation was found between the two variables, where increasing ECa was associated with a lowering of soil respiration, (the coefficient of determination calculated using regression was $r^2 > 0.6$, or 60% of the variation in ECa was accounted for by soil respiration). This was interpreted as the influence of root zone respiration and soil porosity. The ESAP program was used to identify sampling sites and to perform a regression analysis on the results and generate a field pattern of soil respiration based on the regression (Figure 1.7). The use of the program enabled representative sampling sites to be readily identified, reducing the number of points sampled compared with a grid sampling approach.

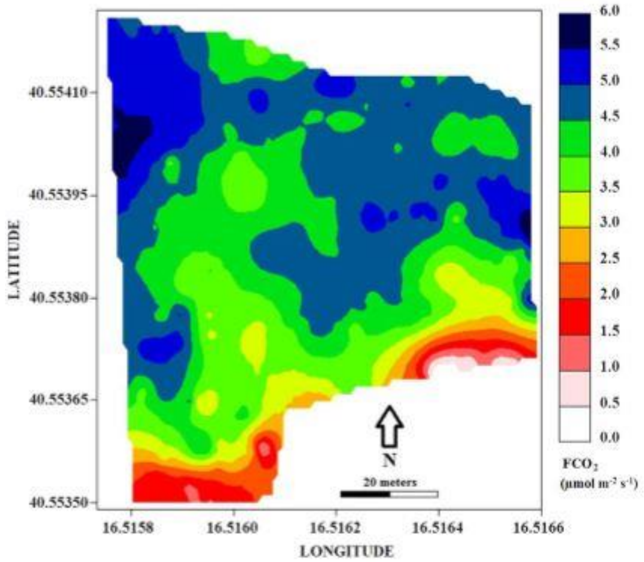


Figure 1.7 A contour map showing soil respiration flux based on the regression analysis of ECa and soil CO_2 emissions using the ESAP program (Lardo et al., 2016)

Examination of conductivity and soil nutrients have also been conducted with a view to defining fertility management zones within fields. A study by Omonode and Vyn (2006) investigated field variations in induced electrical conductivity compared with soil organic matter, phosphorus and potassium within the top 30 cm layer. Correlations between ECa and the soil nutrients were relatively weak. Location, date and higher rainfall influenced the strength of the statistical relationships. Regression analysis was carried out which revealed that a maximum of 15 % of the ECa was accounted for by nutrient availability. The researchers claimed that the history of land management at the study site together with the wide variability in nutrient availability gave rise to fluctuating correlations between ECa and soil nutrients at varying distances across the area. Although the topography of the area was relatively flat one section was noted as a deposition area for eroded soil particles. In one year a significant positive correlation was observed between ECa and extractable phosphorus ($r = 0.50$).

The influence of topography on soil properties, crop yields and ECa was studied by Singh, Williard and Schoonover (2016) in a small agricultural watershed in Illinois. Crop yields were significantly lower at deposition areas that at either shoulder or back-slope zones, when rainfall was higher than average. Electrical conductivity was higher at deposition areas and lowest at the shoulder zones. Soil moisture levels were thought to be the primary factor responsible in both instances. In addition the influence of small soil particles providing a greater conductive surface area was also thought to be important at deposition zones; mean silt content was higher in this area that at the other locations, although clay content was lower.

Coincident with the findings of Omonode and Vyn, the researchers observed significantly higher levels of extractable phosphorus at the deposition zone compared with the back-slope. No significant difference was found between the deposition and shoulder zones, the authors suggested that the removal of surface soil at the latter area may have released phosphorus from the subsoil and bedrock. A significant correlation was observed between ECa and extractable phosphorus at the shoulder location ($r=0.67$) but the correlations declined at the other areas.

In a two year study of a potato crop covering 13.8 ha in Quebec, Canada, scientists found that ECa was significantly and positively correlated with extractable phosphate -

values of r ranged from 0.29 to 0.33 (Cambouris et al., 2006). A significant correlation was observed between ECa and clay content, in particular where the clay substratum was at a lower depth higher conductivity readings were reported (Figure 1.8). Moisture levels in the soil were thought to be the defining factor, where the presence of clay at shallow levels enhanced water holding capacity. Where high levels of sand were observed a very significant negative correlation with ECa was found.

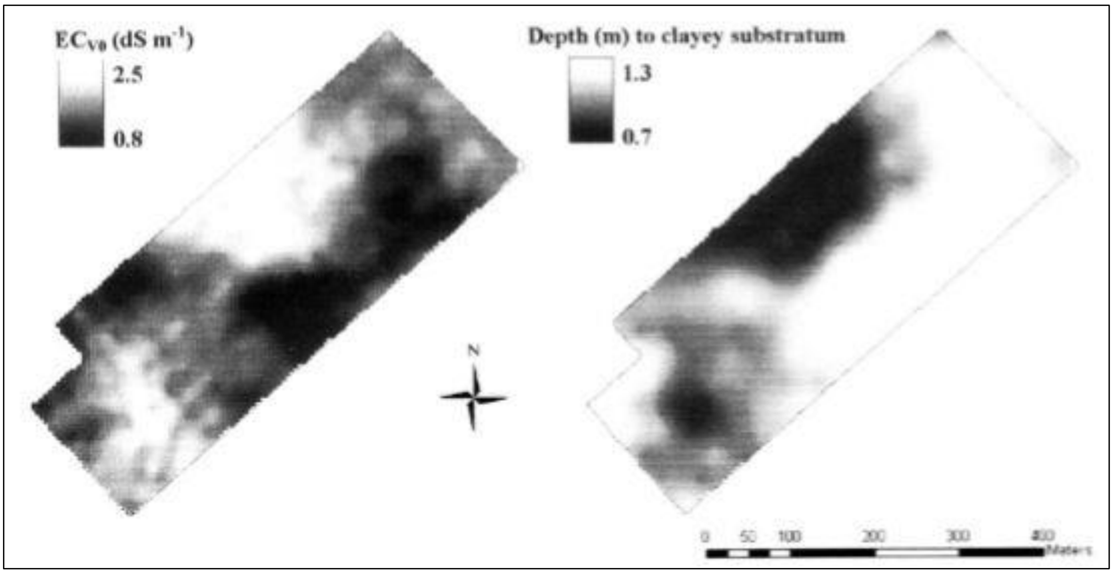


Figure 1.8 Cambouris et al (2006) observed a very significant negative correlation between ECa and depth to the subsoil clay

The researchers also found that potato yield was positively correlated with extractable phosphate levels, along with other soil chemical properties such as total nitrogen, and negatively correlated with depth to the clay substratum. These findings allowed the researchers to define two separate and stable management zones within the field, based on the depth to the clay layer. Yields between the two zones varied by an average of 5.9 t ha^{-1}. The data on phosphate levels also allowed for more precise application of fertiliser. This study is also of particular relevance to this project as the field crop exhibits similar properties to those of flower bulbs, particularly in terms of potential for soil erosion, an aspect not addressed by the Canadian researchers.

The complementary investigative method of Electrical Resistance Tomography (ERT) provides an insight into the variable nature of the electrical resistivity of the ground.

For instance materials such as clays exhibit low resistivity (around 1 - 100 ohm-metres), whereas granite is typically at the higher end of the spectrum (from 300 - $1.3*10^6$ ohm-metres, depending on the crystal composition), (Reynolds, 2011, p.291). In order to measure the resistance profile of a cross-section of ground a series of electrodes are connected to a control unit. This enables the resistance to be measured at varying depths and for the resistance of the electrodes to be minimised compared with that of the ground. Further details of this technique are provided in the methodology section. A secondary aspect of electrical resistivity, termed induced polarisation, was also measured. This relates to the ability of materials to retain electrical charge once the applied current has been terminated and it can be measured using the same electrode configuration as for ERT. For instance, the charge decay curve for many clays is gradual, influenced by the greater surface area of the fine grains (Reynolds, 2011, p.398).

Research on eroded land in South Africa by Chaplot et al (2010) found a significant correlation (r=-0.59) between soil electrical resistivity and thickness of the mineral-organic soil A horizon (a sand-dominated layer overlying more dense clayey material). Incorporating measurements of soil water content and bulk density into a regression model improved the accuracy of the mapping.

Electrical resistivity has also been used to gather evidence on soil loss over time. A French study at an archaeological site (Querrien, Moulin and Tabbagh, 2013) showed that the depth of the fine clay/silt layer over limestone had reduced by 20 cm within four years (accounting for differences in soil moisture). This was thought to be caused primarily by soil erosion and compaction by agricultural machinery. Stratigraphic data from earlier excavations also provided corroborating evidence.

Specific project objectives

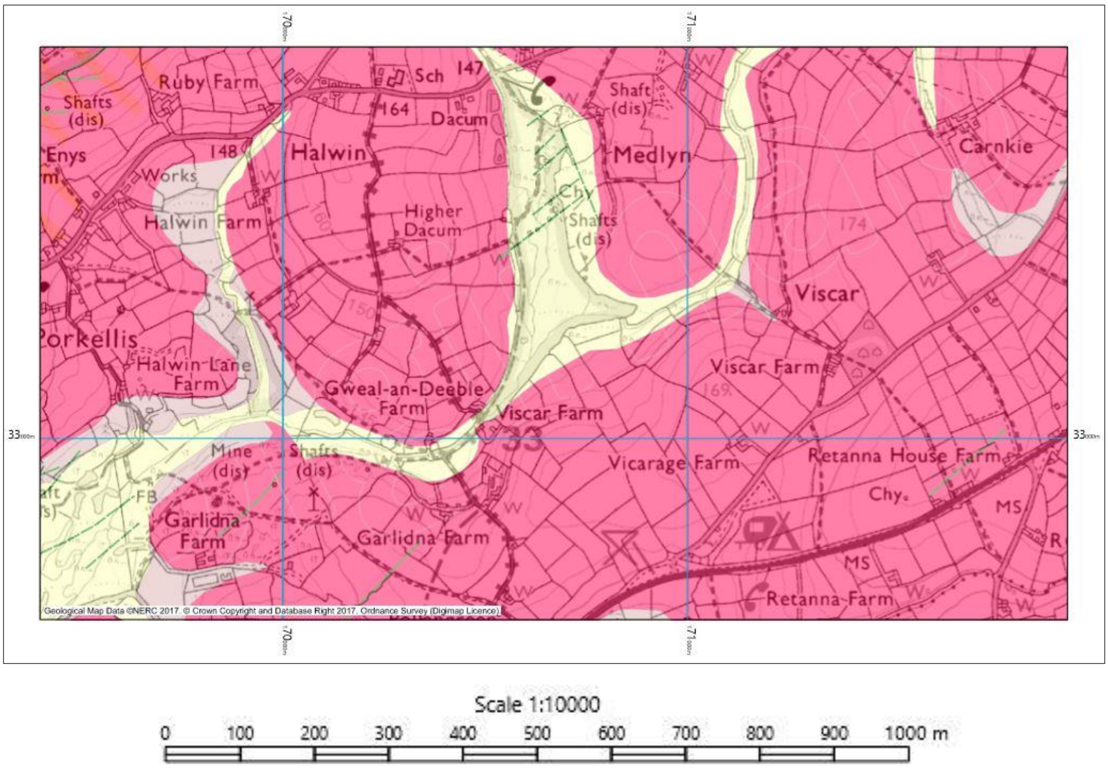
- To use electromagnetic induction methods to measure variability in apparent conductivity of the soil, across different conditions
- Analyse soil samples for variation in available phosphorus across conditions and correlate with the geophysics data, to examine the use of conductivity as a proxy

- Observe whether variations exist within fields for the variables studied, particularly considering whether soil erosion is present and if aggradation zones can be defined
- Use electrical resistivity tomography to estimate depths of deposited material and to compare with electromagnetic results and soil profiles

Methodology

The location of the research

The location for this study was chosen following consultation with a manager at Natural England and a representative from the Upstream Thinking Project. The farm is predominantly beef-rearing on semi-improved pastures, with some arable crops and in the last year a horticultural crop of daffodils has been planted on four fields by a commercial grower. The farm is situated to the east of the village of Porkellis on hilly ground at the northern stretches of the catchment of the River Cober (Figures 1.2 and 2.1). The holdings extend for approximately 54 hectares, most of which is owned by the farmer and radiate to the north, east and south of the farmhouse. Mining took place to the east of the farm at Medlyn Moor Mine, where small quantities of tin were extracted from cassiterite ore in the nineteenth century (Mining in Cornwall, 2017).



Key: Alluvium ▭ Head ▭ Bedrock (Carnmenellis Intrusion – Microgranite) ▭

Inferred mineral veins are indicated by dashed green lines

Figure 2.1 Geological formations in the study area. Image courtesy of British Geological Survey/Ordnance Survey (2017, scale 1:10000)

This farm was chosen because possible erosion and run-off issues had been identified in relation to the horticultural fields and the ground was of varied topography with steep gradients.

The British Geological Survey map for the area (1:50000 scale, printed at scale 1:10000) shows that the bedrock geology is characterised by the Carnmenellis Intrusion of microgranite (Figure 2.1). Superficial deposits of alluvium are present adjacent to the streams to the east and south of the farm. An adit is present adjacent to the east of one of the lower fields where the farm adjoins an area of willow carr and is coincident with a mineral vein running south-west to north-east. The Carnmenellis Intrusion is one of five granite intrusions in Devon and Cornwall from the Cornubian Batholith (LeBoutillier, 2002, p.81). Significant mineralisation characterises the intrusions. The dominant rock type at Carnmenellis is microgranite, a medium-grained biotite granite present in dykes (Figure 2.2). Microgranite is formed of quartz, potassium feldspar and plagioclase feldspar, along with biotite, muscovite and tourmaline, and may include other minerals such as hornblende (LeBoutillier, 2002, p.99).

Figure 2.2 A specimen of excavated microgranite from the study site (approximately 30 cm wide)

The soil type was claimed to be predominantly a podzol, with accumulations of iron and aluminium oxides, possibly forming a pan at depth (Upstream Thinking, 2017, personal communication). A high quartz content was also present, mostly from weathered microgranite and farmers in the area have used agricultural sand to raise soil pH. The soil texture was previously found to be a medium clay loam, with signs of peat, which has implications for soil erosion potential (Upstream Thinking, 2017, personal communication). A sub-soil stony clay layer at about 30cm depth is often present. Soil testing carried out by the Upstream Thinking Project showed that average pH values were around 5.9, indicating an acid soil. Testing of samples was also carried out as part of this investigation, owing to the significance of pH on nutrient availability and soil condition, and is detailed below.

This soil condition is greatly influenced by the extent of weathering and the decomposition rate caused by rainfall along with soil acidity and parent material (Trudgill, 1989, p.340). Weathering processes concerning microgranite typically results in chemical weathering of the feldspars and micas (biotite and muscovite), where percolation of acidic rainwater dissolves the bonds of the metal atoms and clay minerals are formed (Drury, 2008, p.103). Soluble metal ions are released and where weathering is intense, and the oxidation status of the soil permits, only quartz and clay may remain. The elevated concentrations of quartz in the soil on the site results in it being freely draining. The weathering of microgranite and related rocks has given rise to extensive deposits of the clay mineral kaolinite in Cornwall.

Rock weathering and soil erosion are influence by precipitation. The climate of the area measured over the thirty year period 1981 – 2010 indicates moderate rainfall when seen alongside the UK average (998.8 mm yr^{-1} measured at Culdrose Climate Station compared with 1154.0 mm yr^{-1} (Met Office, 2017)). The highest values were recorded in December and the lowest in May. The average minimum temperature over the period was 3.7 ^{o}C (February) and the mean maximum value was 19.2 ^{o}C (August) which indicates a narrower range of temperatures than that shown by the UK averages (0.7 ^{o}C to 19.4 ^{o}C). Air frosts were also comparatively rare events at Culdrose, with only 14.8 air frost days recorded annually compared with a UK average of 54.6. The relatively mild climate has allowed for an extensive range of produce to be grown in Cornwall, often reaching the markets considerably before other regions of the UK.

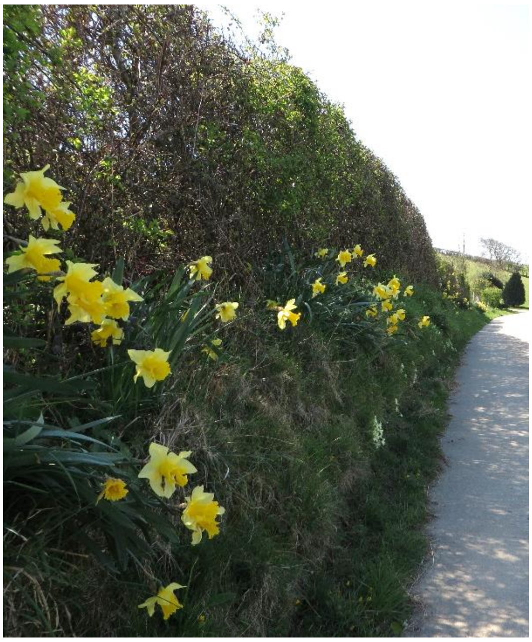


Figure 2.3 Flowering native, naturalised and cultivated daffodils are a regular feature in the spring landscape in Cornwall

Procedure

The site was visited in June 2017 by the author and an adviser from the Upstream Thinking project. The visit provided a good overview of the main issues concerning soil conditions and crop management. A number of suitable fields comprising either daffodil crops or pasture were identified. Signs of soil erosion and sediment deposition were evident in the daffodil fields. Requests were made to the landowner regarding access and during one conversation it was mentioned that one field contained both buried and overhead electricity cables. As the presence of the cables would interfere with the geophysical measurements it was decided to remove this field from the sample list. Electric fences surrounding the pastures were switched off during the data collection exercise. The grids were also situated at a distance from metal gates and troughs.

Detailed Ordnance Survey maps were studied that showed the field boundaries (scale 1:1000, Figures 2.4 and 2.5). This enabled the approximate dimensions of the fields to be measured using a GIS package (QGIS) and approximate locations of the survey grids to be defined. Two arable and two pasture fields were selected for investigation in order to compare geophysical and soil chemistry properties between the conditions. The arable fields D2 (field 2) and D3 (field 3) were selected as they were at a similar elevation to the two pasture fields (field D1 was at the highest point on the farm). Within-field variation was also studied by locating the grids at upper and lower elevations, following the incline of the land. Figure 2.4 shows two grids in the east of field 3 because an additional grid was set-up, on one occasion, that ran between the deep furrows (the results are presented in the Appendix, p.79). A topographic study of the fields was also completed to enable gradients to be defined and to be considered in studying soil erosion. The two pasture fields were studied because they were the only pasture grounds available at the time of the study.

