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Precision Farming and Archaeology

Henry Robert Webber

A dissertation submitted to the University of Bristol in accordance with the requirements for award of the degree of Doctor of Philosophy (PhD) in the Faculty of Arts, Department of Archaeology and Anthropology

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Abstract:

This research investigates the interconnections between Precision Farming and archaeology. It highlights the impacts that human activity has on soils throughout time and situates them within the context of new, digital, agricultural methods for mapping, monitoring and managing land in the UK.

Precision Farming is new to archaeologists, and modern archaeological approaches are not well recognised in the agricultural world. This research aims to cross this divide, promoting mutually beneficial dialogue and shared understanding between the two.

Three detailed case studies demonstrate the variety of technologies and techniques used in both archaeological investigations and Precision Farming systems on the same area of land. Each case study brings together the archaeological and agricultural background of each area, as well as targeted soil sampling for pXRF analysis of soils to evaluate soil stratigraphy and geochemistry. Combining this with GIS analysis of over 13 different datasets allowed comparison of how archaeological data might be useful for future agricultural land management, and how Precision Farming data may be considered for aiding the mapping, monitoring and management of archaeological sites.

The results display a wide variety of impacts that human activity can have on the soil, and that many are relevant for agricultural management today. Archaeological sites can impact soil nutrients and soil contaminants, as well as explain anomalies in Precision Farming data. Results have demonstrated Precision Farming data can be used to discover new archaeological sites, add information about existing sites, and help engage the modern farming community. Factors such as the type of archaeological site, the data available and the spatial resolution of that data can all have effect on these results. This is the first attempt at studying the breadth of interactions between Precision Farming and archaeology, with further research needed to develop these ideas and promote knowledge exchange in both the archaeological and agricultural worlds, at a practical, academic and a policy level.

“What have the Romans ever done for us?”

(Monty Python’s Life of Brian, 1979)

Written in Helsinki
Edited over central Asia
Finished on the farm

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I would like to thank my supervisors most of all; Mark Horton, Volker Heyd, Martin Bell, Wendy Matthews and Amanda Chadburn, for encouraging and constraining my enthusiasm for researching this topic.

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Publications:

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Author's declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's *Regulations and Code of Practice for Research Degree Programmes* and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: .... DATE:..........................

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List of Abbreviations:

ADS – Archaeology Data Service
Agri-Tech – Agricultural Technology
AOD – Above Ordinance Datum
BCE – Before Common Era
CAP – Common Agricultural Policy
CE – Common Era
CHL – Chlorophyll Index
CIfA – Chartered Institute for Archaeologists
COSMIC – Conservation Of Scheduled monuments In Cultivation
CV – Coefficient of Variation
CwF – Clay-with-Flints
DBA - Desk Based Assessment
Defra – Department for the Environment, Food and Rural Affairs
Degrees C – Degrees Centigrade
DTM – Digital Terrain Model
EMI – Electromagnetic Induction
ER – Earth Resistance
ERT – Electrical Resistance Tomography
EU – European Union
FMIS – Farm Management Information Systems
GIS – Geographical Information Systems

GLONSS – GLobal Orbiting Navigation Satellite System

GNSS – Global Navigation Satellite Systems

GPR – Ground-Penetrating Radar

GPS - Global Positioning System

Ha – Hectares

HAR – Heritage At Risk

HER – Historic Environment Record

ICP-MS – Inductively Coupled Plasma Mass-Spectrometry

IDW – Inverse Distance Weighting

KML – Keyhole Markup Language

LIDAR – Light Detection And Ranging

LOD – Limit of Detection

MARS – Monuments At Risk Survey

MS – Magnetic Susceptibility

NDVI – Normalised Difference Vegetation Index

NGR –(UK) National Grid Reference

NIR – Near Infra-Red

NMP – National Mapping Programme

NSRI – National Soil Resources Institute

OASIS - Online AccesS to the Index of archaeological investigationS

OM – Organic Matter

OS – Ordnance Survey

PAS – Portable Antiquities Scheme

PC – Principal Component

PCA – Principal Components Analysis

PF – Precision Farming

ppm – Parts Per Million

pXRF – Portable X-Ray Fluorescence

RCHME – Royal Commission on the Historical Monuments of England

RGB – Red Green Blue

SD – Standard Deviation

SHINE – Selected Heritage Inventory for Natural England

SOB – Soil Brightness Index

UK – United Kingdom

UNESCO – United Nations Economic Social and Cultural Organisation
US – United States

N, S, E, W, NE, NW, SE, SW – Cardinal directions
Chemical elements will generally be in their shorthand form: Phosphorus = P
Where specific forms of an element are important this is noted by Total, Available, Exchangeable *etc*.

Chapter 1

1 Introduction, Aims and Conceptual Approach

1.1 Introduction

It is widely recognised that human activity can have an impact on soils. These anthropogenic impacts could have happened thousands of years ago, one day ago, or could happen in the future. Some anthropogenic impacts remain relatively unaltered for millennia (buried stone walls), while others can be unrecognisably changed by natural and cultural processes (organic materials). This thesis takes a holistic approach to studying soils in agricultural landscapes, both their natural development and anthropogenic alteration over time. It situates human impacts on soils, with the development of modern, digital, agriculture to inform mutual dialogue between archaeologists, heritage managers, farmers and agricultural specialists.

Agriculture has changed substantially over the past century due to the challenges of declining natural resources, increasing human populations, and significant environmental degradation (FAO, 2017). Developed and developing societies across the globe have embedded, and continue to embed, science and technology in agriculture to tackle plateauing yields, rising costs and unsustainable agricultural practices (HM Government, 2013; FAO, 2017). '**Precision Farming' (PF)** (term used in this thesis), 'precision agriculture' or 'site-specific farming' (terms sometimes used), is a digital agricultural methodology playing a core role in the future of agriculture. While it's definition is slightly amorphous, it is commonly understood to be the recording and management of variation in crops and soils within a field, aiming to reduce inputs, increase productivity and aid environmental sustainability (Stafford, 2000; McBratney *et al.*, 2005; Oliver, 2010). PF presents a significant increase in the quantity of recorded data, from many different sources, on a large spatial scale but also at a higher resolution than ever before in agriculture. This data collection is intended to produce more effective and timely monitoring of plants and soils, enhanced data analysis and, ultimately, better agricultural decision-making (Mulla and Khosla, 2015).

Archaeological sites are often the foci of past human activity and there are a wide variety of impacts that these activities can have on the soil (Rapp and Hill, 2006; French, 2015). Habitation sites, for example, often contain waste materials from buildings; animals and humans, preserved in buried pits, ditches and deposits. Other activities such as the production of metals, or the quarrying for natural resources, are common reasons for the movement and concentration of materials in particular places. Broader land management practices, for example the manuring of fields, can additionally impact on a soil's physical and chemical composition (Entwistle *et al.*, 2000). As well as the landscape of the living, the landscape of the dead (burials, cemeteries, enclosures) contributes to the many different types of disturbance to soils at archaeological sites. Each occurrence of human activity can change the biological, chemical and physical components of the soil in different ways, successively creating the **soil palimpsest** that can be observed today.