The first daffodil field to be investigated was field 3 (Figure 2.4) which was ploughed approximately east-west and was planted with bulbs in August 2016. In previous years crops of barley and then potatoes were grown. Field 2 was managed in a similar manner. Pasture P1 had not been ploughed for at least ten years and was sown with a uniform sward. The field had been used exclusively for grazing cattle. The second pasture field, P2, was sown approximately four years previously and was only used for cattle. The landowner commented that compaction was a problem and dips and poaching was observed.

Within the arable fields three general zones were identified in relation to the topography and the literature on soil erosion. These were: relatively stable and evenly sloping areas; steeply sloping zones at lower elevation within the fields and finally areas at the end of inclines where material was likely to have been deposited. The Statistical Analysis section below considers the data analysis in more detail.

Figure 2.4 The electromagnetic induction grids on two of the arable fields, overlying a contour map (background map courtesy Ordnance Survey (2017c, scale 1:1000).

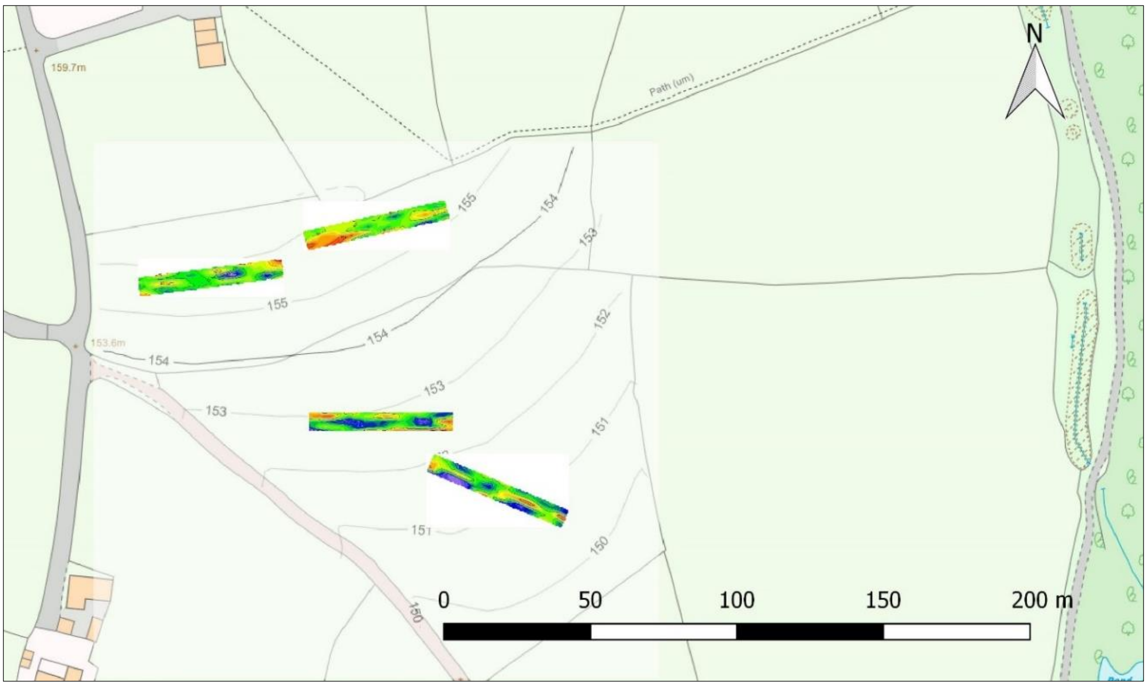


Figure 2.5 The four electromagnetic induction grids on two pastures on the south side of the farm, pasture field 1 is to the north of field 2 (background map courtesy Ordnance Survey (2017c, scale 1:1000)

Table 2.1 Equipment used in the study
Standard Surveying Equipment Trimble R10 GNSS Receiver (RTK Rover Configuration) Trimble TSC3 Controller Canon PowerShot Digital Camera *Ground Electrical Conductivity - additional equipment* Geophysical Survey Systems Inc. Profiler EMP-400 Plastic pegs Reel of rope marked in metres Plastic 50 m tape measure *Electrical Resistance Tomography - additional equipment* FlashRes64 Universal Electrical Resistance Unit and Battery Metal pins and earth rod Plastic 50 m tape measure *Soil Sampling - additional equipment* Extech ExStik EC500 pH and Conductivity Meter Plastic pegs and pots Sampling plan Soil auger

Electromagnetic induction and the GSSI Profiler

To examine any change in soil characteristics across the field it was decided to survey two grids, one at the westerly end and one at a lower elevation to the east. Both grids comprised five lines each and were 50 m in length. The ridges of daffodils were grouped in parallel pairs and the furrows suggested that each line could be placed in the middle of each furrow between the two ridges of daffodils (Figure 2.6). A wider and deeper furrow ran between the pairs of ridges. This approach resulted in data being gathered from a relatively even surface with reference to the furrows and ridges. Each grid was 7 m in width and each line was spaced at 1.75 m intervals. The grid was set out using plastic pegs and a 50 m tape measure, the pegs were lined up by eye with several points inserted into the ground along the lengths of the transects to improve accuracy (a complete equipment list is given in Table 2.1). The hypotenuse of the right-angled triangle formed by the 7 m x axis and the 50 m y axis was calculated (50.49 m) and was used to check that the grid was set-out at right-angles. This method was not used in pasture field 2 as the grids were located towards the sloping contours.

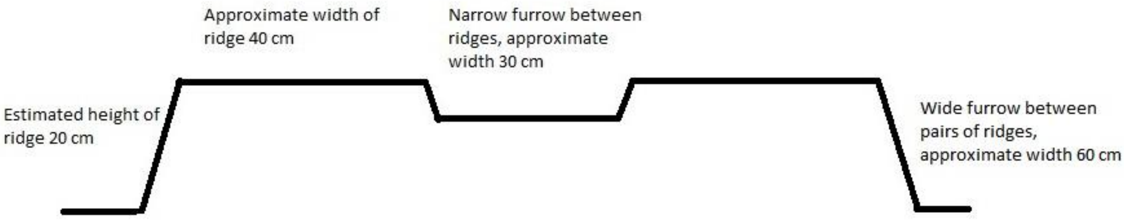


Figure 2.6 The top image shows the bottom left-hand corner of the grid at the western end of field 3, the EMP-400 is shown on the left. Below this is a representation of a section view of the furrows and ridges in the daffodil field

The coordinates of the points at the start of each line and at the end of the first line was measured, so that the resultant data could be georeferenced. A Trimble R10 GNSS Receiver was used to measure the coordinates starting at the bottom left-hand corner of the grid. The coordinates provided precise dimensions for each grid and allowed for the locations of each data point gathered by the Profiler to be defined, 25 recordings were made along each line (see post map figure). Obtaining the accurate length of the line allowed for the increment between each conductivity measurement in eastings and northings to be calculated using the formulae:

$\Delta E = \frac{B0-A0}{25}$ A0 was the start of line 0 and B0 was the end

$\Delta N = \frac{B0-A0}{25}$

A balance was sought between coverage of the grids in a timely manner and obtaining data at a suitable sampling interval for interpretation (Reynolds, 2011, p.11). It was decided that a measurement would be taken at every two metre step along each transect. This interval was felt to be sufficient to measure changes in soil conditions via electrical conductivity. The inclusion of soil sampling at selected locations enhanced the validity of the subsequent analysis.

The collection of geophysical data was commenced using the EMP-400 Profiler, once the instrument had been calibrated in the field. Two frequencies of electromagnetic energy were used, 15 kHz and 3 kHz. Of particular interest to this study were the higher frequency measurements as these are thought to detect changes in ground conditions at a more shallow level than the lower setting (Reynolds, 2011, p.436). The orientation of the instrument was also defined during the early stages of the project - vertical coils corresponded to a horizontal magnetic dipole, which produced a more sensitive measure of conductivity at shallower depths of investigation than with a vertical dipole (Reynolds, 2011, p.433). A comparison of the two dipoles was made by repeat observations over the same grid at field 3 (see Appendix).

The transmitter and receiver coils were separated at a fixed distance and measurements were obtained at the central point between the two (Reynolds, 2011, p.433). A primary electromagnetic field was broadcast by the transmitter at a specific frequency, this in turn generated currents within conductive materials in the soil. This secondary electromagnetic field was sensed by the receiver coil which also measured the primary EM field. The difference in the measured response gave information about the presence and nature of conductive materials (Reynolds, 2011, p.407).

The focus of the study was on the quadrature aspect of the EM data, as this revealed the degree of electrical intensity characteristic of the ground at particular locations and indicated subsurface features. The apparent conductivity data used in the data modelling was calculated by the Profiler software, using an algorithm on the quadrature data collected at 15 kHz (Reynolds International, 2017). Prior to entering the conductivity data into the model a correlation test was completed to check the statistical relationship between this data set and the quadrature figures (a near perfect correlation, $r = 0.999$, was obtained for each grid). As mentioned in the literature review the electrical intensity of the ground is influenced primarily by the moisture content of the soil and also factors such as proportion of clay and, of interest to this study, soil nutrients such as phosphate. Of lesser interest was the in-phase aspect as this related to the levels of magnetic susceptibility shown by the ground conditions and this was not of direct relevance to this study. Granite exhibits low magnetic susceptibility, unless magnetic minerals are also incorporated (Reynolds, 2011, p.87).

Once all of the data had been collected from each grid the measurements were transferred into a spreadsheet. The data was gridded using the software package Surfer and the interpolation method known as kriging was used on each file. This enabled post maps and contour maps to be produced of the measured apparent electrical conductivity (primarily the 15 kHz quadrature components). The grid spacing used was calculated automatically by the software, although manual modifications were occasionally made to examine how different settings modified the quality of the final contour maps. The resultant images were imported into the GIS package QGIS, overlying Ordnance Survey maps of the farm which placed the grids in their geographical context. Analysis of the images was made using the original files from Surfer as this allowed for a more detailed identification of anomalies. The data was also analysed using the software package ESAP (to locate soil sampling points) and by MS Excel for statistical significance testing.

Electrical resistivity tomography and induced polarisation

The reciprocal of electrical conductivity is resistivity, given by the formula

$$resistance\ (ohms) = \frac{potential\ difference\ (volts)}{current\ (amps)}$$

Resistivity methods provide an alternative to measuring soil phenomena and have been used since the early part of the 20th century for studying groundwater resources, mineral deposits and other subsurface features in relatively large areas (Corwin and Lesch, 2005a; Reynolds, 2011, p.289). Electrical resistivity tomography (ERT) is a more recent development and utilises electrodes inserted into the soil that are connected to a switching unit. Current is first passed via current electrodes and then potential electrodes, placed in series, measure the potential difference or voltage (Figure 2.7). Resistance is calculated, which is contingent on the electrode spacing.

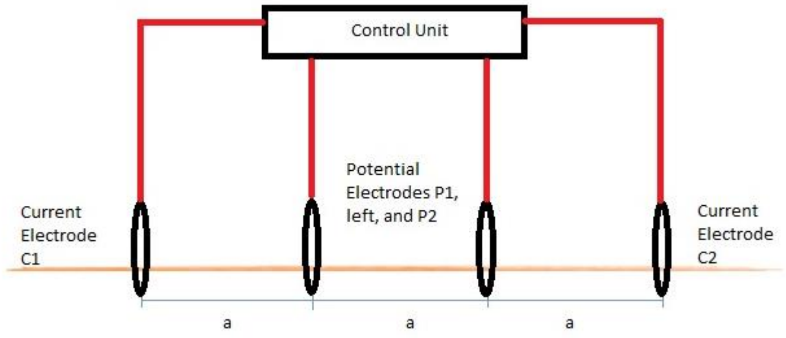


Figure 2.7 Schematic representation of an electrical resistivity circuit. Electrodes are inserted into the ground at a specified depth and separated by a defined distance (a)

Figure 2.7 shows only four electrodes, however ERT utilises a series of electrodes to map a vertical section through the ground. This is achieved by taking measurements in a series of stations, where the switching unit increases the electrode spacing by one electrode on each scan (Reynolds, 2011, p.306). As the electrode spacing is increased so the depth of investigation and volume of ground measured increases (Corwin and Lesch, 2005a). Gradually levels of data are obtained and specialist software is used to generate resistivity sections.

The ERT lines were installed to coincide with the arable field lower elevation grids that were used for the EC study. The primary purpose was to measure the depth of any deposited material, as the sediment should provide a contrasting material against the sublayer. The Trimble R10 was used to locate the coordinates of the lower corners of the EC grids at the eastern side of fields 2 and 3. This enabled the ERT line to be installed at a right-angle across the grids (Figure 2.8). One line was also located across the centre of the EC grid in field 2, running west to east, to correlate the images.

Figure 2.8 The positions of the three ERT lines at the lower elevations of two of the arable fields; the background image is courtesy of Ordnance Survey (2017c, scale 1:1000)

As the focus of this project was on near-surface ground conditions a total line length of 31.5 m was defined, this measured electrical resistivity to a depth of approximately 6.5 m. A line of 64 electrodes was placed in the ground at a spacing of 0.5 m and to a depth of approximately 3 cm (to maintain good contact with the soil). This provided a higher level of data resolution. A multi-core cable was attached to each electrode and was connected to the switching unit (a FlashRes 64 Universal system), which was powered by a 12 volt battery (Figure 2.9).

Figure 2.9 The resistivity line of electrodes at the lower end of daffodil field 2

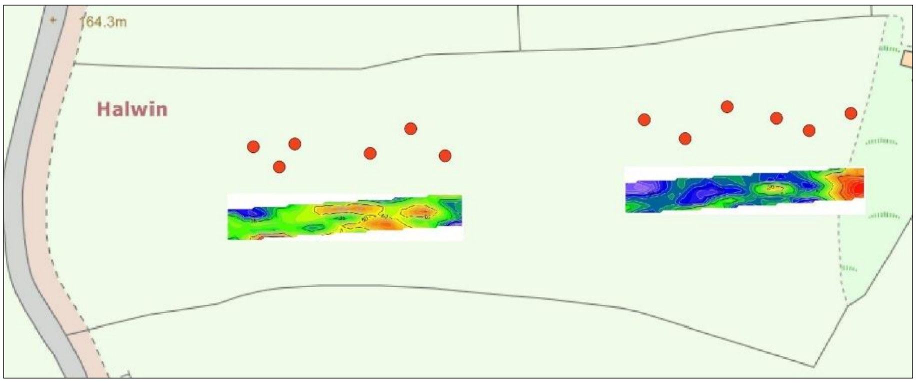
The computer control unit attached to the FlashRes was used to test the electrodes to check that good contact was made with each. The survey parameters were defined so that both resistivity and induced polarity were measured. There are many types of electrode array used in resistivity studies (Reynolds, 2011, p.294) and three configurations were selected: Wenner, ZZ and dipole-dipole. The ZZ data was used to produce the images as the technique gathered 15616 points of data and yielded high-resolution sections (ZZ Resistivity Imaging, 2017).

Whilst the resistivity data was being collected the coordinates of the line was measured using the Trimble R10. The exact location of the sections could be defined on the map, using GIS. It also provided information on the elevation and coordinates of each electrode, this data was used in the computer software that processed the resistivity data and accounted for variations in topography across the line. All of the resistivity data was stored onto a portable memory device and was then processed using the FlashRes 64 software which used inversion to calculate a theoretical model of the ground and then compared this with the pseudosection obtained from the field data. Further modifications were made during repeated iterations of the model until the difference between the two sets of data were minimised. This resulted in the production of resistivity and IP sections in the form of contour maps.

Computer data analysis and soil sampling

In order to clarify whether variations in available phosphorus was one of the primary factors influencing the variations in electrical conductivity it was necessary to obtain soil samples. This approach is recommended in many types of ground investigations, where data from non-invasive methods are checked, or ground-truthed, using soil samples (Nathanail and Bardos, 2004, p.58). Specific anomalies were identified in the geophysics images and targeted sampling on those areas was planned.

The literature review highlighted the use of the software package ESAP (EC Sampling, Assessment and Prediction), developed by the USDA to define a precise soil sampling strategy based on electrical conductivity data gathered by induction methods (Corwin and Lesch, 2005b). The first module of the program, ESAP-Response Surface Sampling Design (ESAP-RSSD), was used to calculate the locations of six sample points from a grid of electrical conductivity data. Three grids were selected, two from arable field 2 and one from the west of pasture field 1. The points were generated according to the variation of the data set, based on standard deviations from the mean value. The locations were also at a maximum distance between the points (Figure 2.10). As the program used conductivity data the correlation between this data set and the quadrature data was obtained for each grid. A correlation of 0.99 was calculated for each area and it was decided that the conductivity variable was suitable to use in the overall analysis of the soil data.



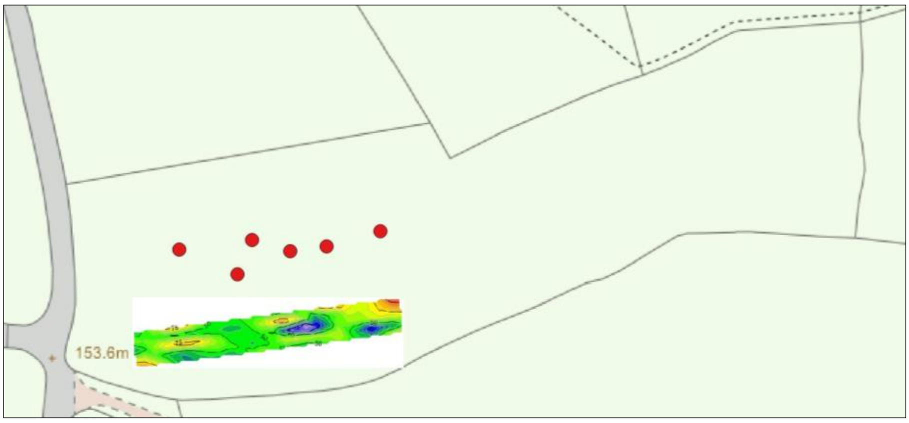


Figure 2.10 The soil sample locations across arable field 2 and pasture field 1, the EMP images are shown below the grid for comparison

Once the sample locations were defined the details were entered into the R10 GNSS Receiver, which was used to geo-locate the position on the ground where the sample was to be taken.

The soil samples were obtained using a hand-held auger and were placed into sealed plastic tubs. Each container was labelled with a code and the date of collection. The codes were noted alongside the sample locations in the field notebook. In the daffodil fields the samples were taken to a depth of 15 cm which approximately corresponded to the root zone (the recommended depth for these conditions, Rowell, 1994, p.14). For the pasture fields the depth of sampling extended to the top 8 cm. Removed soil was replaced into its original location at the end of the sampling exercise.

Measurements in the field were taken of soil pH, temperature and conductivity as these were likely to vary with time after the samples were taken (Nathanail and Bardos, 2004, p.61). The variables were obtained using an Extech EC500 digital meter that was inserted into samples containing 30 ml of soil and 30 ml of deionised water (the mixture was thoroughly shaken beforehand). The digital meter compensated for the variation in conductivity owing to temperature increases relative to 25 ^{o}C, (1.9% per 1 ^{o}C), and all values reported here are the compensated figures. The digital meter was calibrated prior to use with a standardising solution provided by the manufacturer and was rinsed with deionised water between each sample to improve accuracy.

The soil samples were sent to a professional laboratory for analysis. Each sample was tested for extractable (plant available) phosphorus using sodium hydrogen carbonate solution ($NaHCO_3$). Ammonium molybdate was then added to the samples to form a complex which was then reduced and analysed using colorimetry (Chemtest, 2016). This technique is capable of detecting small concentrations of phosphate, (Rowell, 1994, p.207). The results were analysed using MS Excel.

Data Analysis and Interpretation

Results of soil sampling for passive electrical conductivity

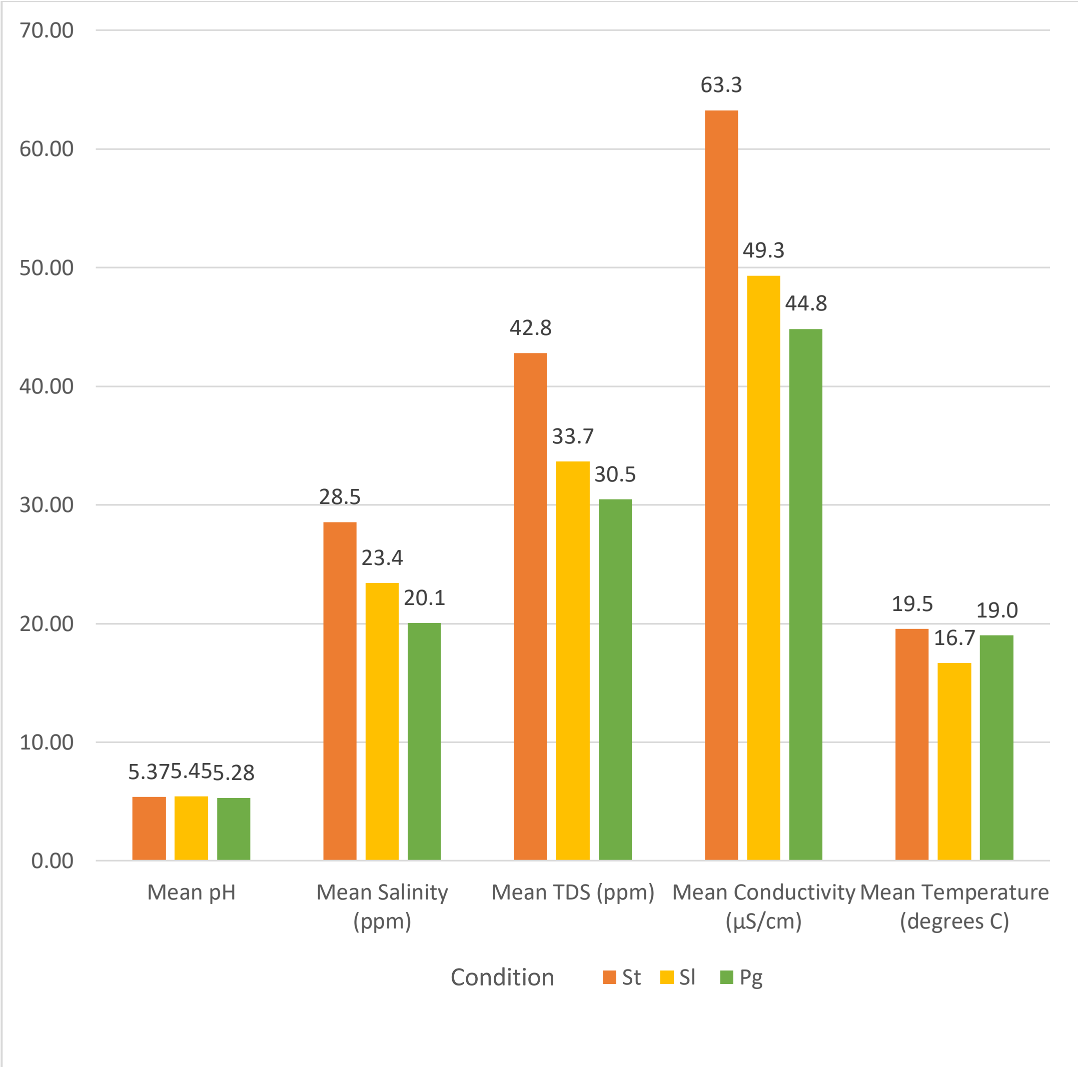


Figure 3.1 Summary statistics of soil variables across three zones

The mean pH levels obtained ranged from 5.28 – 5.45 and were lower than the anticipated values from earlier discussions with the Upstream Thinking team. The lowest values were recorded in the pasture (Pg) field and a significant difference was found using a two-tailed t-test comparing the values for the steeply sloping (Sl) arable grid with the pasture condition, t=3.81, p(T<=t)=0.005. Statistical significance was narrowly achieved between the relatively stable (St) grid at the top of the arable field and the pasture, t=2.27, p(T<=t)=0.05. No significant difference was found between the two zones in arable field two, $t=-1.96$, $p(T<=t)=0.085$. These values were surprising as pH levels are often raised for successful cultivation of bulbs. They indicate the acidic nature of the weathered bedrock and possible erosion of soil materials.

Passive soil conductivity, measured using a simple digital probe, produced very low readings overall. Owing to the large variance a significant difference was narrowly missed between the stable arable grid and the pasture condition, $t=2.25$, $p(T<=t)=0.054$. However significance was achieved between the two arable zones, $t=2.50$, $p(T<=t)=0.036$. The highest conductivity readings were recorded in the stable zone, this will be elaborated further in discussion of the electromagnetic induction results. No significant difference existed between the pasture and the steep arable grid, $t=0.49$, $p(T<=t)=0.636$. Soils are categorised as saline if the value is greater than 2500 ppm (4 dS/m; White, p.196), clearly none of the fields were vulnerable to salinity. The available phosphorus results are discussed below, in relation to the electromagnetic induction data.

The lower mean temperature detected at the steep region of the arable field was caused by changing weather conditions (increased wind and precipitation), as all of the data was collected on the same date.

Soil profiles and textures

The first soil profile extracted was from a sampling point at the western end of the pasture grid (field one) and extended to a depth of approximately one metre (Figure 3.2 left). A number of earthworms and other invertebrates were present in the top 30 cm of soil, which also contained many roots. The top horizon was composed of dark brown earth, of mostly rounded grains and small particles of medium sand size and some organic matter. This soil can be classified as a brown podzolic soil as a slightly darker horizon was present below the top horizon, suggesting some iron and organic compounds had been washed from the upper layer. The podzolic horizon included some angular particles of gravel size and of low sphericity in shape. At a depth of approximately 75 cm orange iron staining was visible, this was indicative of weathered parent material, the freely draining soil above promoted oxidation. These particles were mostly small and of a sandy texture. The texture of the upper layers was gritty, making it a sandy silt loam. As this field had not been ploughed for over ten years this soil type can be regarded as characteristic of the more natural soil formations in the locality.

Figure 3.2 Profile from pasture field 1, upper horizon at the top of the picture, *image left*. Profile from the compacted pasture field 2

The compacted soil profile from field 2 (Figure 3.2 right) was similar to that from field 1 except for the thicker layer of dark organic matter at the top and the greater proportion of angular pieces in the paler eluvial horizon below (from which materials were washed). This resulted in the overall soil appearing to be poorly structured. A notable proportion of clay was also observed below 60 cm depth.

The arable fields showed a distinctive contrast in soil profiles compared with those from the pastures. The cultivation layer extended to around 30 cm and was a very dark, peaty material of gritty texture – a sandy loam (Figure 3.3 left). Very few soil biota were observed. Below this angular fragments were visible and at around 80 cm depth orange stained weathered particles were present. The soil texture was enriched with clay – a sandy silt loam.

By contrast the profile obtained from the deposition area of arable field 2 (Figure 3.3 right) contained mostly uniform fine-grained silty and sandy particles to a depth of approximately 90 cm. This strongly suggested that eroded material had been deposited in this area over time. The soil texture approximated to a sandy loam. Beneath this layer a notable number of angular particles were present, mostly of a fine gravel size, together with sand sized particles. The lower 40 cm was characterised by weathered granite fragments (Figure 3.5 top), clay and orange stained particles of mostly sand size.

Soil conditions were very similar at the deposition area in field 3 (Figures 3.4 and 3.5 lower). More stony angular materials were observed throughout the profile and few weathered particles were seen. Although a distinct pan was not visible in these profiles the high clay content at depth together with the iron staining indicated that the acidic conditions were favouring the formation of solid complexes between the iron minerals and other particles (White, 2006, p.65). The presence of pans would restrict water movement. Further samples were taken in the field to correlate with the ERT results, discussed below.

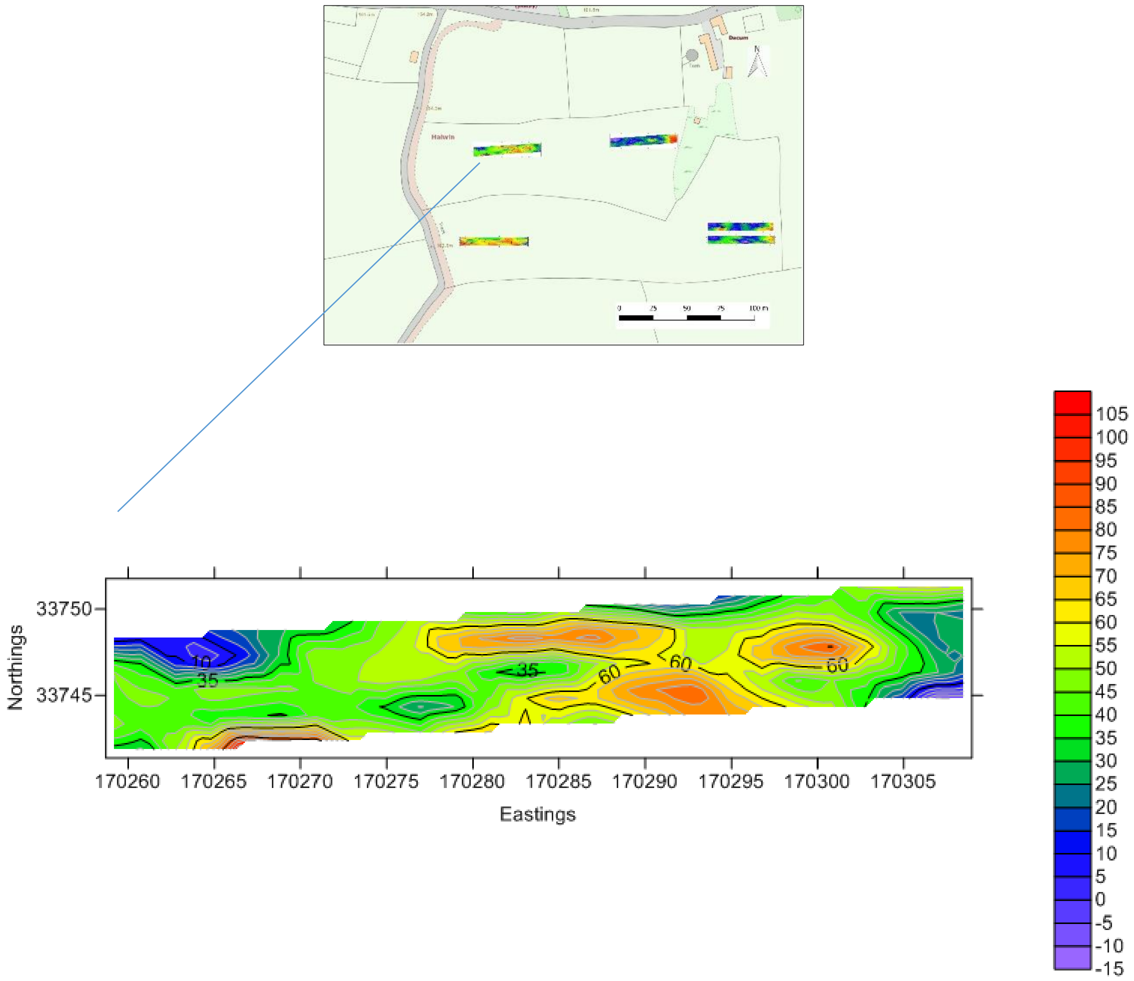
Figure 3.3 Profiles from field 2. Left was taken from the sample location St1 (1m depth). Right shows a 1.5 m profile 2m south of location Ag at the base of the field

Figure 3.4 A 1.5 m profile from field 3 aggradation zone

Figure 3.5 *Top*, weathered microgranite fragments from sample end field 2, *below*, aggradation zone field 3

Electromagnetic induction across arable and pasture fields

The contour maps for the upper elevation grids from the arable fields indicated moderate levels of apparent conductivity (ECa, 15 kHz frequency, quadrature), with higher values being recorded in a number of areas within each grid, but no particular pattern emerged. However, for the lower elevation grids considerably higher conductivity readings occurred towards the end of each grid in a region occupying approximately five metres west to east. This area corresponded with the lowest elevation areas in each field where it was hypothesised that eroded material was being deposited. Low to negative conductivity readings were present elsewhere in the lower elevation grids, with some anomalies visible at particular points. In order to investigate this the results were subjected to statistical analysis (see below).



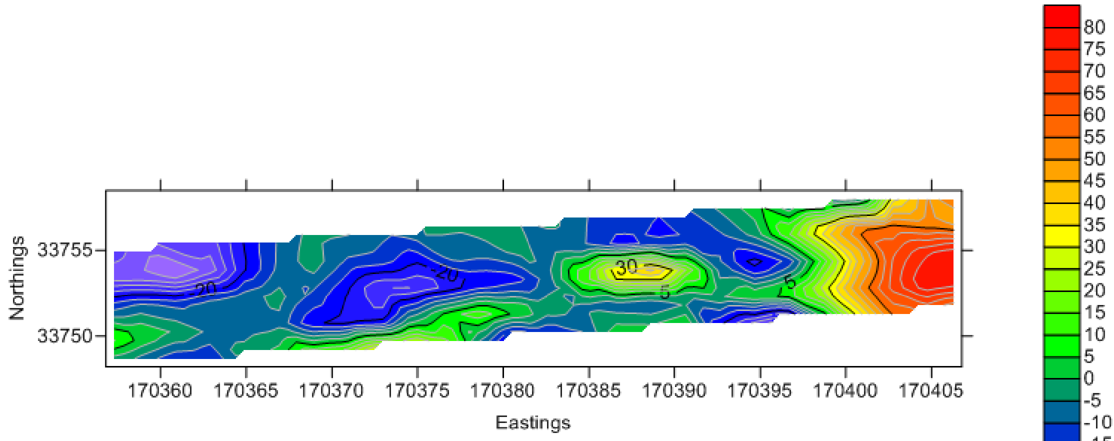


Figure 3.6 Electromagnetic induction images from bulb field 2 (quadrature component, 15 kHz frequency), the upper image is from the top of the field (stable zone) and the lower is from steeply sloping end. Note the higher conductivity at the possible deposition zone at the right of the image, figures in ppm

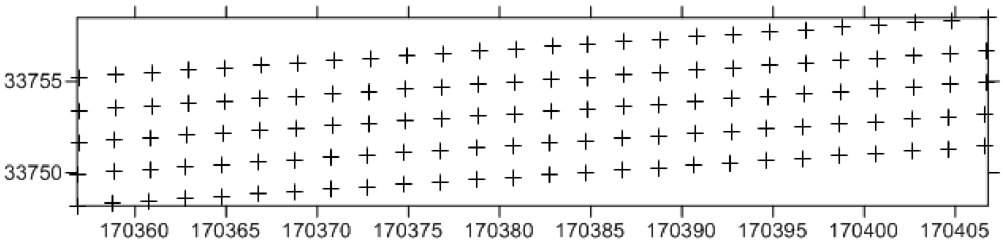


Figure 3.7 Post-map showing the even array of data points across the stable arable EM grid