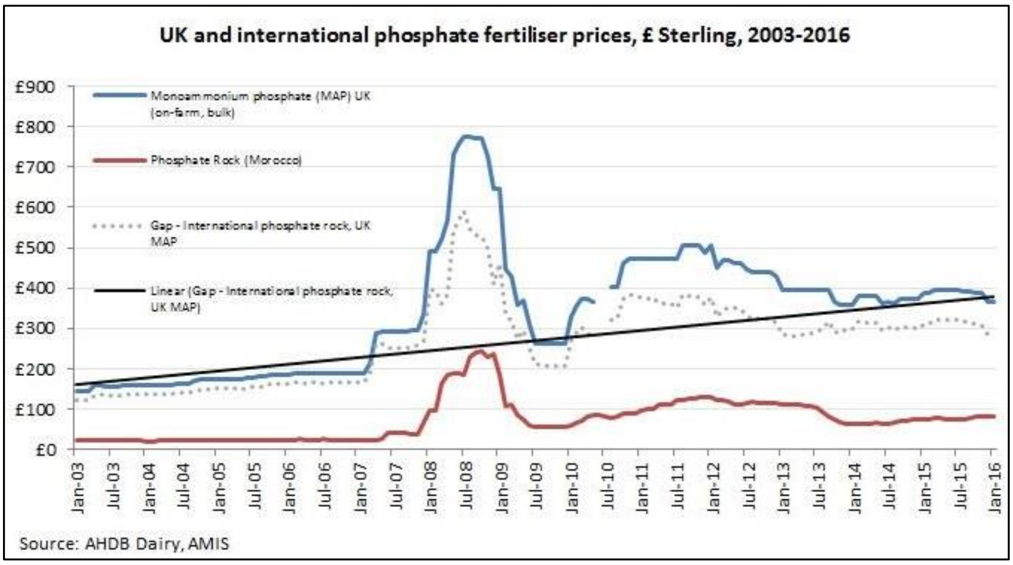
Globally agricultural land covers 4.9 billion hectares (ha) (FAO, 2017: p.32), in the United Kingdom (UK) 72% of land is under some form of agricultural land use (Defra, 2018b). It is not surprising then, that archaeological sites are often found on agricultural land, particularly in areas that have been intensively settled by humans for millennia (Oxford Archaeology, 2002). In some cases this can be positive, for example the discovery of archaeological sites through cropmarks, but unavoidably it can have negative effects such as the degradation of archaeological sites due to the cultivation of soils. For an individual farmer or archaeologist, this intertwined nature can lead to tensions surrounding the access to land or the conservation of archaeological sites. Making the understanding and management of archaeological sites more difficult.

As a consequence of many archaeological sites being situated on agricultural land, changes to agricultural practices can have deep impacts on the archaeological record. Historic buildings can be destroyed by poorly planned re-development, or even a lack of maintenance (English Heritage, 2009). Changes in the crop rotation can bring with it different methods of cultivation to prepare the soil, root crops typically have deeper cultivation zones due to late harvesting increasing compaction that needs remediation before the next crop (Lambrick, 1977). Deeper cultivation increases the risk of irrevocable damage to sensitive archaeological sites (Oxford Archaeology, 2002). Archaeologists and heritage managers have needed to keep pace with such changes in agricultural practices to effectively manage archaeological sites on agricultural land, and will need to continue to do so in the future. The two above examples are of negative effects, however this is not to say that agricultural changes can only be negative. This thesis will consider the positive, as well as the negative effects that PF may have on the study of archaeology and on archaeological sites themselves.

As an archaeologist specialising in archaeological prospection, having worked in the PF industry, and a farmers' son, I have had many personal experiences in combining archaeology and PF through a core interest in soils that have led to the formation of these ideas. This research was funded in the first round of the Arts and Humanities Research Council, South West and Wales Doctoral Training Partnership in 2014. Allowing supervision, equipment, resources and training from two institutions as well as a third collaborating partner. For myself these were the University of Bristol, the University of Reading, along with Historic England as the collaborating partner. This allowed access to important equipment such as the portable X-Ray Fluorescence (pXRF) analyser and geoarchaeological expertise at University of Reading, fieldwork equipment and broader archaeological expertise at University of Bristol. These were combined with advice and guidance from Historic England for a policy and heritage management perspective. During my study I had the opportunity for a three month placement at The Royal Society working in science policy, which after provoking interest, subsequently led to my employment by the UK Government Department for the Environment, Food and Rural Affairs (Defra). This personal background has helped this research to have both an academic core, a policy context and a real world emphasis.

1.2 Timeliness

Today a simple word search on the Internet for 'PF' will highlight the wide array of small and medium sized companies (between 20 and 30 in the UK) offering PF services such as soil mapping, satellite imagery and more recently drone imagery and agronomic services over hundreds of thousands of hectares. Yet in 2014, at the start of this research, the number of companies was below ten. This commercial situation reflects a surge in practical uptake and interest from the farming community in the UK. This surge was, and still is, being driven by the increasing costs of inputs such as fertilisers, seeds and chemicals, but also the decreasing costs of software and hardware that make PF feasible (Graham, 2014; Jarman *et al.*, 2016). The prices of seeds, fertilisers and chemicals have remained high since the economic crash in 2008 that saw prices rise dramatically (Figure 1), meaning that agricultural profitability focused towards the reduction and targeting of costly inputs; rather than the increase of yields by further inputs. At the same time rising consciousness of agriculture's environmental impact also contributed, and continues to do so, towards resource efficiency drivers.



UK and international phosphate fertiliser prices, £ Sterling, 2003-2016

Source: AHDB Dairy, AMIS

Figure 1: Graph of fertiliser prices over time (©AHDB Dairy, AMIS)

From the policy perspective PF has been viewed as a core breakthrough within the UK Governments' Agri-Tech strategy (HM Government, 2013; Parliamentary Office of Science and Technology, 2015). It has received millions of pounds of investment to translate technological and agricultural research into practical outcomes for UK farming sectors, and continues to hold high regard in agricultural policy making. This movement comes as Defra has published its' 25 Year Environment Plan (2018a) setting out the Government's goals for improving the environment, reducing chemical use, mitigating climate change, while sustaining productivity and enhancing the natural and cultural environment. PF has a role to play in a number of these objectives (Parliamentary Office of Science and Technology, 2015).

At a European level, PF has received similar attention for its potential to aid resource efficiency, productivity, as well as part of the digitising of agricultural policy to make it easier to take up (European Commission, 2019). It is also recognised as having wider implications for the European Union (EU) in terms of legal, social and ethical considerations (Joint Research Centre (JRC), 2014; Kritikos, 2017).

Internationally there is less policy coordination in relation to PF, but the growth and embedding of PF technologies in agricultural systems is still occurring. From countries that were early adopters such as the United States (US), Canada and Australia, to a wider range of agricultural systems in countries such as Brazil, China, India, as well as countries on the African continent (Zhang *et al.*, 2002; McBratney *et al.*, 2005).

It is not only PF that makes this thesis timely. Out of all the threats to the historic environment, agriculture is one of the most significant (Trow *et al.*, 2010). Agricultural land is where 84% of the UK's nationally important scheduled monuments lie (The Heritage Alliance, 2017), it is also the most difficult to manage due to the lack of legal protection, the large area of land involved, the invisible nature of buried archaeological sites and the historic lack of systematic recording and monitoring of buried rural archaeological heritage (Trow *et al.*, 2010).