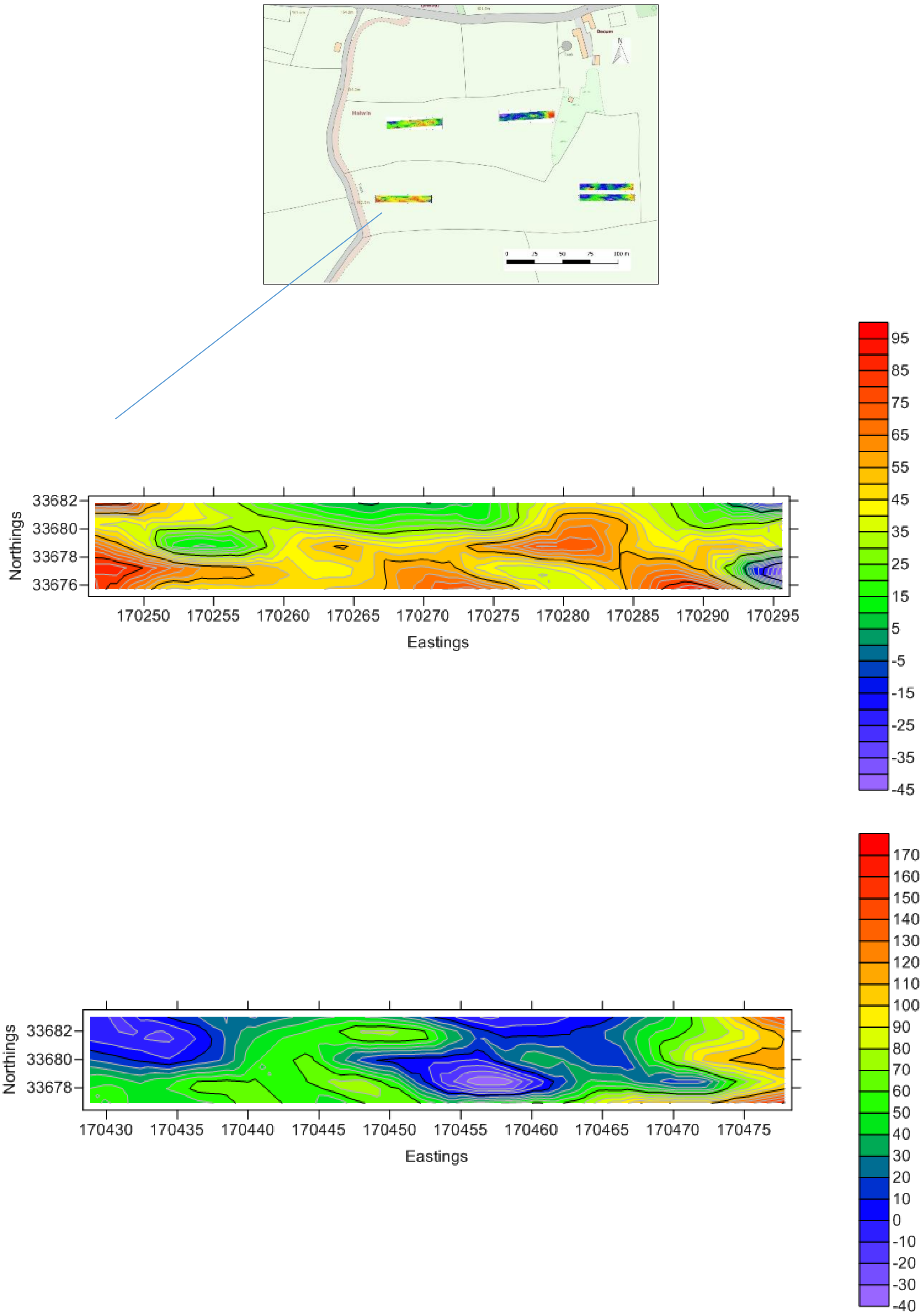
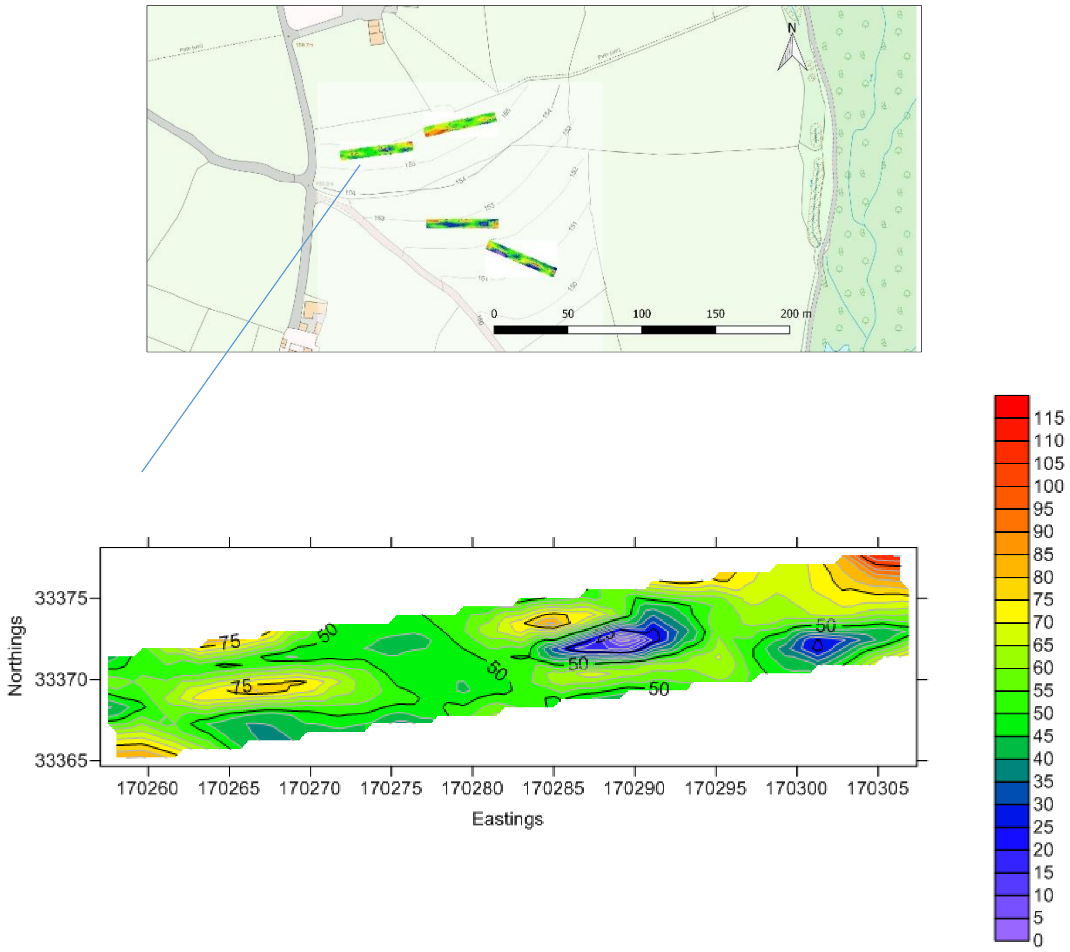


Figure 3.8 Electromagnetic induction images from bulb field 3 (quadrature component, 15 kHz frequency), *top*, stable grid, *below*, steeply sloping grid at lower elevation

Comparisons with the pasture fields also revealed major differences between the conditions. The first pasture grids showed that higher conductivities were generally found compared with the arable conditions (Figure 3.9). Only two anomalies of low conductivity were visible and higher readings were found at the east of the first grid and the west of the second, indicating an elliptical area of greater conductivity. The results from the second pasture land were surprising as very low values were obtained across the grids (Figure 3.10). This was likely to be influenced by soil compaction which the author was notified about (Figure 3.11). The compressed soil particles reduce the movement of soil water and influence conductivity. Soil testing for bulk density would confirm this.



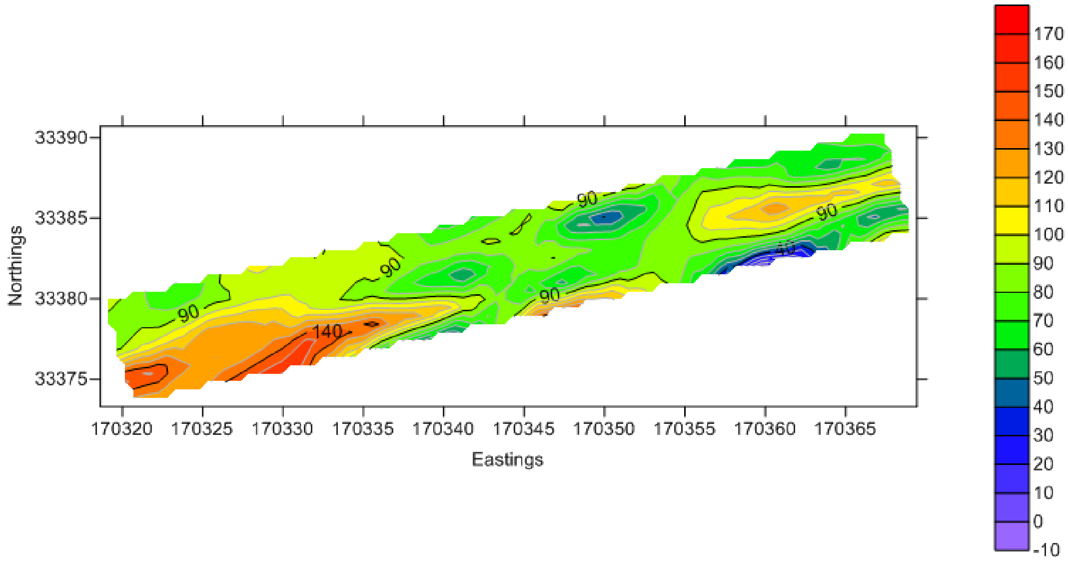
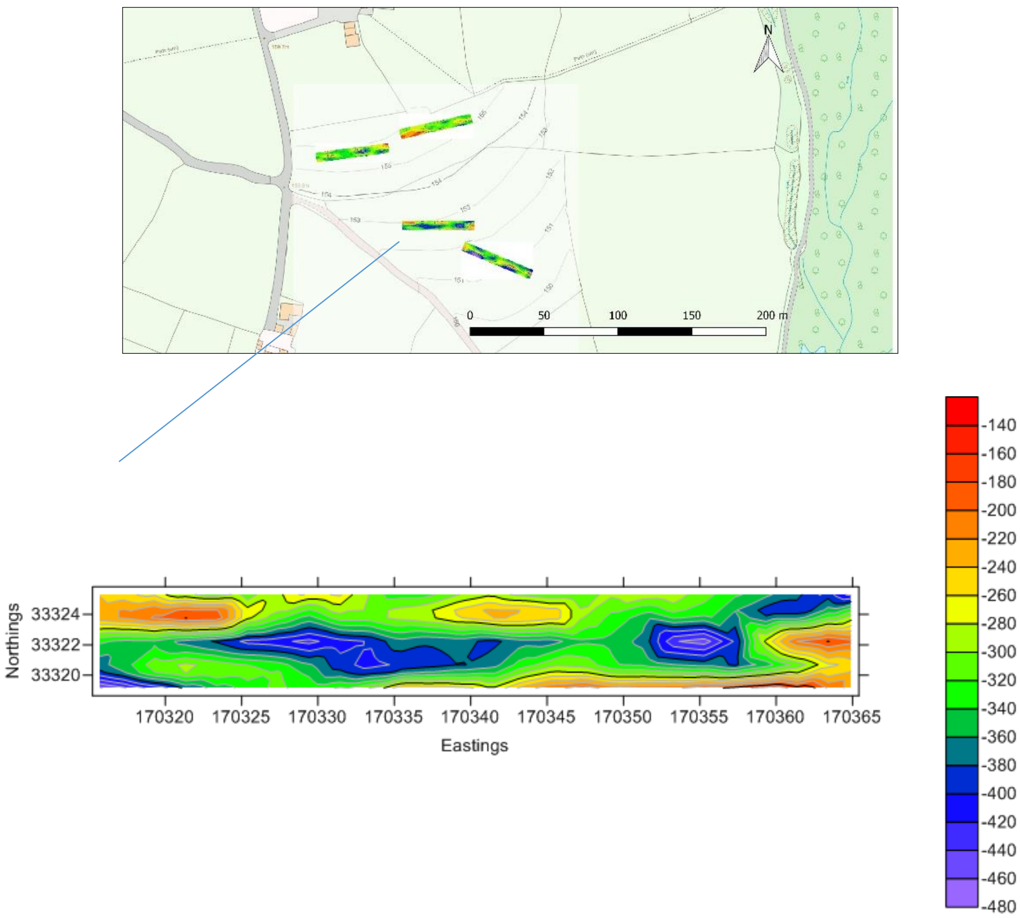


Figure 3.9 Electromagnetic induction images from pasture field 1 (quadrature component, 15 kHz frequency), the upper image is from the west of the field and the lower is from the east



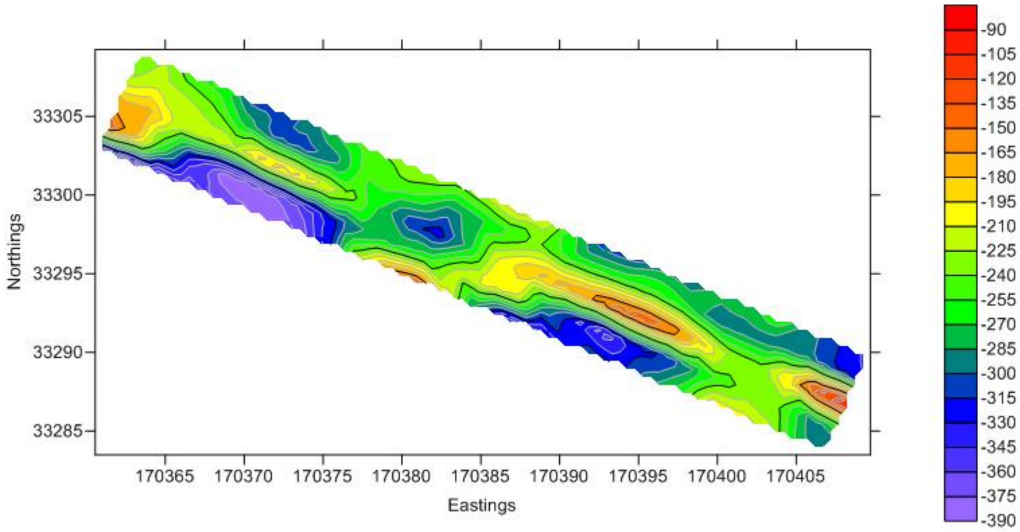


Figure 3.10 Electromagnetic induction images from pasture field 2 (quadrature component, 15 kHz frequency), the upper image is from the west of the field and the lower is from the south east

Figure 3.11 Signs of compaction in pasture field 2

Statistical analysis

A single factor ANOVA was used to examine differences in ECa between pasture field 1 and arable field 2. In order to test for only the variable of cultivation just the two grids that occupied similar gradients from each condition were chosen, both grids contained the same number of data points. The contour maps showed that the western grid from arable field 2 was on an even 3% gradient whilst the easterly grid from pasture field 1 was on a gradual 2% gradient. Results showed a highly significant difference between conditions (P-value = $1.72*10^{-30}$, P << 0.05, F>>F crit) and the average pasture ECa value was nearly twice that of the arable condition (Table 3.1). The higher vegetation coverage and greater root systems present in the pasture condition reduced bulk density and may have enhanced water infiltration and retention.

Table 3.1 Descriptive statistics ECa arable and pasture grids	
Mean arable quad 15 kHz = 46.2 ppm	Mean pasture quad 15 kHz = 90.1 ppm
Standard deviation = 22.7	Standard deviation = 30.7

Average values for the compacted pasture field two varied between -308.8 ppm (westerly grid, sd=83.0) and -263.1 ppm (easterly grid, sd=66.2).

Of vital importance to this study was whether conductivity differences were observed within the arable fields, and in particular if zones of erosion and aggradation could be identified. Conductivity values were shown to vary in general terms between the higher elevation positions and those on more steeply sloping lower ground and end of slope areas. The contour map for the arable fields was analysed in QGIS to measure gradients across the fields and to identify three zones: higher elevation, gradually sloping areas; steeply sloping lower elevation areas and finally base of slope zones.

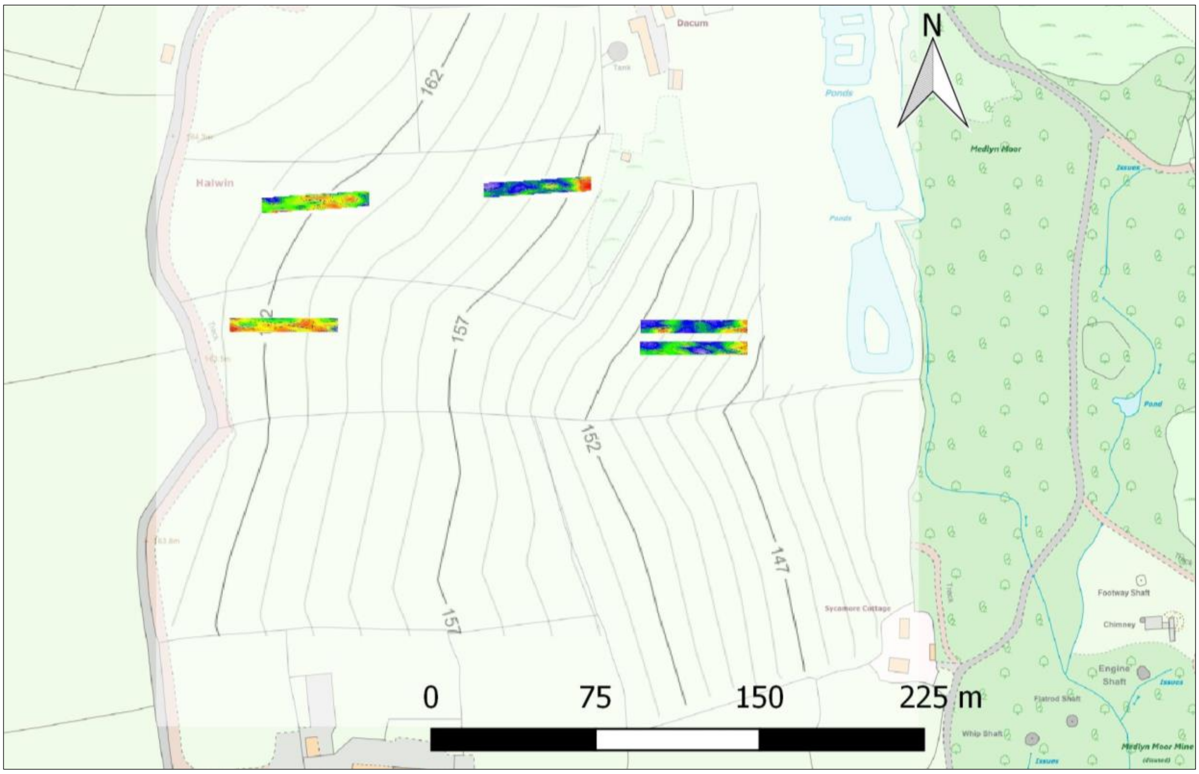


Figure 3.12 Contour map showing the arable fields and the EMP grids

The gradients for each grid are given in Table 3.2, it shows that the ground towards the east of both fields begins to steeply dip away below elevation of 159 m AOD and is steepest at around 149 m. In contrast the grids in the west of the fields are more evenly sloping. Researchers have posited that changes in gradient are usually critical in determining erosional areas (Heckrath, 2005). Consequently two sample locations measuring 6 m in length by 7m width were selected from the start of the westerly and easterly grids in both fields, the reasoning being that these corresponded to areas of relatively stable ground and an erosional environment. These were compared with the lowest 6 m of ground in the grids to the east (representing a zone of aggradation).