The application of archaeological prospection techniques and methodologies has developed significantly over the past two decades (Opitz and Herrmann, 2018). Geophysical sensor systems can now cover much larger areas with even greater accuracy and resolution (Gaffney, 2008; Dabas, 2009; Gaffney *et al.*, 2012). Drones fitted with a variety of different spectral and electromagnetic sensors have now become common place in many archaeological investigations despite having their criticisms (Campana, 2017; Cowley *et al.*, 2018). As excavation is costly, destructive and time consuming, non-invasive prospection is likely to continue to be a vital part of work to record archaeological sites. The limitations of single technique surveys are often noted, leading to the promotion of multi-technique sensor platforms and the combination of different methods and techniques applied to the same archaeological site for best results (Gaffney, 2008; Hill *et al.*, 2008; Cuenca-García, 2012). The management, access, and sharing of that vastly increasing array of data is also becoming more important for the future of archaeology (Bevan, 2015; Opitz and Herrmann, 2018). In addition the multi-disciplinary value of those datasets is starting to be realised, for example where geophysical datasets might be of use for PF services as well as archaeologists, and drone imagery useful for land use planning and environmental monitoring (B. Urmston, pers. comm.).

'Soil health' has become a prominent issue in contemporary narratives surrounding agriculture, the environment and climate change. It has been recognised in UK Government reports such as the 25 Year Environment Plan, in public media, and subject of a Parliamentary Select Committee investigation (Environmental Audit Committee, 2016; Defra, 2018a; Harvey, 2018). Awareness of soil degradation, what this means for the web of interconnected societal and environmental systems that depend on it, and how soils can be improved or negative change mitigated, is therefore of utmost importance to a range of communities.

PF is developing rapidly, with the potential to impact not only on the natural environment through more efficient use of inputs and better management of soils and crops, but also on the historic environment through changing management practices. Its effects on the study and practice of archaeological prospection and heritage management are as yet unknown. Soils mark the junction between agriculture and archaeology and any contribution this thesis can make to the wider debates over soil health, soil mapping, monitoring and soil management would be beneficial. These reasons set out why it is relevant now for archaeologists, heritage managers, farmers and agricultural specialists to be aware of PF and archaeology in combination.

1.3 Aims, Objectives, and Research Questions:

There have been few studies that link the perspectives of archaeologists, and those working on the historic environment more widely, with PF specialists. Furthermore, little evidence has been collected to test how archaeology and PF interconnect, or where areas of mutual understanding or information exchange may be possible. This thesis aims to provide both an archaeological (including the many sub-specialisms for example archaeological geophysics, geoarchaeology, heritage management etc) background and a PF (and more widely agricultural) background to an audience of archaeologists, heritage managers, farmers and agricultural specialists. It will establish the key topics of both areas and highlight why soils are central to this interdisciplinary approach, as well as signpost to existing detailed studies. It will then aim to demonstrate these approaches in practice through case studies.

This thesis puts forward four key research questions:

1. To what extent are archaeological data similar or different to PF data for assessing soils and crops?
2. How do archaeological sites impact soils and are those impacts relevant to PF methods and data?
3. Which archaeological data have most potential to be integrated within a PF system and vice versa?
4. How far can integrating archaeological and PF approaches be used to manage agricultural soils as well as heritage in the future?

There are several important objectives for this thesis:

- To highlight a ‘field history’ approach. Archaeological investigations are often limited to specific areas by scope of archaeological interest, area of risk (such as development), or cost and resources. This, while sometimes unavoidable, neglects a more objective approach to studying landscapes and limits the multi-purpose nature of certain datasets. As changes in the quality, quantity and cost of data occurs, as well as better awareness of the multi-functional requirements of landscapes, there could be value in assessing wider areas to enhance archaeological understanding, as well as more valuable multi-purpose datasets.

- Promotion of mutual dialogue and knowledge exchange between communities such as archaeologists and farmers, archaeological companies and agricultural companies, heritage managers and policy makers.
- Draw together data and results from this research to contribute to wider dialogues relating to soils, agricultural policy, the historic environment and archaeological prospection.

1.4 Conceptual Approach

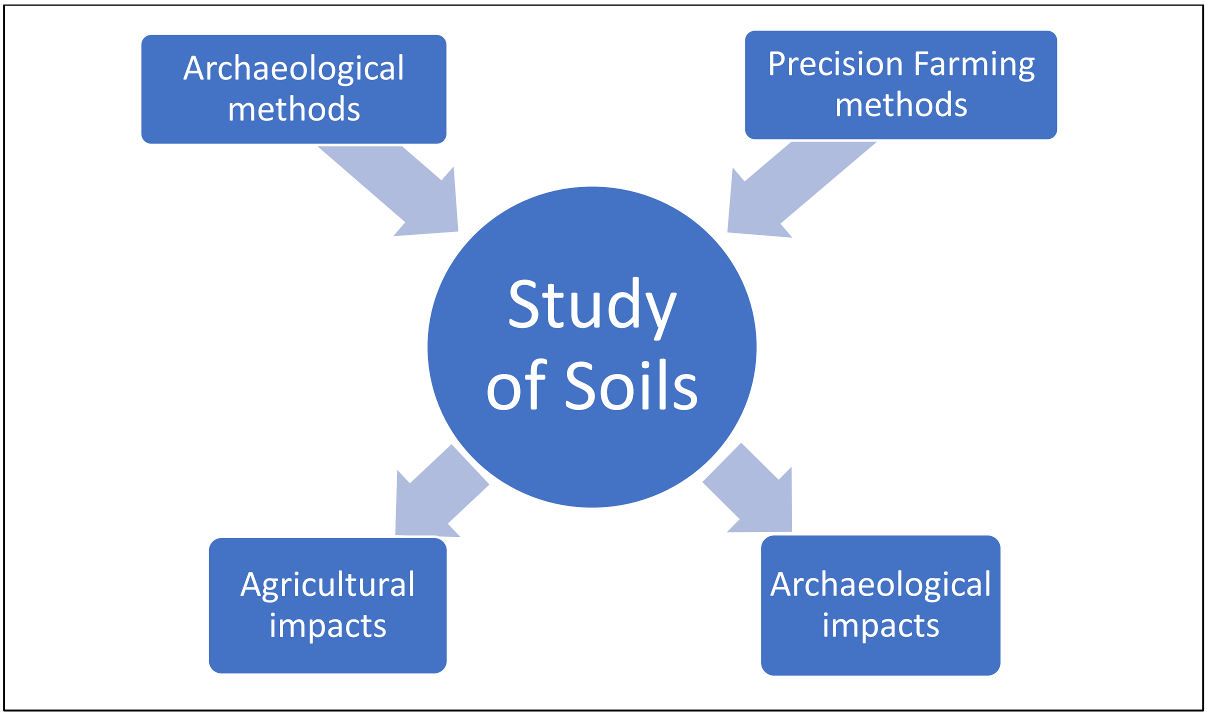


Figure 2: Diagram showing the conceptual approach

To answer the research questions, the approach will focus on the study of soils, from both archaeological and PF methods. It will then look at the impacts of this study on both archaeology and PF (Figure 2). Archaeological investigations, whether involving prospection for new sites, or evaluation of existing sites, depend on an understanding of the soils and geology in an area (Historic England, 2015a). PF decisions regarding crop management also depend fundamentally on underlying soil variations (Oliver, 2010).

A case study approach is the most appropriate way to merge archaeological and PF methods on the same area of land. This will allow testing of how similar or different archaeological and PF methods are for assessing soils. Enabling any impact of archaeological sites on soil variation to be demonstrated and for this impact to be put in the context of PF practices. Simultaneously the agricultural and PF impact on archaeological sites can also be addressed.

1.5 Case Study Selection

The primary geographical focus for this research will be in the UK. This is partly due to my background and extensive experience in UK agriculture and archaeology, but the UK is also a suitable location for this research due to its diverse geologies and mixture of soil types, the range of different PF practices applicable and the rich archaeological record. This does not preclude wider European and International perspectives that will be drawn from work I have undertaken on related projects and exposure to wider PF and archaeological backgrounds at conferences.

Case study sites will be chosen within lowland areas within arable zones, acknowledging that the development of PF has occurred most intensely on arable landscapes in lowland areas. This is also where archaeological sites are at most threat from agricultural damage (Historic England, 2018b). Case study sites will be restrained to one or potentially two adjacent modern fields. Archaeologically and geologically this represents a compromise between site specific investigations and landscape scale investigations. It will lead to a more complete ‘field history’ from an agricultural perspective and allow determination of whether in field variation is related to modern agricultural practices that would have been applied over the whole field.

The selection of case study sites was made on a mixture of three criteria: **archaeological considerations**, **geology**, and **agricultural/PF considerations**.

1.5.1 Archaeological Considerations

An archaeological site can encompass thousands of different types of evidence, varying amounts of evidence and unique spatial and temporal relationships. As such it is hard to include the huge variety of different site types without some sort of prioritisation. The main considerations for site types were:

- sites covering a range of archaeological periods
- single vs multi-site
- variation in the spatial extent of sites
- mixture of types of archaeological deposits within archaeological sites

The first consideration is the chronological age of the site, or sites, across all case studies. There may be advantages having the same type of site, from the same period, across all case study sites to allow straight comparisons. While this may be possible, it is unlikely that comparisons will be effective because of changing agricultural practices and variations in geology and geomorphology, and the archaeological variation even on sites of the same type and period. Instead it is more desirable that there is a mixture of different periods of archaeology.

Some archaeological sites can be found isolated from other archaeological sites, whereas other sites can become complex palimpsests of occupation and activity that interconnect with each other. This adds another dimension to the choice of a case study, where it might be expected that multi-site areas could lead to greater impacts through longer periods of activity. They may also lead to more complicated patterns that are difficult to interpret in comparison to single sites on relatively consistent areas of soil.

Often archaeological sites vary in their scale and can range from small collections of pits to large settlement enclosures and wider landscapes. This could mean that their impacts on the soils surrounding them are also variable, altering how they are perceived by farmers and PF specialists. Ideally a range of archaeological sites would be present at each case study site to demonstrate how different scales of site could impact PF data.

Further to this overall site scale, the individual deposits that form the basis of archaeological evidence for every site can vary. A historic ditch line will alter the existing soil profile in a different way to a buried pit, or the foundations of a building, for example. Areas of use within enclosures and buildings can also produce different archaeological signatures due to different activities within such spaces. The case study sites chosen should aim to represent those varieties.

1.5.2 Geology

Geological, geomorphological and pedological criteria are important for case study selection. The bedrock geology, after weathering, erosion and with the addition of superficial deposits and later pedological developments throughout time have created the soil environment within which farmers grow their crops, and where archaeological sites were originally created and are preserved to varying extents. The parent material of any soil will inherently have a great effect on the composition, structure and variability of the soils that develop upon it. The main bedrocks that occur in the lowland zone of England where the case studies are located consist of chalk, Tertiary and Pleistocene sands and clays, and finally mudstones, sandstones and limestones (Avery, 1990). Among these there are more local characteristics of soil development related to topography, vegetation, climate and time. Although it could be beneficial to choose case study sites that represent different geological bedrocks, it is also of perhaps greater importance to exhibit the variability of the soils that have developed over comparatively similar geological bedrocks, and this will be a focus across the case study sites in this thesis.

1.5.3 PF and Agricultural Considerations

The final criteria for case study site selection is the agricultural or PF context of the site. Not every farmer or farm utilises PF methods. Neither does every farm that is using PF methods, use the same methods as other farms. This is partly due to different commercial pursuits by different companies, but also because farmers have to make choices about how much money to spend on data collection and on what methods they believe to be most useful and ‘successful’(Barnes *et al.*, 2019). Another issue that may arise is whether a farmer is willing to share their data with researchers (European Parliamentary Research Service, 2016: p.28). The existing knowledge a farmer has about the farm is also a factor, larger farms tend to be more inclined to use PF methods because they do not have the local specific knowledge about every field whereas on a smaller farm the farmer may do.

For case study selection, clearly the farmer must be using PF methods of some kind on land they manage. The length of time using PF methods or the amount of data collected is not as important for the decision on case study sites. It would be beneficial for each case study site to demonstrate some of the wide range of different PF technologies and techniques, and a range of different farm types (owned, rented, contract farmer) to provide a broader background of how PF is used by different farmers.

1.6 Thesis Structure and Selected Case Study Sites

This thesis considers, for the first time, archaeological interactions with, and implications for, PF. Both PF and archaeology, have their own technologies and techniques, underpinning core questions, and standardised skill sets (explained in Chapters 2 and 3 respectively), but also the possibility for mutually beneficial dialogue. At the centre of both is the soil (Chapter 4), the material that is produced by a combination of natural and cultural processes. Soil studies from agricultural perspectives and archaeological, and geoarchaeological, perspectives need to be combined to provide a holistic approach to understand soils. The methodological approach taken in this thesis has been genuinely multi-disciplinary to deal with the diverse range of technologies and techniques used by both archaeologists and PF specialists, this will be outlined further in Chapter 5. The case study Chapters (6, 7 and 8) will then present the results of each case study site in the UK (Figure 3).

Figure 3: Location of the three case study sites

(contains OS data © Crown copyright and database right 2019)

Chapter 6 contains the results from Myncen Farm in Dorset. The farm is a family run farm that makes use of a selection of PF methods (Normalised Difference Vegetation Index (NDVI) imagery, soil nutrients, soil zoning) but does not have yield maps. The site lies across shallow chalky soils at each slope, with the heavier textured clay-with-flints (CwF) lying on higher ground. The archaeological site comprises of an undated large hill top enclosure, common for this area and on the Heritage at Risk Register (HAR) 2015 latest findings for the South West (Historic England, 2015a). It also includes a smaller Iron Age enclosure with associated pits, indicative of more permanent habitation or livestock penning and a number of other ditch features, as well a Roman villa nearby (Wessex Archaeology, 2004; Sparey-Green, 2007; Wickstead and Barber, 2010). Archaeological work has been completed by local societies, Bournemouth University and the Time Team.

The second chosen site (Chapter 7) lies in the Vale of Pewsey (Wiltshire), and surrounds the Wilsford henge. The area surrounding the field contains a barrow cemetery, while the field itself contains potential Roman buildings, field enclosures, and the Neolithic henge itself (Linford *et al.*, 2013; Leary, 2015, 2016). The field also lies on the boundary between Upper Greensand and Lower Chalk geologies, having multiple soil types within the one field. Archaeological work undertaken at Wilsford has been done by English Heritage (now Historic England) and by the University of Reading making it a site that has been studied intensively with a research focus. The farm is contract farmed by a farmer who uses PF methods from the same company as at Myncen Farm. This site, does however, have yield maps in addition to NDVI imagery, soil nutrient maps and soil zoning data.