Table 3.2 Gradients of each grid

	Gradient (%)		
Westerly grids – Field 2	3	Overall gradient for centre of arable Field 2	4%
Field 3	5		
Easterly grids – Field 2	6	Overall gradient for centre of arable Field 3	6%
Field 3	9		

The descriptive statistics show a clear difference between the zones in observed ECa (Figure 3.13), with the highest values found at the end of the sloping fields (the aggradation zone). The lowest ECa was noted on the steeply sloping grid. A statistical test of difference (ANOVA) showed a significant variation in means between the conditions, P-value = 9.90×10^{-18}, $P \ll 0.05$, F>>F crit (Table 3.3). Further analyses showed a significant difference between the stable grid and the aggradation grid (P-value = 6.15×10^{-5}, $P \ll 0.05$, F>>F crit) and also between the stable grid and the steeply sloping zone (P-value = 1.97×10^{-10}, $P \ll 0.05$, F>>F crit).

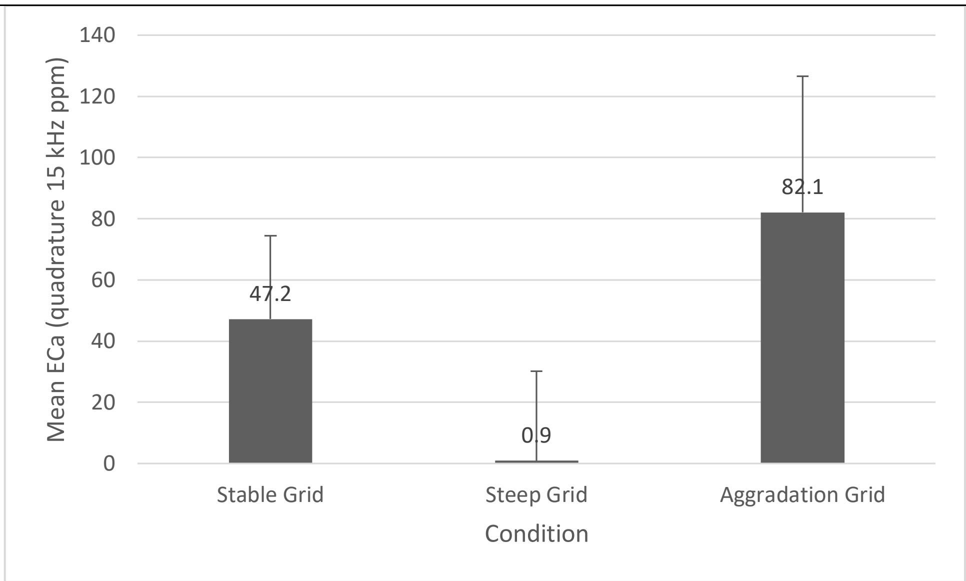


Figure 3.13 Differences in mean ECa between three arable field positions. The error bars represent standard deviations.

Table 3.3 Statistical test of difference between ECa means

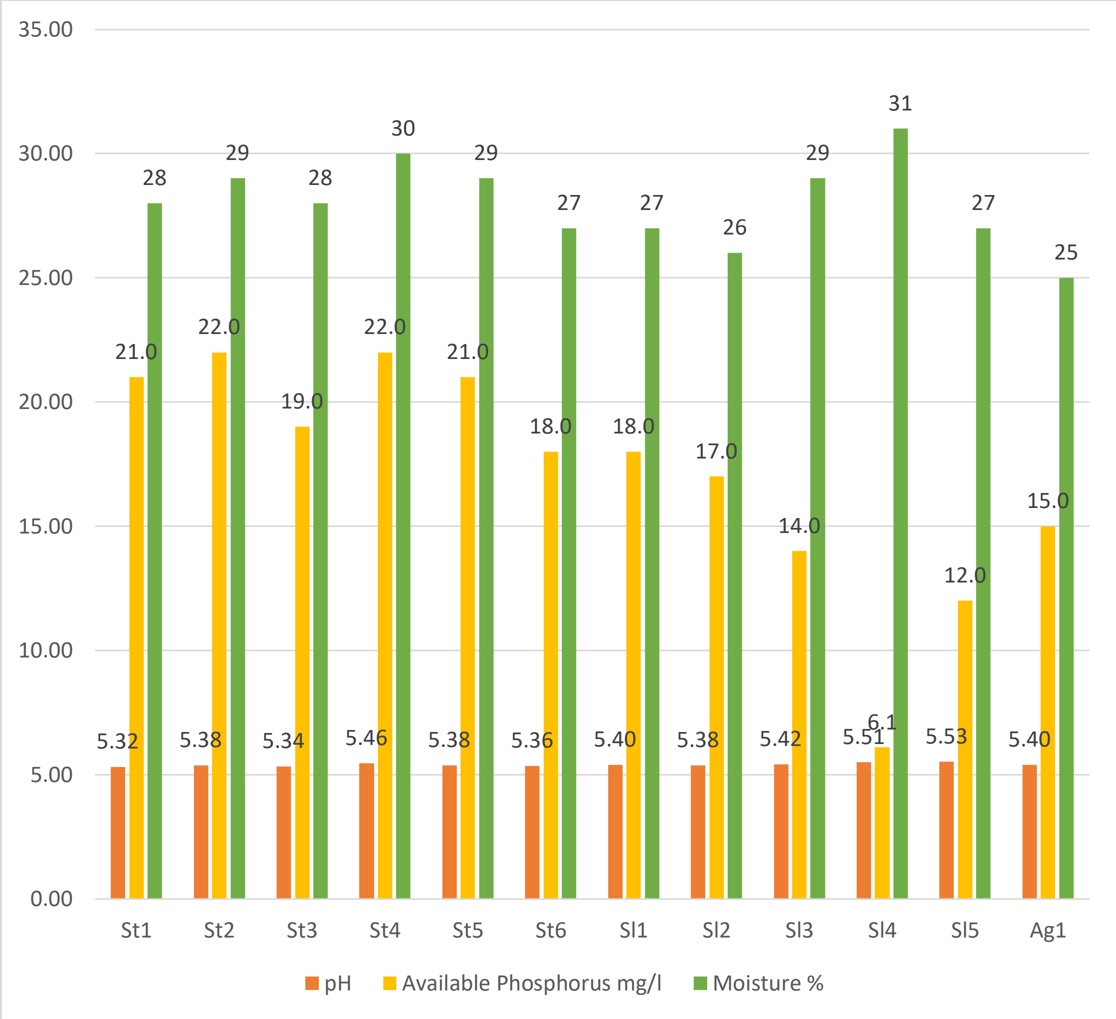
ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	132727.62	2	66363.81	55.7435	9.90E-18	3.0738
Within Groups	139290.98	117	1190.52			
Total	272018.59	119				

The results were significant, however the notable differences in ECa between the two arable fields at the westerly end deserve examination (Figure 3.14). The weather conditions were noted on each day, as moisture impacts on EM readings, both surveys were conducted during dry and warm conditions. However, the field conditions were different in that the furrows in field 3 were approximately 8 cm deeper than those in field 2 and contained less vegetation. This could suggest that the field 3 rows were more freely draining and also the steeper gradient may have promoted erosion. Statistical analysis using a two-way ANOVA produced a significantly lower ECa in field 2 compared with field 3 (P-value = $1.23*10^{-10}$, P << 0.05, F>>F crit). It was expected for these findings to be reversed, possible reasons for the situation may include differences in nutrient applications and the deeper furrows acting as sinks.

Figure 3.14 The contrast in furrow depth and vegetation between fields 2 (left) and 3 (right)

To further explore the variable soil properties across the arable and pasture fields 18 soil samples were collected and analysed for extractable phosphorus and moisture. All samples were collected on the same day and the results are summarised in Figures 3.15 and 3.16.



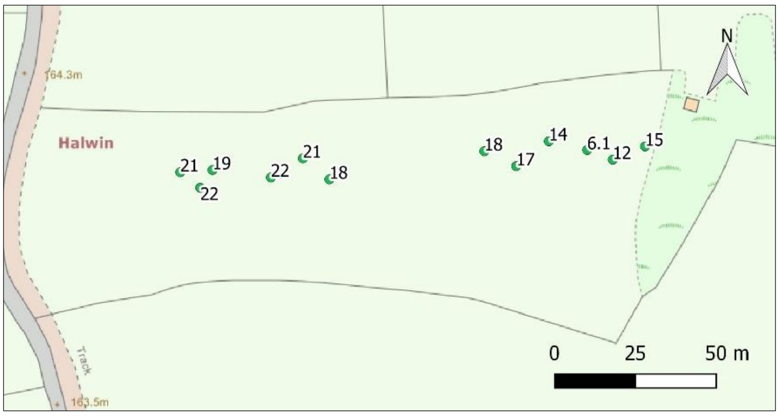


Figure 3.15 Variation in soil chemistry and moisture in arable field 2 (available phosphorus shown on map). Chart key: St stable grid Sl steeply sloping grid Ag aggradation zone

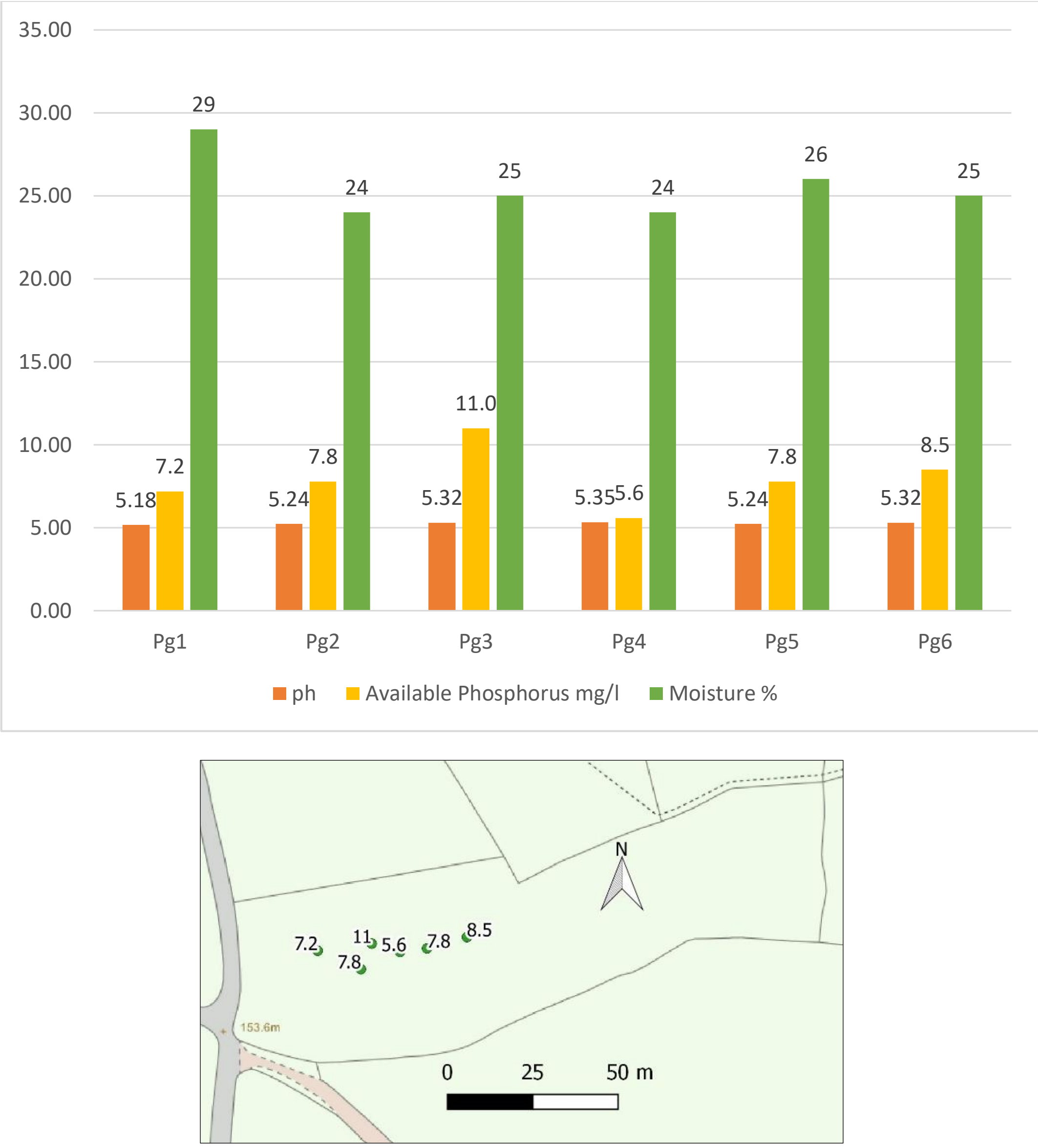


Figure 3.16 Soil chemistry and moisture results from pasture field 1 (chart and map)

The Figures 3.15 and 3.16 clearly show higher available phosphorus in the arable compared with the pasture condition. Levels of pH and soil moisture were also slightly higher in the former. Phosphate was applied to the arable field more recently than the pasture area, which accounted for the enhanced levels. Attention was focused on understanding the variation of soil chemistry within the bulb field. The samples were taken across the field in descending order of elevation and Figure 3.15 indicates falling levels of available phosphorus with decreasing elevation. The exception is the final sample taken from the aggradation zone. Statistical tests explored the relationships more fully. Within the arable field as the aggradation zone value was treated separately an even number of samples in both the stable and sloping grids was achieved by removing one of the samples from the former grid (sample St5 which was selected by the ESAP program along with St3 because they were at 0 standard deviations from the mean for conductivity). Likewise in the pasture grid sample Pg5 was removed for the analyses that follow, to give five values in each condition.

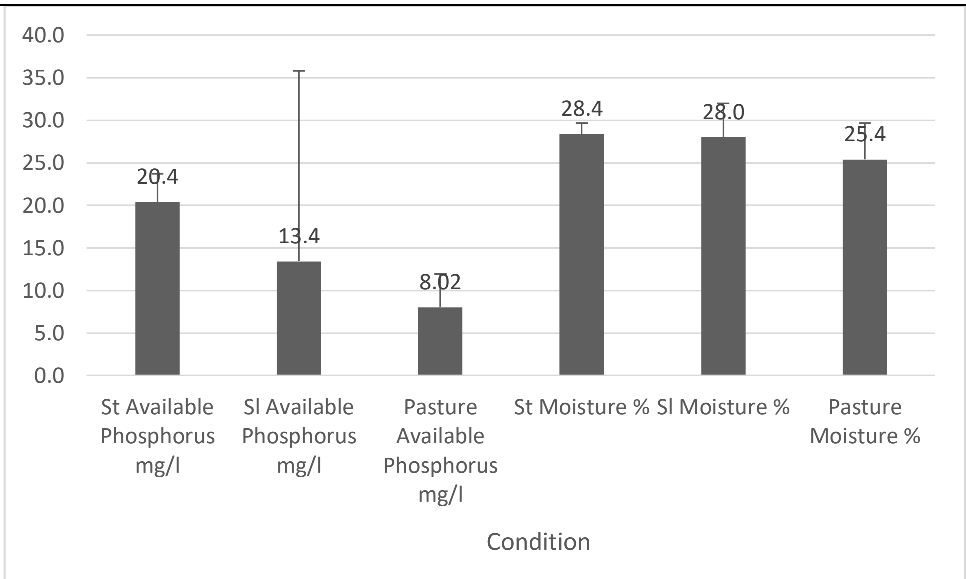


Figure 3.17 Mean phosphorus and moisture values across conditions; error bars show variance

The summary Figure 3.17 shows that the highest concentration of available phosphorus was in the stable grid on the arable field. The one-way ANOVA showed a significant difference between phosphorus in the pasture grid compared with the stable arable zone (P-value = $6.8*10^{-6}$, P << 0.05, F>>F crit); a significant difference was also found between the stable and steeply sloping zones in the bulb field (P-value = 0.015, P < 0.05, F>F crit), see Tables 3.4 and 3.5. Widest variance was in the steeply sloping zone, which is coincident with the earlier findings of a wide spread of conductivity values and indicates highly variable ground conditions. The mean value of 13.4 mg/l is considerably lower than the 15.0 mg/l in the sample at the aggradation zone. This indicates that nutrients were being lost from the inclined ground at several points and were being deposited in the sediment at the base of the field. An important caveat is that only a small number of soil samples were taken at one depth across the site and there was a wide variance in the nutrient concentration in the steep zone.

Table 3.4 Analysis of the pasture and stable arable zones (phosphorus)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	383.161	1	383.161	106.1094	6.8E-06	5.317655
Within Groups	28.888	8	3.611			
Total	412.049	9				

Table 3.5 Results of the stable and steeply sloping zones (arable field phosphorus)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	121.801	1	121.801	9.466889	0.01519	5.317655
Within Groups	102.928	8	12.866			
Total	224.729	9				

Moisture content of the samples was significantly higher in stable arable zone compared with the pasture condition (P-value = 0.022, $P < 0.05$, F>F crit). However the difference between the stable and steeply sloping arable zones was not significant (P-value = 0.71, $P > 0.05$, F<F crit).

Of particular interest to the study was whether significant correlations existed between measured apparent conductivity and available phosphorus. The data for each of the three conditions was tested using the Pearson correlation method. A positive correlation r=0.77, was obtained in the stable arable grid (Figure 3.18). Subsequent regression analysis showed a non-significant relationship between the variables (P-value = 0.13) and an r^2 value of 0.59 (59%). It should be noted that the sample size was very small for regression analysis, the relationship indicated in Figure 3.18 may have reached significance if further samples were taken. It can be concluded that using electromagnetic induction methods does not accurately predict available phosphorus concentrations in cultivated bulb fields.

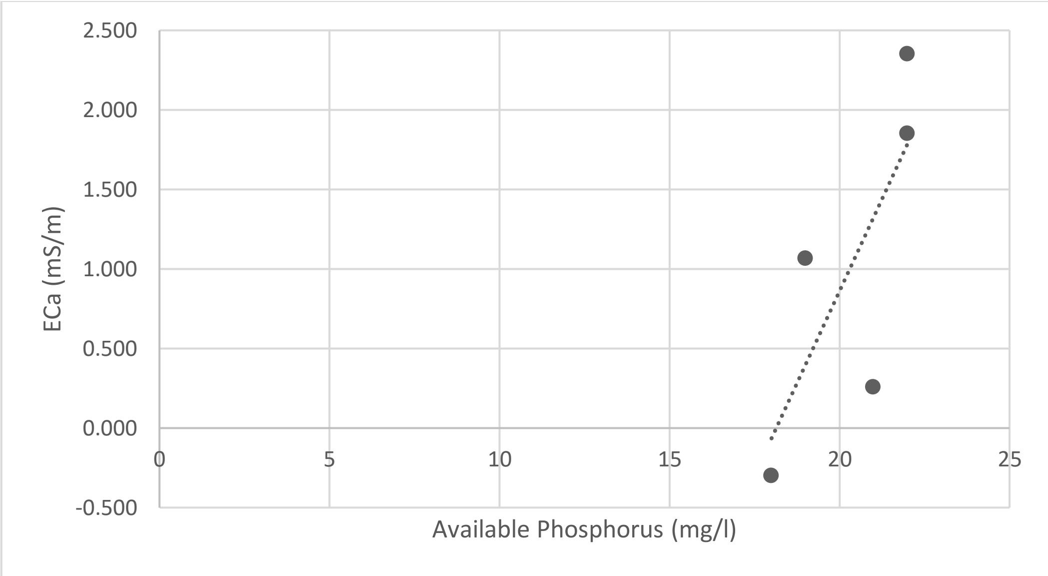


Figure 3.18 Positive correlation between available phosphorus and ECa, stable arable grid

The remaining conditions also yielded non-significant statistical relationships (Figures 3.19 and 3.20). The negative correlation in the steeply sloping zone was in concordance with previous findings (Singh, Williard and Schoonover (2016) and is likely to be influenced by the higher sand content and possible erosion of fine particles.

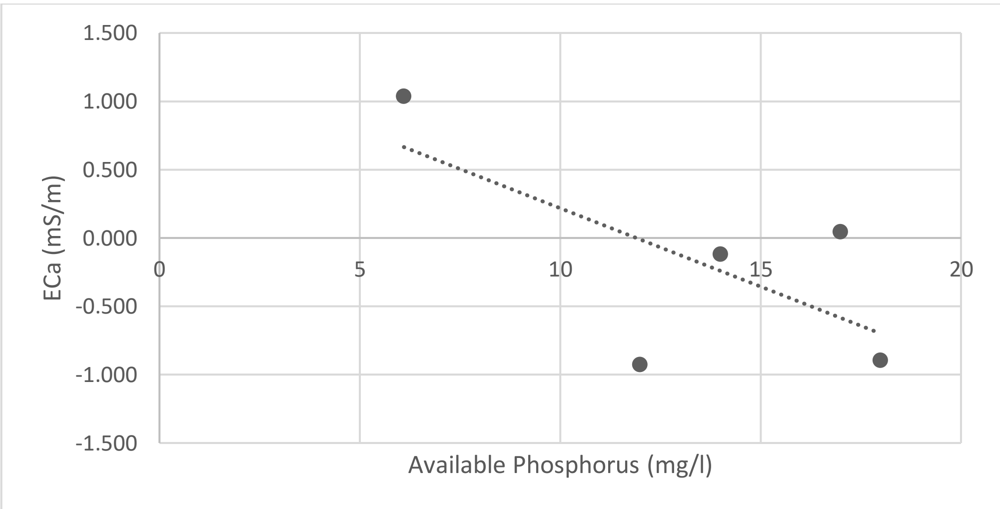


Figure 3.19 In the steeply sloping arable grid a negative correlation was found r=-0.67 and a non-significant regression obtained, r^2 = 0.45 (P-value = 0.21)

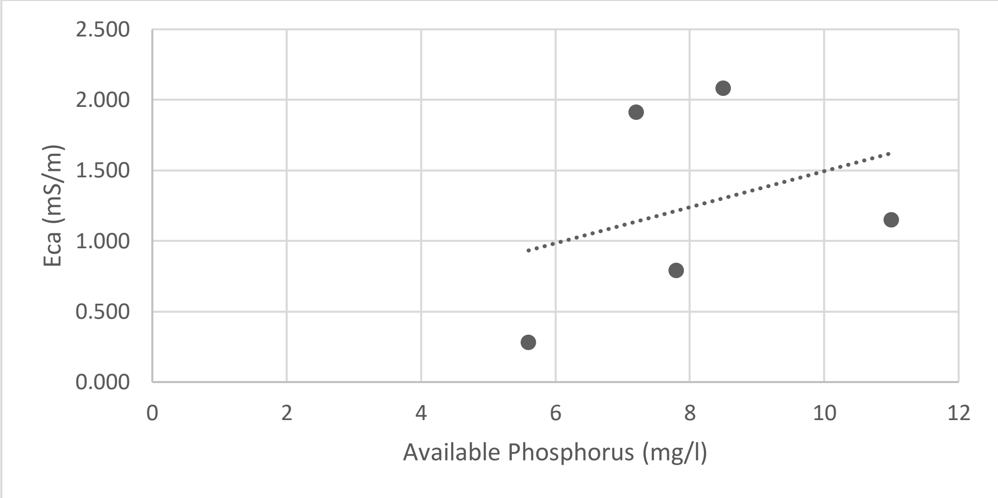


Figure 3.20 The pasture grid showed a modest positive correlation, r = 0.33 and a non-significant regression, r^2 = 0.11 (P-value = 0.58)

The often cited relationship between soil water content and ECa was generally supported in this study. Correlations between the two variables were all positive and were strongest in the stable arable grid and weakest in the pasture condition (Figures 3.21, 3.22 and 3.23). It was likely that intervening variables such as soil bulk density moderated the correlation in the pasture field. The analysis was complicated as the study was conducted during summer months when the soil was not at field capacity. The sample from the aggradation zone showed low moisture content (Figure 3.15) which may have been caused partly by the soil texture being a loose sandy loam owing to the deposition of soil (Figure 3.3 above).

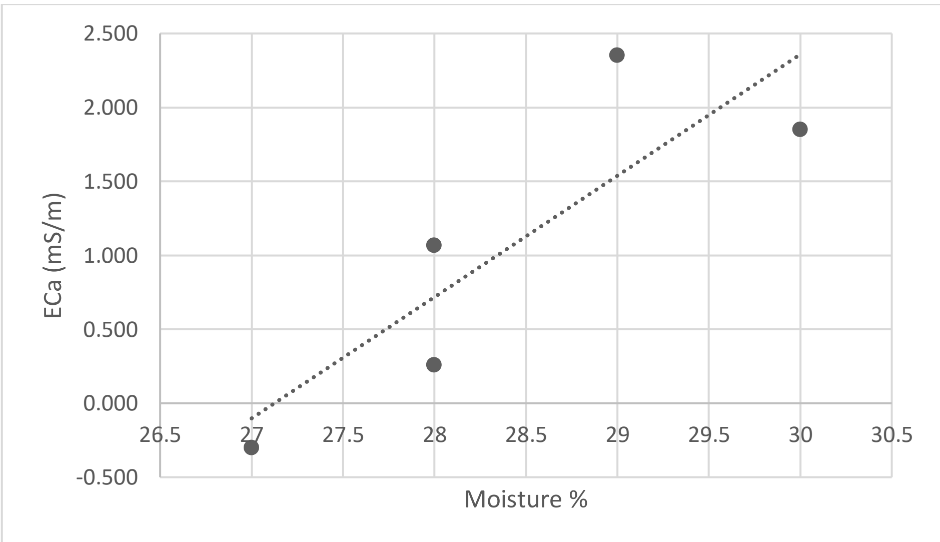


Figure 3.21 In the stable arable grid a positive correlation was found r=0.85, the regression analysis just failed to reach significance, r^2 = 0.73 (P-value = 0.065)

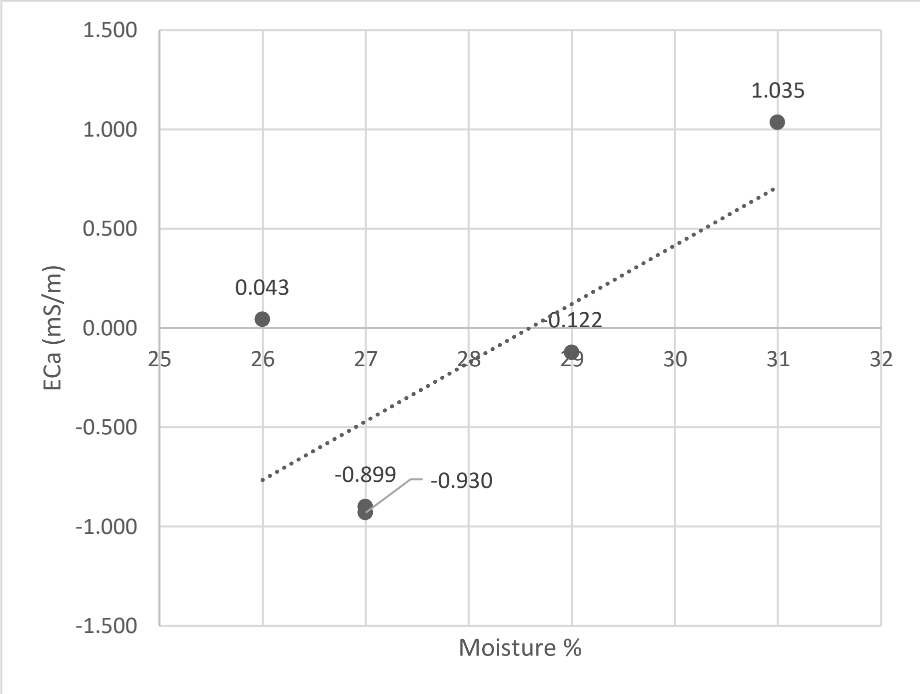


Figure 3.22 In the steeply inclined arable grid the correlation was lower, r=0.73, regression analysis was non-significant, r^2 = 0.54 (P-value = 0.160). Labels added for clarity.

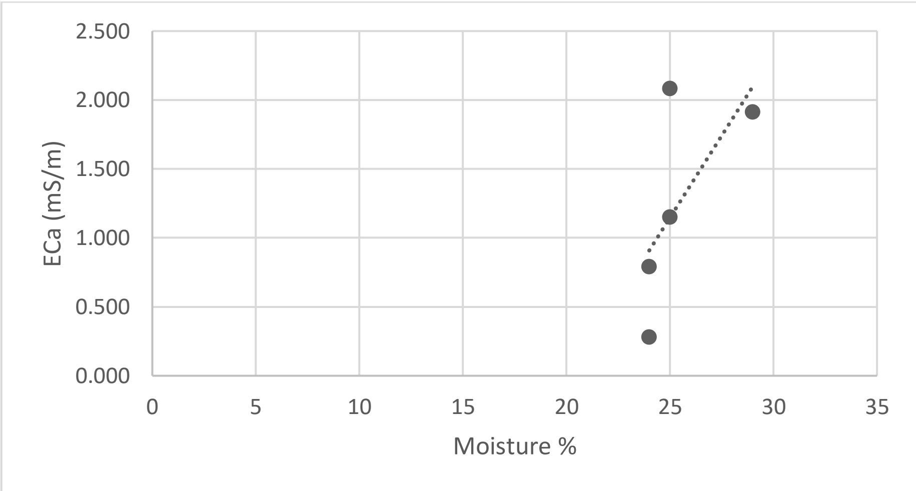


Figure 3.23 The pasture grid exhibited the lowest correlation, r=0.65, regression analysis was non-significant, r^2 = 0.65 (P-value = 0.233).

Electrical resistivity and induced polarity findings

The first line across 30 m of the base of arable field 2 showed that material of very low resistance was present in the upper layer throughout the transect (Figure 3.24) and complements the highly conductive zone that is visible on the conductivity images. The depth of the layer varied considerably, from approximately half a metre in the northern higher elevation area to almost 4 metres at around 17 metres along. The layer extended to a considerable thickness at the lower elevation to the south. This strongly suggested that eroded material had been deposited at this location. The highly resistive anomaly at 14 m is approximately 3 m below the surface and is likely to indicate the presence of microgranite. The soil profile image (Figure 3.3) was obtained at around 15 m along the transect and shows the presence of weathered and oxidised mineral fragments below 1 m depth. The soil profile also exhibited deposited soil within the upper 1 m and clay at deeper levels.

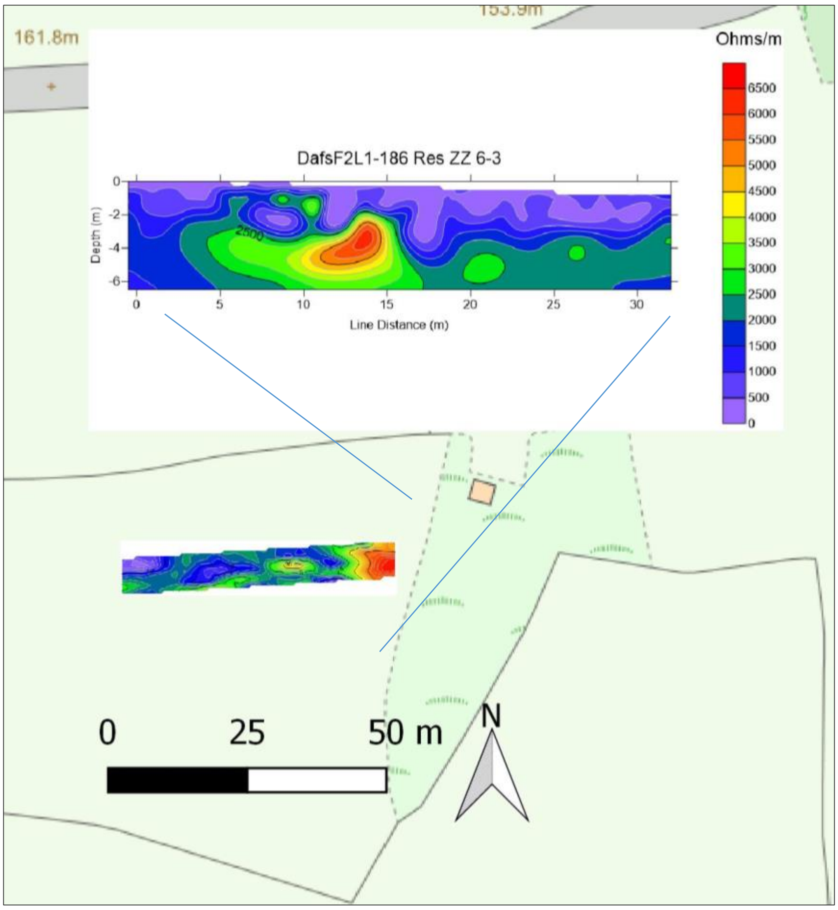


Figure 3.24 The ERT resistivity profile across the aggradation zone of field 2 (profile images are not the same scale as the background)

The induced polarity image (Figure 3.25) shows material of very low chargeability in the upper layer. The anomaly centred on 16 m across and 3 m depth is highly chargeable material and may represent clay from weathered rock. As mentioned in the soil profile analysis above, the presence of a clay pan is likely to hinder water movement. A perched aquifer may be present, which would also represent a route for water to flow laterally beneath the surface and carry entrained phosphorus out of the field.

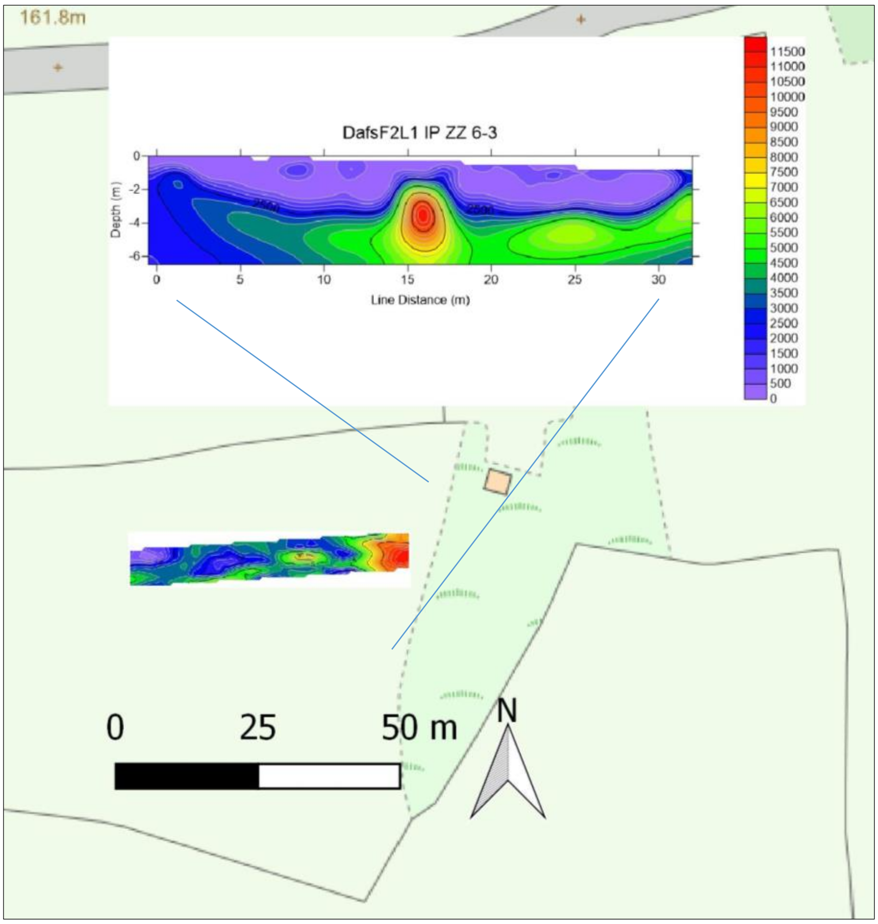


Figure 3.25 The ERT induced polarity profile across the aggradation zone of field 2

The resistivity profile from the aggradation zone of field 3 also displays an upper layer of conductive material (Figure 3.26) but this extends to a shallower depth than in field 2 until 15 m along the transect. However, there appear to be interesting anomalies present of conductive material at around 11 m, 17 m and again at 23 m which appear to be coincident with the presence of gullies running to the east (Figure 3.5, soil profile section). Resistive anomalies are also present at around 7 m and 12 m (microgranite).