The third case study site (Chapter 8) is located in Oxfordshire, at Perdiswell Farm. The site consists of one large field that has a relatively consistent geological background of Cornbrash (limestone) with thin topsoils overlying this fragmented bedrock. The field contains a scheduled monument (a Roman villa), as well as some Late Iron Age activity, post-Medieval field boundaries and 20th-century impacts during the World War Two (Bray and Taylor, 2014; Dawson and Bray, 2014; Preston, 2014). Archaeological fieldwork undertaken has produced a desk-based assessment (DBA), geophysical survey, and a detailed programme of excavation to evaluate the entire field for a development proposal. The land is contract farmed by an ‘early adopter’ who has been using PF techniques for over a decade. The farmer does not follow any one particular PF companies approach but instead has trialled techniques himself, resulting in no consistent level of data, but this site does have other datasets not covered by other case study sites (N-Sensor data).

Chapter 9 then focuses on evaluating the results. It will compare and combine results from all the case study Chapters to link with points and discussions highlighted in the earlier Chapters 2,3 and 4. Chapter 10 will then conclude, drawing out the wider themes that this research contributes to, a critique of the research, consideration of its impact and suggestions for future research.

1.7 Research Ethics

This research has been conducted within the ethics guidelines of the University of Bristol. Consideration was given to the possibility that information and locational data might be sensitive for either archaeological or agricultural reasons. Therefore at the beginning and end of the research farmers and landowners who gave permission for this work to continue, were asked if they were happy with the information and data presented in this thesis or if any anonymity was desired. Permissions were sought for every part of this work, especially regarding the drone work, to ensure relevant people were consulted.

Chapter 2

2 Precision Farming and Agri-Tech

2.1. Introduction

PF as a methodology for optimising resources, is not new. Farmers have practised these sorts of approaches for hundreds, if not thousands, of years. For example medieval peasants applied manure to fields close to the manor where high nutrient requirement crops were grown, and to save labour carting manure further (Jones, 2012). Water management systems irrigating Angkor (Cambodia) in the ninth century CE channelled water to where it was needed (Fletcher *et al.*, 2008). Farmers today manually alter the forward speed of a tractor while spreading fertilisers to variably apply fertiliser where it is needed. What makes modern PF different, is its use of technology and information management, it is the digital approach to optimising resources using technology to improve yields, cut costly inputs and improve productivity.

Work in the 1920s quantifiably demonstrated that soil variability was far more complex than existing soil sampling methodologies could represent, and that there was value in varying inputs appropriately (Linsley and Bauer, 1929). With little demand for this at the time, the topic did not draw much interest until the 1970s and 80s (Mulla and Khosla, 2015). It was in the agricultural engineering departments at various universities where academics tried experimenting with new electronic equipment that could enable the automatic weighing of yield for example, or the geographical positioning of a machine. Since then, a large increase in research, mainly in the US but also in the UK, other parts of Europe and Australia, began to not only question the variability of soils, or experiment with hardware and software, but attempt to make these processes more automated and usable for farmers (Mulla and Khosla, 2015).

The principles of PF have grown familiar not just to developed agricultural sectors, but to many different types of agriculture and in many different parts of the world (Zhang *et al.*, 2002; McBratney *et al.*, 2005; Khosla, 2010). PF not only encompasses the traditional arable sector, but now has expanded to precision forestry (Holopainen *et al.*, 2014), precision livestock farming (Joint Research Centre (JRC), 2014: p. 22; McConnell, 2017) and precision viticulture (Joint Research Centre (JRC), 2014: p.20).

Mulla and Khosla (2015) have reviewed worldwide research and development of PF, while Awan (2016) provides a UK perspective, but neither contain awareness of archaeological linkages with PF, which this thesis addresses. It is worth noting that due to the commercial and fast moving nature of this area, much of the most up to date research and trends in this area are not represented in academically published literature, but in websites and other grey literature.

2.2. The PF System

In the literature, and in practice, PF may be used to achieve multiple goals (such as increased yield or reduction of labour) and these will influence the particular choice of technologies and techniques taken up by the farmer (Zhang *et al.*, 2002). No matter what goals are intended, or technologies used, the underlying methodology of the PF system is the same cyclical process (Figure 4). The point at which a farmer may decide to adopt PF could be because of new equipment, such as a combine harvester, that has Global Positioning Systems (GPS) and yield mapping technologies embedded. This would enable the farmer to begin monitoring within-field yield variation routinely without extra cost. Or, adoption could be initiated by a desire to reduce costly inputs by mapping the soil nutrients within-field, variably applying fertiliser at different rates according to the soil nutrient levels.

Farmers wanting to adopt PF often start by taking up one technology to begin with, trialling and testing its use, before making decisions about further investment in other technologies (M. Dafforn, pers. comm.). Once adopted, it is not common for a farmer to continue using only one technology, since most technologies work collectively (for example GPS guidance allows variable rate fertiliser application and variable rate seed planting). This may be due to commercial pressures, for example a company marketing its own software and hardware may provide the same piece of software to deal with multiple datasets. Simultaneously it could be more cost effective for the farmer, making it easier if multiple techniques can be applied with the same piece of software.

This is also a result of the ‘systems’ approach that underlies PF. A farmer who is interested in reducing phosphate fertiliser use will have to map soils to some extent, leading to the collection of satellite imagery that additionally enables variable nitrogen application. Whilst there is a marketing angle to adoption, farmers do appear to genuinely get more out of PF systems by utilising multiple techniques, and get better value by spreading the cost of the equipment or software across the farm area. This can be seen by an increase in all the major technologies adopted by UK farmers, rather than just one technology (Defra, 2013a).