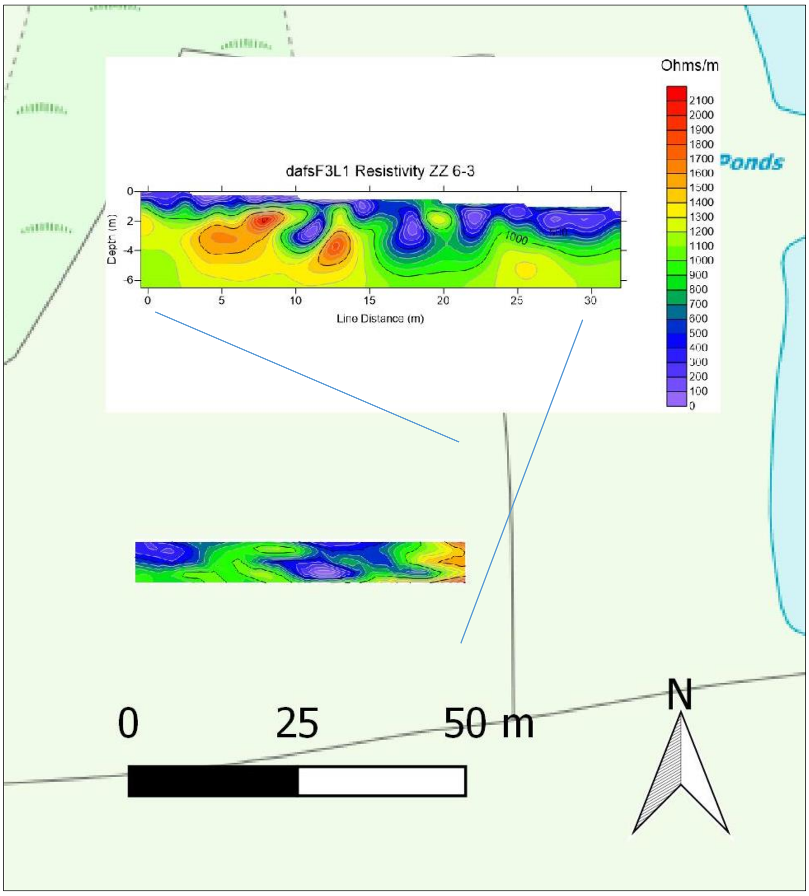


Figure 3.26 The ERT resistivity profile across the aggradation zone of field 3

The induced polarity image (Figure 3.27) indicates that clay is present close to the surface within the first 7 m length of the transect and again at around 21 m, but very little clay is found in the lowest elevation zone (Figure 2.4).

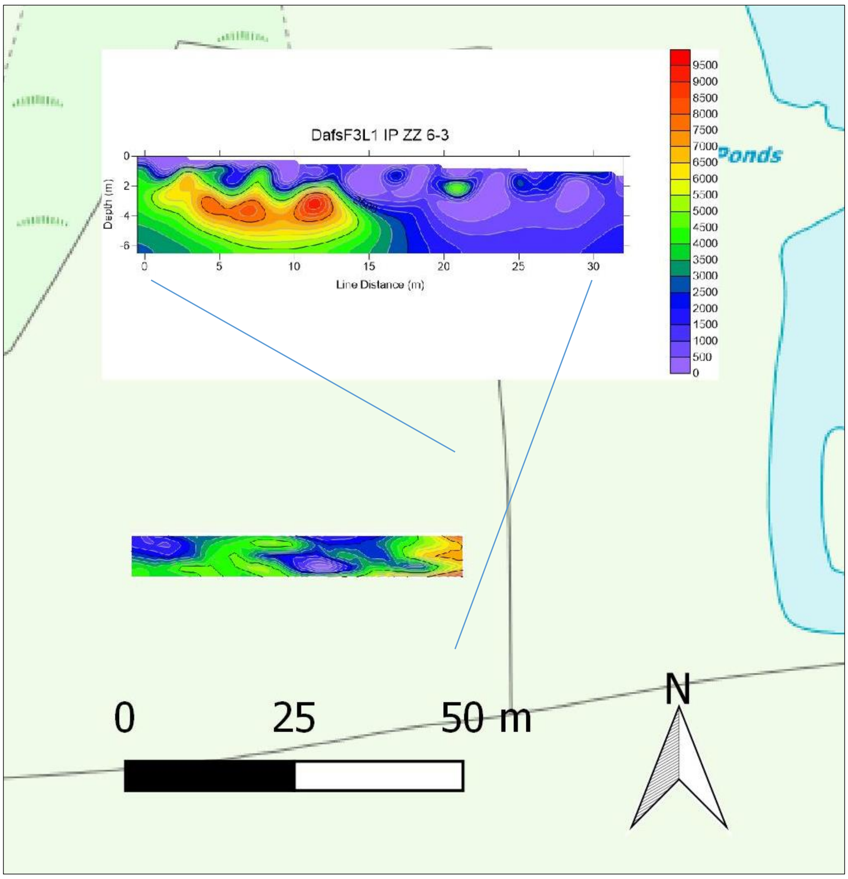


Figure 3.27 The ERT IP profile across the aggradation zone of field 3

The resistivity transect that ran west to east over the centre of the steeply sloping conductivity grid in field 2 produced complementary data – the line was characterised by relatively low resistive material, however very resistive underlying strata emerged at several sites (Figure 3.28). This indicated highly variable ground conditions were present, borne out by the nutrient analysis and the statistics detailed above. It is likely that erosive conditions at this steeply sloping location have removed conductive fine particles and much of the clay from sections of the upper profile. Some clay anomalies remained and the soil sample from around the site of the central anomaly showed a high clay content (Figures 3.29 and 3.30).

Viewing the in-phase images from the electromagnetic induction studies showed that close to the surface noticeable areas of magnetically susceptible material were present 7 m from the end of the grid and 30 m west (Figure 3.31). These areas may indicate weathered minerals and the presence of high iron content. There is some degree of correlation with the IP image. The deeper level in-phase image shows negative values (Figure 3.32), most probably from the bedrock.

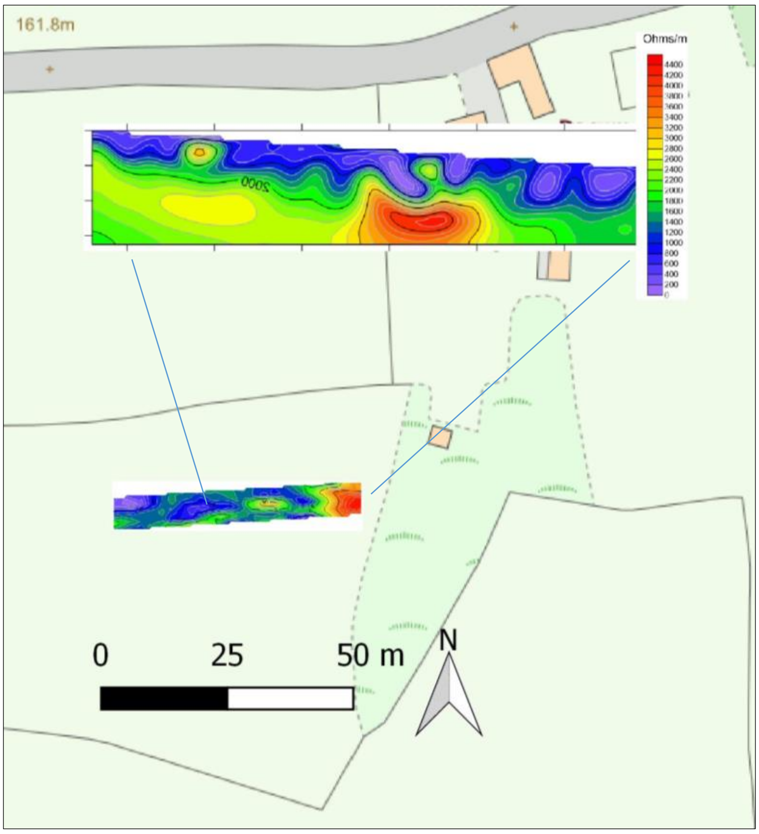


Figure 3.28 The ERT resistivity line in field 2 running across the centre of the EMP grid west to east

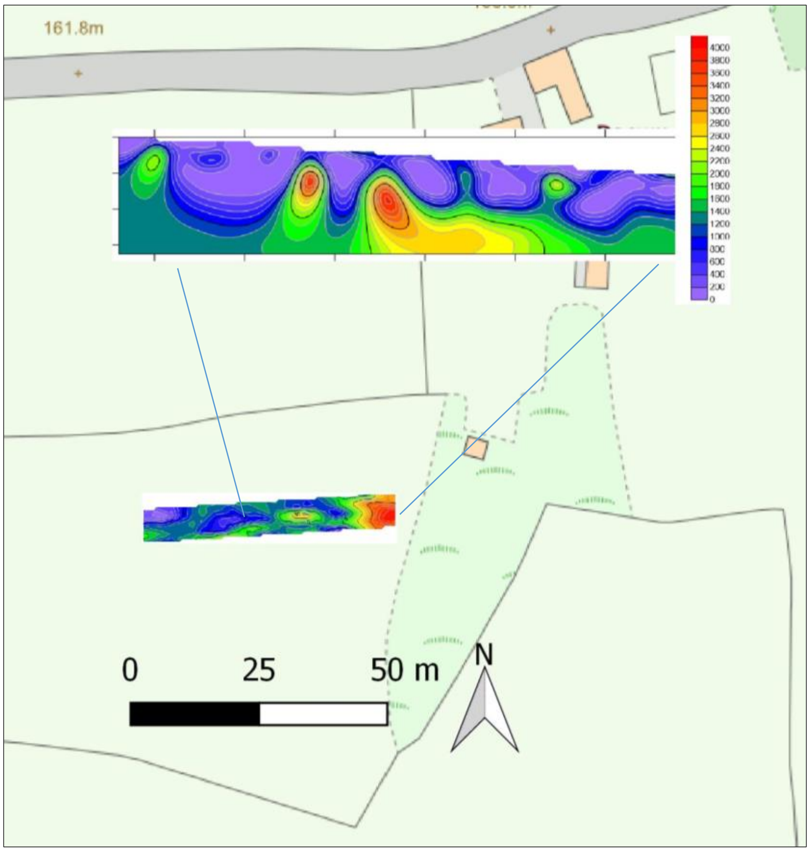


Figure 3.29 The ERT IP line in field 2 running across the centre of the EMP grid west to east

Figure 3.30 A 1 m depth soil profile from close to the site of the central IP anomaly, west-east transect, field 2

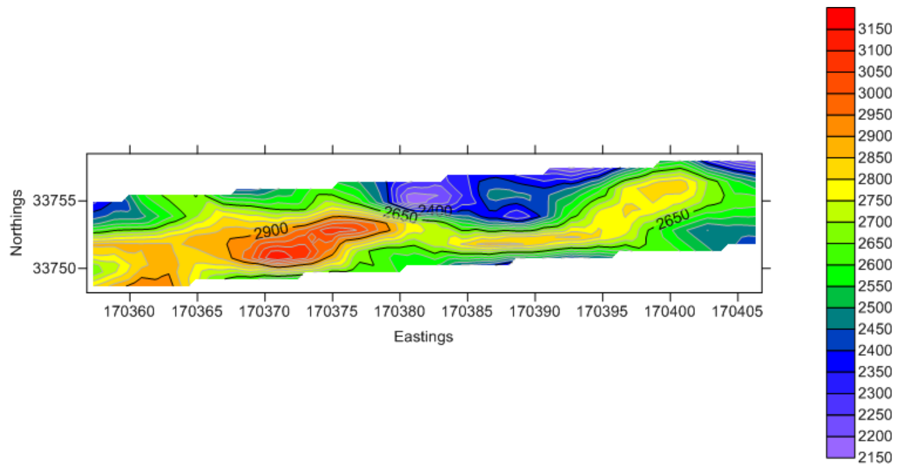


Figure 3.31 Electromagnetic induction image using 15 kHz in-phase component

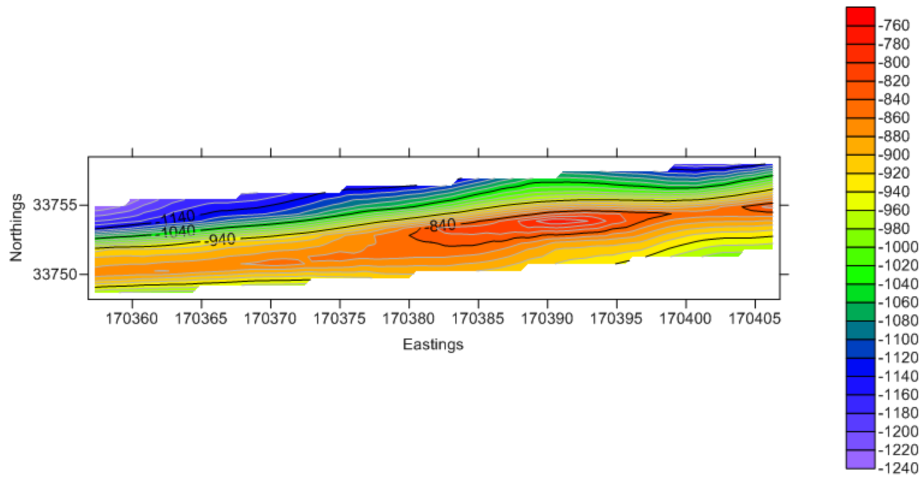


Figure 3.32 Deeper level induction image using 3 kHz in-phase component

Synthesis and Recommendations

In conclusion, this project has shown that geophysical methods combined with soil testing can offer valuable insights into soil chemical conditions found within arable and pasture fields. Significantly higher levels of available phosphorus were found in the arable fields compared with the pasture condition. Studying variation within the arable field defined three areas according to their gradient and whether they were likely to be erosive or aggrading areas. Significantly higher concentrations of available phosphorus were present in the stable zone compared with the steeply sloping area. Although the regression analyses were not statistically significant the geophysical and soil testing approach combined offered encouraging results for the use of non-invasive methods. More detailed soil sampling and the selection of samples from different depths would have provided additional avenues to explore. The sensitivity of conductivity measurements to soil water content were also a factor and conducting the study when the fields were near field capacity may have resulted in clearer correlations. The controlled experiment method would offer the best option for studying the variables.

The soil profiles provided a useful means of validating the findings from the geophysical approaches. Considerable deposited material was found at the lower elevation zones of the arable fields and this was indicated by the resistivity sections. This method also indicated that high clay content was present at depth and had implications for water flow.

The low levels of available phosphorus that were found may have been the result of erosion but could also have been influenced by limited application of fertiliser. Records of nutrient application would shed light on this issue. It is recommended that further available phosphorus and pH testing are conducted (the pH levels were low for bulb production).

As signs of soil erosion were present it would be advisable for erosive crops not to be grown at the steeply sloping areas of the fields. The planting of buffer strips and possibly short rotation coppice would encourage binding of the soil and conservation of nutrients at these locations.

Appendices

Project planning

In order to conduct the study in an efficient and logical manner it was necessary to define the key stages of project completion and then to consider the equipment and logistical aspects of the practical work. The experienced geophysics researchers Corwin and Lesch (2005b) have outlined the necessary stages in the completion of field-scale electrical conductivity surveys, a summary was adapted for this project and is given below.

a)	*Define the objectives and scope of the study*	The examination of differences in ground conductivity between fields planted with daffodil crops and pastures, with particular reference to soil erosion. Examine conditions at different field locations, i.e. upslope and downslope. Utilise several methods of investigation to identify key factors influencing soil variability.
b)	*Set the site boundaries for the study*	Define which fields will be studied and establish where the grids will be laid out.
c)	*Define parameters for electrical conductivity investigation, i.e. frequencies used, position of dipole and transect spacing*	Frequencies suited to shallow investigations were chosen, along with using a horizontal dipole. Transect spacing allowed for measurements at equal intervals and in similar conditions for the furrowed arable fields.
d)	*Consider sources of possible electromagnetic noise and reduce such interference to as low as practicable*	Ensure that data is collected without interference from magnetic sources either on the operator or in the surrounding environment, e.g. electricity cables.

e)	*Record precise coordinates of grids and then collect conductivity data*	A Trimble R10 GNSS Receiver enabled precise locational information to be recorded.
f)	*Analyse data using contour images to identify anomalies and compare with other methods, such as electrical resistivity tomography.*	Data processed in MS Excel and in Surfer to produce clear images of electrical conductivity variability across the grids.
g)	*Design soil sampling strategy to adequately examine the anomalies and the overall soil variability*	The ESAP program was used to locate soil sample sites and the co-ordinates were entered into the R10 for identification in the field.
h)	*Analyse the data from the soil sampling to identify properties that account for the greatest variation in conductivity*	The focus of the study was on available phosphorus. The samples were analysed at a professional laboratory. MS Excel was used to statistically analyse the results.
i)	*Present conclusions using suitable GIS presentation software and based on evidence; and consider further investigations*	Contour maps of data, along with topographic maps were created. Information was correlated between the images to understand soil conditions.

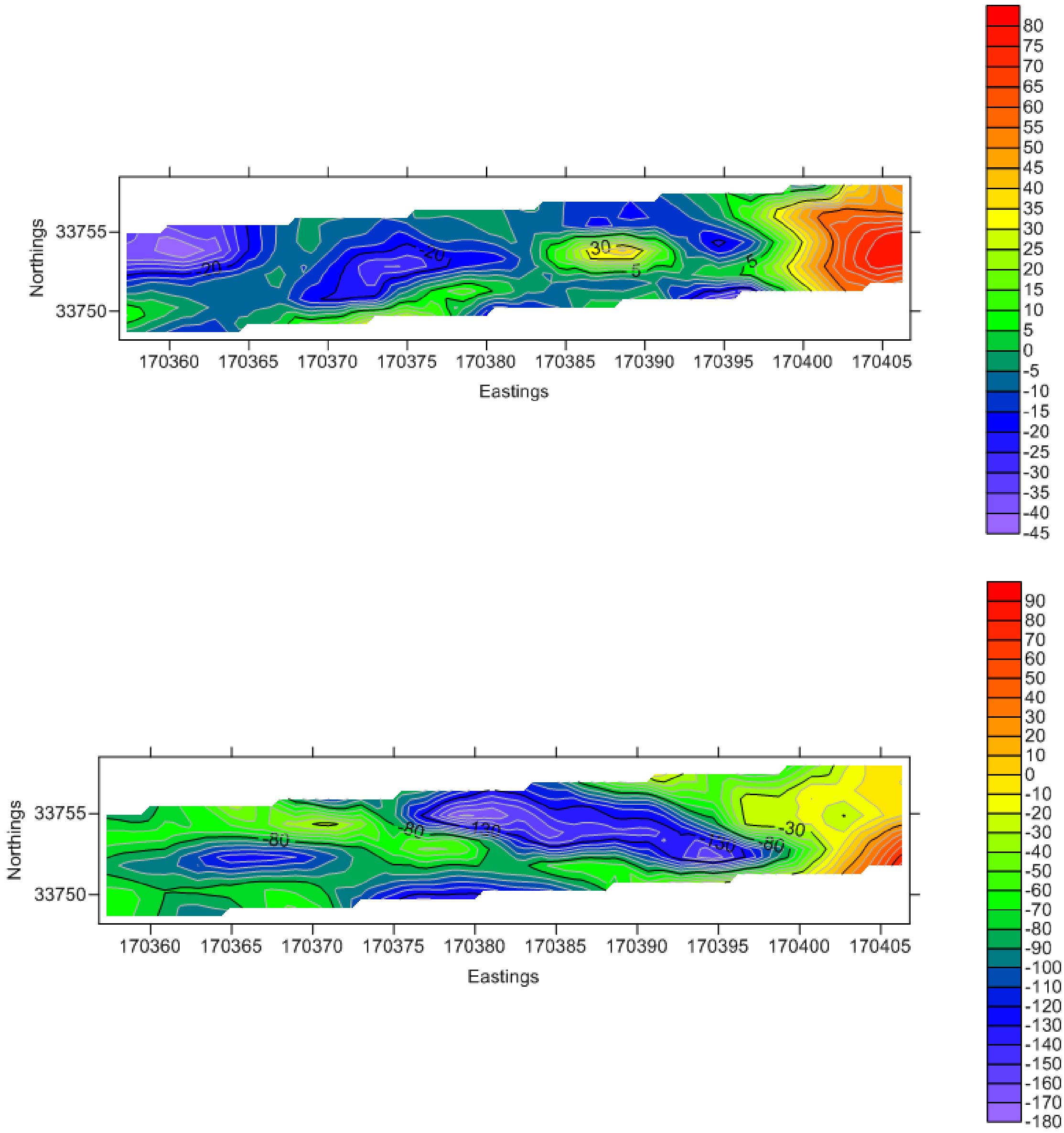


Figure 3.33 The upper image is from 15 kHz quadrature data recorded in arable field 2 using a horizontal dipole (near surface level). The image below is the same except for using a vertical dipole (deeper survey). The horizontal dipole more clearly shows the conductive material at the aggradation zone to the east.

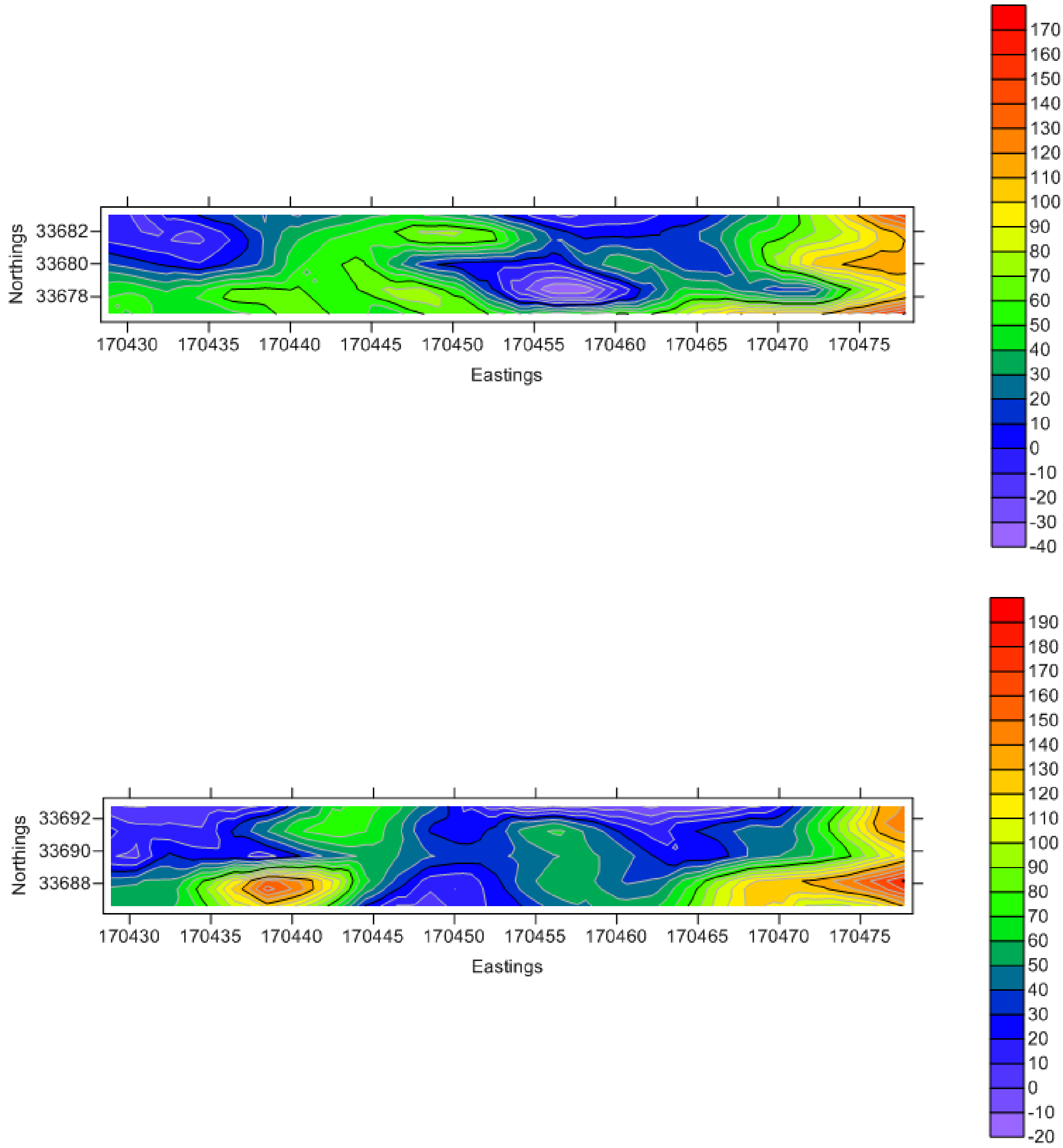


Figure 3.34 The 15 kHz quadrature images for the sloping grid of arable field 3 show slight differences between the grids in-between the bulb rows (top) and those in the furrows. The high conductivity zone at the east end of the grid extends further in the furrow condition, signifying the furrows as a channel for water and soil particles.

References

British Geological Survey/Ordnance Survey (2017) 'Wendron Geology', 1:10000. *Geology Digimap* [Online] Available at: http://digimap.edina.ac.uk/roam/geology (Accessed 11 May 2017)

Cambouris, A.N., Nolin, M.C., Zebarth, B.J. and Laverdière, M.R. (2006) 'Soil management zones delineated by electrical conductivity to characterize spatial and temporal variations in potato yield and in soil properties.' *American Journal of Potato Research*, vol.83, no.5, pp.381-395 [Online] Available at: https://link.springer.com/article/10.1007%2FBF02872015?LI=true (Accessed 14/07/2017)

Carpenter, S.R. and Bennett, E.M. (2011) 'Reconsideration of the planetary boundary for phosphorus'. *Environmental Research Letters*, vol. 6, pp.1-12 [Online] Available at: http://iopscience.iop.org/article/10.1088/1748-9326/6/1/014009 (Accessed 12/06/2017)

Chaplot, V., Lorentz, S., Podwojewski, P. and Jewitt, G. (2010) 'Digital mapping of A-horizon thickness using the correlation between various soil properties and soil apparent electrical resistivity'. *Geoderma*, vol.157, pp.154-164 [Online] Available at: http://www.sciencedirect.com/science/article/pii/S0016706110001138 (Accessed 14/06/2017)

Chemtest (2016) *Soil Method Summaries* [Online] Available at: http://www.chemtest.co.uk/wp-content/uploads/2016/09/Method-Summaries-Soils_2016.pdf (Accessed 15/07/2017)

Coard, M.A. et al. (1983) 'Paleolimnological studies of annually-laminated sediments in Loe Pool, Cornwall, UK'. *Hydrobiologia*, vol.103, pp.185-191. Available at: https://link.springer.com/content/pdf/10.1007%2FBF00028450.pdf (Accessed 12/07/2017)

Corwin, D.L. and Lesch, S.M. (2005a) 'Apparent soil electrical conductivity measurements in agriculture'. *Computers and Electronics in Agriculture*, vol.46, pp.11-43 [Online] Available at http://www.sciencedirect.com/science/article/pii/S0168169904001243 (Accessed 25/04/2017)

Corwin, D.L. and Lesch, S.M. (2005b) 'Characterizing soil spatial variability with apparent soil electrical conductivity I: Survey protocols'. *Computers and Electronics in Agriculture*, vol.46, pp.103-133 [Online] Available at: http://www.sciencedirect.com/science/article/pii/S0168169904001279 (Accessed 28/04/2017)

DEFRA (2009) *Protecting Our Water, Soil and Air: A Code of Good Agricultural Practice for Farmers, Growers and Land Managers*. [Online] Available at:

https://www.gov.uk/government/publications/protecting-our-water-soil-and-air (Accessed 15/06/2017)

Drury, S. (2008) *Exploring Earth's History*. Milton Keynes: The Open University

Environment Agency (2007) *Think Soils: Factors that Influence Erosion and Runoff* [Online] Available at: http://adlib.everysite.co.uk/adlib/defra/content.aspx?id=263233 (Accessed 26/06/2017)

Environment Agency (2017) *Catchment Data Explorer: Cober and Lizard* [Online] Available at: http://environment.data.gov.uk/catchment-planning/OperationalCatchment/3094 (Accessed 07/06/2017)

Evans, R. (2006) 'Curtailing water erosion of cultivated land: an example from north Norfolk'. *Earth Surface Processes and Landforms*, vol. 31, pp. 598-605 [Online] Available at: http://onlinelibrary.wiley.com/doi/10.1002/esp.1354/abstract (Accessed 12/05/2017)

French, C.N., Murphy, R.J. and Atkinson, M.G.C. (1999) *Flora of Cornwall: Atlas of the Flowering Plants and Ferns of Cornwall*. Camborne: Wheal Seton Press

Heckrath, G., Djurhuus, J., Quine, T.A., Van Oost, K., Govers, G. and Zhang, Y. (2005) 'Tillage erosion and its effect on soil properties and crop yield in Denmark'. *Journal of Environmental Quality*, vol.34, pp.312-324 [Online] Available at: https://dl.sciencesocieties.org/publications/jeq/abstracts/34/1/0312 (Accessed 15/07/2017)

Heilig, J., Kempenich, J., Doolittle, J., Brevik, E.C. and Ulmer, M. (2011) 'Evaluation of electromagnetic induction to characterize and map sodium-affected soils in the Northern Great Plains'. *Soil Survey Horizons*, vol. 52 (3), pp.77-88 [Online] Available at: https://dl.sciencesocieties.org/publications/sh/abstracts/52/3/77 (Accessed 12/06/2017)

House of Commons Environmental Audit Committee (2016) *Soil Health: First Report of Session 2016-17*. [Online] Available at: https://publications.parliament.uk/pa/cm201617/cmselect/cmenvaud/180/180.pdf (Accessed 20/06/2017)

Jarvie, H.P., Neal, C., and Withers, P.J.A. (2006) 'Sewage-effluent phosphorus: A greater risk to river eutrophication than agricultural phosphorus?' *Science of the Total Environment*, vol.360, pp.246-253 Available on line at: http://www.sciencedirect.com/science/article/pii/S0048969705006066 (Accessed 15/07/2017)

King, J.A., Dampney, P.M.R., Lark, R.M., Wheeler, H.C., Bradley, R.I., and Mayr, T.R. (2005) 'Mapping potential crop management zones within fields: use of yield-map series and patterns of soil physical properties identified by electromagnetic induction sensing'. *Precision Agriculture*, vol. 6, pp.167-181. Available online at:

https://link.springer.com/article/10.1007%2Fs11119-005-1033-4?LI=true (Accessed 08/06/2017)

Lardo, E., Arous, A., Palese, A.M., Nuzzo, V. and Celano, G. (2016) 'Electromagnetic induction: A support tool for the evaluation of soil CO_2 emissions and soil organic carbon content in olive orchards under semi-arid conditions.' *Geoderma*, 264, pp.188-194. Available at: http://www.sciencedirect.com/science/article/pii/S0016706115301087 (Accessed 23/07/2017)

LeBoutillier, N.G. (2002) *The Tectonics of Variscan Magmatism and Mineralisation in South West England*. PhD Thesis, University of Exeter [Online] Available at: http://myweb.tiscali.co.uk/geologyofcornwall/Le%20Boutillier%20Volume%20I.pdf (Accessed 23/07/2017)

McCormick, S., Jordan, C. and Bailey, J.S. (2009) 'Within and between-field spatial variation in soil phosphorus in permanent grassland.' *Precision Agriculture*, vol. 10, pp.262-276 Available online at: https://link.springer.com/article/10.1007/s11119-008-9099-4 (Accessed 08/06/2017)

MAGIC (2017) '*Helston and Wendron'.* 1:20,000 [Online] Available at: http://www.magic.gov.uk/MagicMap.aspx (Accessed 05 June 2017)

Mainstone, C.P., Dils, R.M. and Withers, P.J.A. (2008) 'Controlling sediment and phosphorus transfer to receiving waters – A strategic management perspective for England and Wales'. *Journal of Hydrology*, vol. 350, pp.131-143. Available online at: http://www.sciencedirect.com/science/article/pii/S0022169407006221 (Accessed 12/06/2017)

Met Office (2017) *Climate Averages for Culdrose Climate Station* [Online] Available at: http://www.metoffice.gov.uk/public/weather/climate/gbukbmeyr (Accessed 17/06/2017)

Mining in Cornwall Database (2017) *Medlyn Moor Mine, Cornwall* [Online] Available at: http://www.cornwallinfocus.co.uk/mining/medlynmoor.php (Accessed 10/06/2017)

Morgan, R.P.C. (2005) *Soil Erosion and Conservation*. 3rd edn. Oxford: Blackwell Publishing

Nathanail, C.P. and Bardos, R.P. (2004) *Reclamation of Contaminated Land*. Chichester: John Wiley

Omonode, R.A. and Vyn, T.J. (2006) 'Spatial dependence and relationships of electrical conductivity to soil organic matter, phosphorus, and potassium.' *Soil Science*, vol.171, no. 3, pp.223-238. Available online at: http://journals.lww.com/soilsci/Abstract/2006/03000/Spatial_Dependence_and_Relationships_of_Electrical.4.aspx (Accessed 12/07/2017)

Ordnance Survey (2017a) ‘Helston’, SW62 tile, 1:50,000, *Digimap* [Online] Available at: http://digimap.edina.ac.uk/roam/os (Accessed 06 May 2017)

Ordnance Survey (2017b) ‘Wendron’, SW63 and SW73 tiles, 1:25,000, *Digimap* [Online] Available at: http://digimap.edina.ac.uk/roam/os (Accessed 06 May 2017)

Ordnance Survey (2017c) ‘Porkellis’, SW7033 tile, 1:1,000, *Digimap* [Online] Available at: http://digimap.edina.ac.uk/roam/os (Accessed 06 May 2017)

Querrien, A., Moulin, J. and Tabbagh, A. (2013) ‘Comparison between a geophysical survey, soil analyses and excavation data revealing a combined effect of soil compaction and erosion’. *Near Surface Geophysics*, vol.11, pp.95-100

Reynolds, J.M (2011) *An Introduction to Applied and Environmental Geophysics*. 2nd edn. Chichester: John Wiley

Reynolds International (2017) ‘EM 31 electro-magnetic ground conductivity mapping’ [Online] Available at: http://www.reynolds-international.co.uk/technical-summary-sheets/ (Accessed 21/07/2017)

Rickson, R.J. (2014) ‘Can control of soil erosion mitigate water pollution by sediments?’ *Science of the Total Environment*, vol. 468, pp.1187-1197. [Online] Available at: http://www.sciencedirect.com/science/article/pii/S0048969713006001 (Accessed 28/04/2017)

Rockstrom, J. (2009) ‘A safe operating space for humanity’. *Nature,* 461, pp.472-475 [Online] Available at: http://www.nature.com/nature/journal/v461/n7263/full/461472a.html (Accessed 12/05/2017)

Rowell, D.L. (1994) *Soil Science: Methods and Applications*. Harlow: Longman Scientific

Singh, G., Williard, K.W.J., and Schoonover, J.E. (2016) ‘Spatial relation of apparent soil electrical conductivity with crop yields and soil properties at different topographic positions in a small agricultural watershed.’ *Agronomy*, vol.6, pp.1-22 [Online] Available at: http://www.mdpi.com/2073-4395/6/4/57/htm (Accessed 09/07/2017)

Tompsett, A. (2006) *Golden Harvest: The Story of Daffodil Growing in Cornwall and the Isles of Scilly*. Penzance: Alison Hodge

Trimble Inc. (2017) *Trimble Ag Field Solutions*. [Online] https://agriculture.trimble.com/precision-ag/ (Accessed 21/07/2017)

Trudgill, S. (1989) *Soil Types: A Field Identification Guide*. Montford Bridge, Shrewsbury: Field Studies Council

Walker, T. (2017) *Cober Catchment Management Project: 2017 Management Review and 2027 Plan*. [Online] Available at: https://loepool.org/research-reports/catchment-management-reports/ (Accessed 08/07/2017)

White, R.E. (2006) *Principles and Practice of Soil Science: The Soil as a Natural Resource*. 4th edn. Malden, MA: Blackwell Publishing

ZZ Resistivity Imaging Pty.Ltd (2017) *What is a ZZ array?* [Online] Available at: http://www.zzgeo.com/zz-resistivity-faq_data_collection_3.3.html (Accessed 10/08/2017)