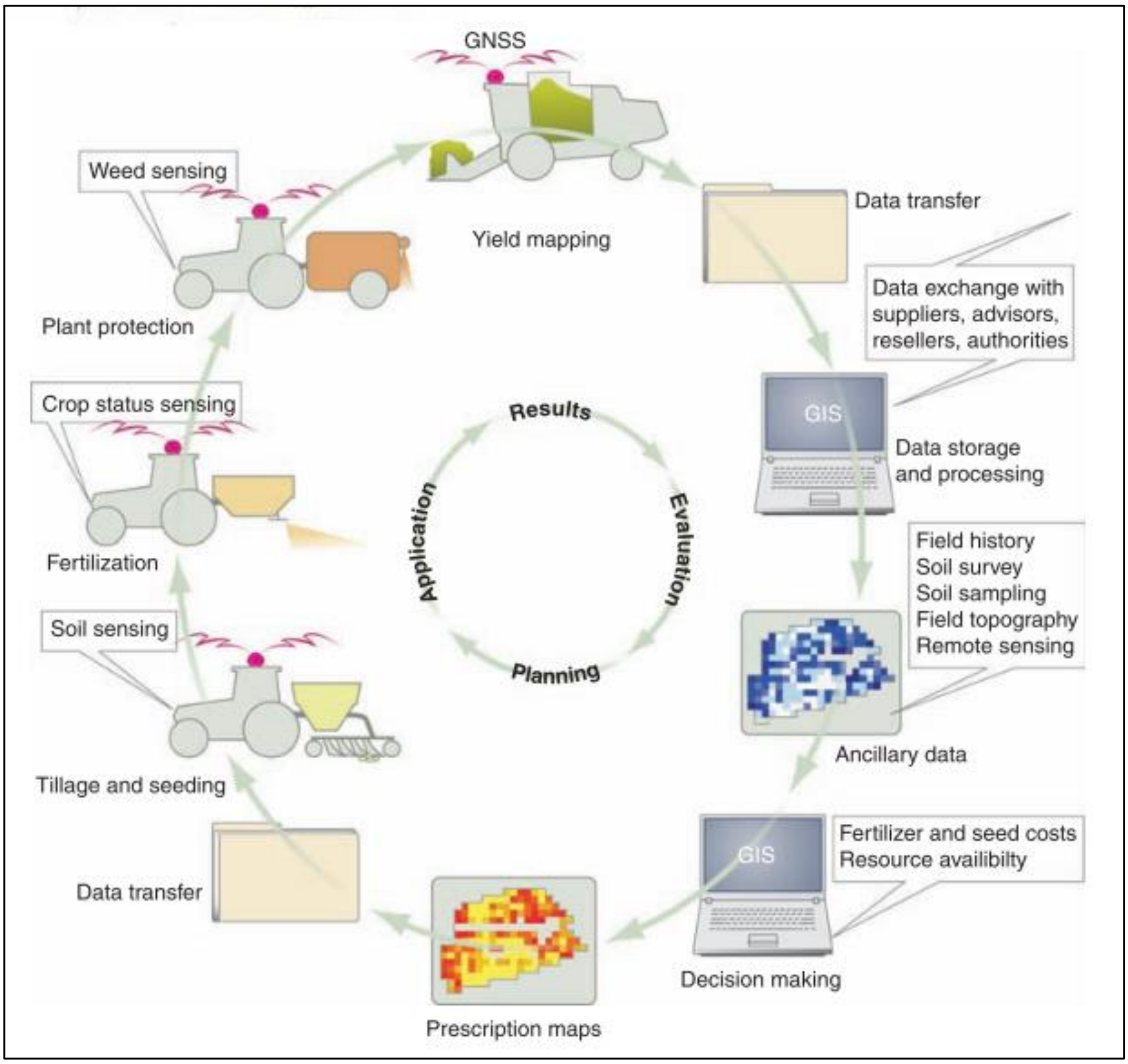


Figure 4: The cyclical process of PF approaches (from Gebbers and Adamchuck, 2010)

An important element of this cyclical process is temporal repetition, since PF methods generally relate to crop production cycles. PF systems collect data to inform planning, collect results, and evaluate those results to improve future planning, each and every year. Data may be retained for future analysis, for example how soils are changing, or yields have changed over multiple crop rotations which in the UK could be from 3 to 8 year cycles (Joernsgaard and Halmoe, 2003; Maestrini and Basso, 2018).

2.3. Technologies and Techniques

A wide variety of technologies and techniques have been experimented with, and successfully applied to, PF as can be seen from the range of literature contained in key journals such as the *Journal of Precision Agriculture*, the *Journal of Agricultural Engineering Research* and the *Journal of Computers and Electronics in Agriculture*. These are the basis for enabling widespread adoption of PF and have shaped what has been possible so far. What follows is a brief overview of the most common technologies and techniques used, with a focus on application in the UK and those that appear in the case study chapters.

2.3.1. Global Navigation Satellite Systems (GNSS)

A fundamental requirement for PF systems is the ability to record the location of a point within a space. The measurement of soil for example must be located repeatedly not only to check that measurement, or use that measurement to create a map, but also to be able to use that measurement to drive an action. Since civilian access to the US military's Global Positioning System (GPS) was improved (after President Clinton's decision to discontinue Selective Availability in 2000), together with joint access to both GPS and the Russian GLobal Orbiting Navigation Satellite System (GLONASS), levels of accuracy was a few metres instead of 100m or more (National Research Council, 1997; Conley and Lavrakas, 2000; Mulla and Khosla, 2015). This enabled basic location but not high precision measurements to be made, or similarly high precision between multiple measurements. This could be solved by using a differential system that uses multiple receivers to complete a radio-based triangulation to provide much greater accuracy (sub-metre and often to centimetre level). This technique was used in research experimenting with automated steering of agricultural equipment during the 1990s, but the technical expertise required and availability limited its wider use.

Today standard GPS/GLONASS signals are used for measurements that do not require sub-metre accuracy such as most soil sampling, conductivity mapping and for most drone surveys (Rudolph *et al.*, 2018). However, the differential method is necessary for any type of machine-guidance systems (such as Controlled Traffic Farming) to be effective (Pérez-Ruiz *et al.*, 2011). Both the automatic steering of combine harvesters and tractors is common on large and medium sized farms in the UK and requires a high levels of accuracy (+/- 2cm) provided by differential systems. Machinery manufacturers provide multiple levels of accuracy depending on the farmers requirement (for an example see -https://www.claas.co.uk/products/easy-2018/retrofit-gps-steering-systems/correction-signals accessed 02/02/19). GNSS guidance is the most adopted PF technology by UK farmers, due to its reliable results and integration with modern farm machinery (Defra, 2013a; Parliamentary Office of Science and Technology, 2015).

2.3.2. Remote Sensing

Remote sensing techniques are described as the airborne or space-based methods of collecting measurements of reflected or emitted electromagnetic radiation from the soil or a crop. A review by Mulla (2013) gives a broad understanding of the agricultural applications of remote sensing techniques and the key elements are summarised below.

The principle of measuring reflected parts of the electromagnetic spectrum for assessing soils and crops is based on the physical and chemical properties of those materials. Plant pigments such as chlorophyll adsorb radiation in the visible part of the spectrum (red-650nm and blue-430nm) but reflect in the green part, while plant structure (canopy biomass, leaf structure) reflects significantly in the Near Infra-Red (NIR) and Red Edge part of the spectrum (700-2500nm and 717nm respectively). Soils also have particular characteristics that affect their reflection of radiation, these are mainly due to moisture content, but also Organic Matter (OM), calcium carbonate, iron oxides and general mineralogy (Stoner and Baumgardner, 1982; Minasny and McBratney, 2016).

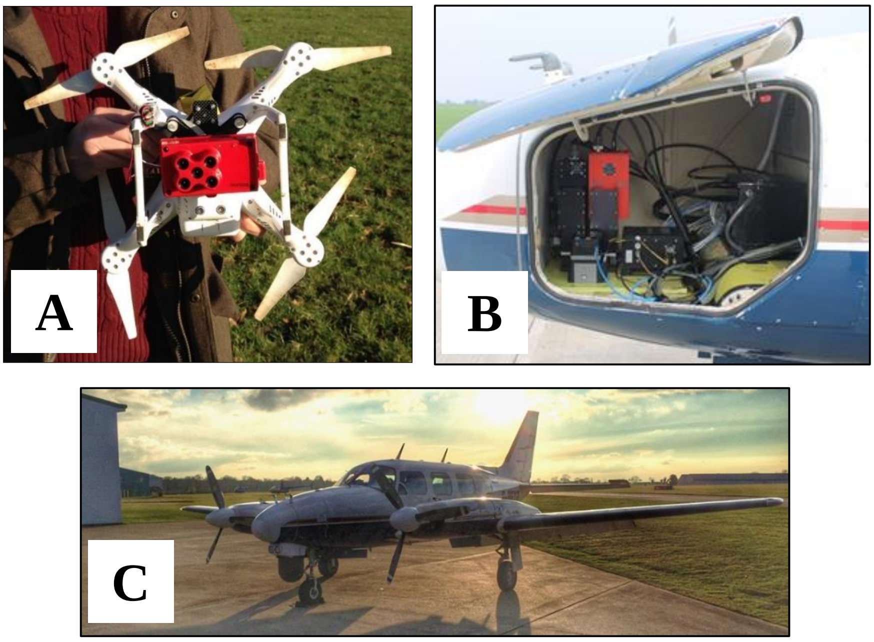


Figure 5: Multispectral camera with five lenses, capturing blue, green, red, NIR and Red Edge bands (courtesy of MicaSense) fitted onto a commercial drone(A), a hyperspectral camera (B) fitted into a light aircraft (C) (Courtesy of 2Excel Geospatial)

Research into these specific reflectance patterns has enabled many ‘indexes’ to be calculated using set bands of wavelengths from multiple parts of the spectrum (multispectral), alongside the visible bands, targeting particular applications (such as chlorophyll content and weed mapping). NDVI is the most common index and is used to assess the general health of a plant by taking into account its ‘greenness’ relating to its chlorophyll content, and its leaf area/biomass response in the NIR band. The disadvantage of multispectral imaging is that sensors can only extract information in those set bands of wavelengths, which can limit the amount of spectral information from a dataset. Hyperspectral imaging instead measures the whole spectrum detected for each pixel, allowing far more complex spectral analysis to be completed and be used for many more purposes (including chemical analysis of materials) but does come at increased cost because of expensive sensors, increased data storage and complex analysis (Adão *et al.*, 2017).

Data collection methods can be by satellite, aeroplane or drone and there are now (within the last decade) sensors for multispectral and hyperspectral imaging across all of these survey methods (Figure 5). Each method has its benefits and limitations; satellite applications are limited greatly by cloud cover, especially in the UK, while drone surveys can only cover a certain area per day. Aeroplane methods present a compromise in many situations but at greatest expense.

Remote sensing has an advantage over ground-based sensing or physical sampling because of its temporal frequency and spatial resolution. For example, the resolution of spectral data required for variable rate fertiliser application depends on the spreading width of the spreader typically 20-30m and on the variation of the crop. Image pixels of 1-20m tend to be used. The resolution required for weed detection or disease mapping however, would be much higher (between 5 and 50cm is essential) (Lamb and Brown, 2001). Crop growth can change considerably at different stages of a plants life, and weather conditions mean that management can be time-constrained, therefore temporal frequency of imagery is essential. Having the ability to collect the right data, at the right resolution, at the right time is fundamental to PF systems.

Use of remote sensing data has increased over time due to a number of factors. Spectral cameras are becoming smaller, less expensive, and more easily integrated into aerial platforms. Making it easier to collect more data with greater spectral depth. The accessibility of drones and the availability of free satellite imagery is also improving. The drone market has dramatically increased in the past decade down to products like the DJI Phantom range (https://www.dji.com/uk/products/phantom?site=brandsite&from=nav accessed 13/10/19). These allow non-technical users to fly systematic surveys and produce orthorectified images with ease via web-applications such as Drone Deploy (https://www.dronedeploy.com/ accessed 13/10/19). Additionally the launch of new satellite constellations such as the Sentinel family, part of the Copernicus programme for earth observations run by the European Space Agency, will have a large impact on future remote sensing because of free access to data and a wide variety of sensor types and spatio-temporal resolutions (Malenovský *et al.*, 2012).

2.3.3. Ground-Based Sensing

Measurements made at the ground's surface can be split into two groups, those that measure the surface of a crop or soil (optical sensors), and those that measure below the surface (geophysical sensors).

During the early 2000s, and particularly when there was a drive for more integrated, real time and automated decision-making, a product was designed that actively sensed the crop biomass and green area index while the tractor was driving through a field, providing real time outputs in the form of variable applications of nitrogen fertiliser rather than relying on satellite imagery (Tremblay *et al.*, 2009; Mulla and Khosla, 2015). Since then multiple systems such as the N-Sensor, Isaria and CropCircle, have been developed and are regularly used within arable PF systems in the UK (Professional Nutrient Management Group, 2018).

While measuring the surface of a soil or crop is useful, for some actions the measurement of subsurface properties are essential. Geophysical methods play a large part in PF for mapping soils. A common measurement, that has had a long connection with PF, is the electrical conductivity of soils (Corwin and Lesch, 2005). Measurements can either be made by direct contact of electrodes with the soil, or by electromagnetic induction methods. Conductivity measurements correlate to a number of key soil properties such as salinity, moisture content, soil texture. This enables conductivity maps to improve the spatial resolution of existing soil maps (Allred *et al.*, 2008; Mertens *et al.*, 2008). Interestingly, the magnetic components of soils have not received much interest from the PF community despite potential for use (Allred *et al.*, 2008). In the UK, a number of major PF companies offer conductivity scanning as an essential entry point to the PF process (Agrii's Soil Quest for example - https://www.agrii.co.uk/products-services/precision-farming/ accessed on 13/02/19). Surveys collect data at 20-30m line intervals and mean 100-200ha can be surveyed in a single day at low resolution.

Figure 6: Precision Farming conductivity scan in progress (© author)

In addition to geophysical measurements of soils, some systems have been developed that can automatically sample soils for spectral analysis of OM and pH while measuring conductivity (Lund, 2011). This comprehensive multi-technique and on-the-go sensing is slowly developing in the UK. It has not had widespread use due to costs and the difficulty in making decisions based on pH (a very variable soil property) and OM, even though this approach may be valuable for evaluating the causes of variations in crop performance.

2.3.4. Soil Sampling

Traditional agricultural soil sampling on arable land in the UK takes place every 3-5 years (AHDB, 2017). For grassland the recommendation is the same, however in practice sampling is not as frequent (Professional Nutrient Management Group, 2018: p.10). This involves taking multiple samples at representative places across a field and then bulking them together for one analysis (plant-available phosphorus, potassium, magnesium and pH) of the whole field. It has long been understood that soils vary significantly and that sampling in more detail would provide the ability to target nutrient applications more accurately (Oliver and Frogbrook, 1998). Yet until PF becomes more widespread, the whole-field soil sample remains the norm.

Since the advent of PF, soil sampling and digital soil mapping has become the main focus for both PF companies, farmers and researchers of sampling design (Oliver and Frogbrook, 1998; Kerry and Oliver, 2003; Minasny and McBratney, 2016). The balance between the costs of sampling, and the required accuracy of that sampling, has driven the development of multiple approaches and attention to ancillary spatial datasets for mapping soil types. Within PF systems it is now common to bulk sample individual soil zones within a field (identified through remote and ground-based sensing, and yield maps) or by systematically grid sampling each 100x100m grid (AHDB, 2013b). There is a wide variety of research that focuses on geostatistical techniques for interpolating soil measurements to predict values in unsampled locations and to tailor sampling designs to the expected variability of certain soil properties (Kerry and Oliver, 2011). In practice the sampling resolution is driven by the application resolution, which relates to the equipment available on the farm (AHDB, 2013b). Inferring soil nutrient variability under 20m, in most combinable crops is not useful regardless of the variability.

The standard nutrients analysed are plant-available phosphate, potassium, magnesium and soil pH. These traditionally have been the major soil properties that require balancing in most agricultural systems - as well as nitrogen, which is not routinely tested for due to its mobility and multiple forms in the soil. Additional soil properties are becoming more relevant in modern agronomy. Traditionally, crop sulphur requirement has not been important in the UK due to adequate amounts deposited atmospherically, as well as use of animal manures and fertilisers incidentally containing sulphur. Since the EU has dramatically reduced emissions of sulphur dioxide, evidence shows many grass and arable crops are deficient in sulphur and now require additional amounts from fertilisers (Webb *et al.*, 2015). Other micro-nutrients (B, Mn, Mo, Cu, Zn and Se) are important in the search to increase yields and enhance certain crop characteristics, as well as being recognised in wider global food security debates for their impacts on human and animal health and environmental sustainability (Richards, 2004; AHDB, 2013a; Jones *et al.*, 2013). Micro-nutrient levels in soils or plants are not currently analysed regularly. They are only measured if deficiencies are visible in crops, but are often added into nutrient management planning in a preventative manner. OM measurements take place on farms far more regularly today. With widespread acknowledgement of the loss of soil OM, especially in arable areas, many farmers are now measuring it, changing management practices, and monitoring longer term trends (https://www.fwi.co.uk/arable/land-preparation/soils/how-three-growers-hope-to-improve-soil-health-in-yorkshire accessed 13/10/19).

2.3.5. Yield Mapping

Crop yield is central to the PF process (Blackmore, 2003; Maestrini and Basso, 2018). Some of the earliest pieces of PF research focused on the ability to use GNSS systems in conjunction with sensors to measure harvested crop yield across a field (Mulla and Khosla, 2015: 8–10). Yields are ultimately the final output that every other possible contributing factor is measured against, and is often a starting point for farmers starting to use PF systems (Awan, 2016). Yield measurements are however the most complicated. Predicting yield has always attracted much attention from the agricultural community, but with little success (Joernsgaard and Halmoe, 2003). Despite this yield maps are still commonly recorded in the UK, as in other countries, partly due to technology being embedded within modern machines, but also because there is value in recording spatial variability in yield for later analysis. Combining multiple types of PF data together over time allows understanding where parts of a field consistently differ in yield and why (Maestrini and Basso, 2018).

Yields maps do have their limitations, especially regarding their data quality. Geo-referencing errors due to time lag of the grain within the combine harvester, partially filled swaths of crop material not being calibrated in the yield data, and human errors are common in data collection (Blackmore, 2003). This makes yield data difficult to work with accurately, coupled with uncontrollable events that might affect yield (such as weather), despite yield being the central interest of farmers.

2.3.6. Geographical Information Systems (GIS)

The concepts of PF, that of a digital methodology for collecting, analysing and creating management decisions from spatially and temporally variable data, would not be possible without the use of GIS computer programs. GIS systems allow data to be imported, converted, presented interactively in a common spatial coordinate system, analysed and exported. From existing paper-based soil maps, land drainage maps and soil nutrient results, to incoming satellite imagery, GPS recorded topography and collected yield data, GIS systems have grown considerably in their use amongst farmers themselves, and development by PF companies (Nikkilä *et al.*, 2010).

From the early 2000s, GIS systems or more specifically known as Farm Management Information Systems (FMIS) in an agricultural context, started to become more web-based, enabling not only one farmer to input, view and export data, but for multiple farmers to access processing and technical analysis done at a another location (Nash *et al.*, 2009; Nikkilä *et al.*, 2010). This led PF companies to develop their own software (Figure 7) that enables a farmer to access data and information, without having the technical expertise of processing an NDVI calculation on a satellite image, or interpolating a set of soil samples. This allows far greater levels of data sharing, from farmer to farmer, but also from machine to manufacturer, and groups of farmers to PF companies (Sharma *et al.*, 2018).

Choose rate

Here you can see how the vegetation index varies within your parcel.

Select cell size: 10x10 | Change cell size

Numbers below show the vegetation index for five different intervals. Enter desired N rate in kg/ha for each interval.

Index	kg/ha	Acreage
		1.83 ha
0.25	80	
		2.78 ha
0.30	70	
		6.04 ha
0.35	70	
		12.71 ha
0.41	65	
		11.54 ha
0.46	60	
		1.84 ha

l/ha ● kg/ha

Read more about nitrogen fertilization

Previous | Next

Nutrient Management Plans
- 2013 - Manor Farm
- 2014 - Manor Farm

New Plan | Delete | Create Fol... | Save Plan | Make Editable

Nutrient Plan Details

Plan ID: 7544
Name: Manor Farm
Area (ha): 32.90
Ruleset: RB209 (8th Edition)
Nutrient Balance ☐

Product Totals

Product	Total Used	Unit
AN	17.108	tonnes
Double Top	4.935	tonnes
MOP	3.374	tonnes
TSP	1.918	tonnes

Add/Remove Fields | Add/Remove Products

RB209 | Albrecht | Analysis

Zone Details

Zone Details		Cropping		RB209 Recommended Rate							Calculated Application Rate				
Field ▲	Zone	Last Crop	Next Crop	NMAX	NMAX ...	N	P	K	Mg	SO3	N	P	K	Mg	SO3
Down Field	A0	DK-Cabe...	JB-Diego -...	240	220	240	0	0	0	40	220	0	0	0	18
Down Field	A2k E	DK-Cabe...	JB-Diego -...	240	220	240	0	84	0	40	220	0	84	0	18
Down Field	A2k S	DK-Cabe...	JB-Diego -...	240	220	240	80	88	0	40	220	80	88	0	18
Down Field	A2k W	DK-Cabe...	JB-Diego -...	240	220	240	98	88	0	40	220	98	88	0	18
Down Field	A3 N	DK-Cabe...	JB-Diego -...	240	220	240	0	0	0	40	220	0	0	0	18
Down Field	A3 S	DK-Cabe...	JB-Diego -...	240	220	240	68	84	0	40	220	68	84	0	18
Down Field	B2	DK-Cabe...	JB-Diego -...	220	220	220	0	75	0	40	220	0	75	0	18
Down Field	B3	DK-Cabe...	JB-Diego -...	220	220	220	0	75	0	40	220	0	75	0	18

Product Applications

Date ▲	Product	Rate	Method	N	P	K	Mg	SO3	Recalc	AutoRecalc
Spring	MOP	140	Surface Ap...	0	0	84	0	0	Recalc	☑
WW 1st App	Double Top	150	Surface Ap...	40	0	0	0	18	Recalc	☐
WW 2nd App	AN	260	Surface Ap...	90	0	0	0	0	Recalc	☐
WW 3rd App	AN	260	Surface Ap...	90	0	0	0	0	Recalc	☐
Autumn	TSP	148	Surface Ap...	0	68	0	0	0	Recalc	☑
Please select ...	Please select a Product	0	Surface Ap...	0	0	0	0	0	Recalc	☑

NMP Notes for this Zone

Export | NMP Report | Confirm Applications | GPS Files | Copy Application | Delete Application | Apply Ruleset

Database updated

Figure 7: CROPSAT web-application with satellite imagery (A) and IPF Toolbox showing soil zones and related agronomic data (B) (courtesy of IPF UK)

A growing issue in PF is the handling of data, the ownership of such data, how it is shared and how it is valued (Kritikos, 2017). For example many pieces of agricultural equipment now embed telematic communications that allow a farmer sitting within an office, to see real time fuel consumption, work hours, engine faults and location etc (Dyer, 2016). The impacts of the ‘Big Data’ term have also stretched into agriculture, and PF, demonstrating how GIS systems can allow companies to aggregate and analyse large datasets of farms and farm management practices, as well agronomic information, but also demonstrating the risks of such practices (Addicott, 2016; Sharma *et al.*, 2018). People, businesses, researchers and governments implementing digital agricultural methodologies will need to consider the social and ethical impacts of PF in the future (Addicott, 2016; Kritikos, 2017). The potential for this scale of both agricultural, and environmental, has data have huge potential for researchers.

2.3.7. Hardware Applications

PF systems can bring large amounts of data to farmers but ultimately this depends on the hardware and equipment available. Without a yield monitor fitted to the combine harvester, there may not be any reason to map soils or variably apply phosphate for example. Purchasing new machinery for the sake adopting PF is not cost effective, however many farms spread costs over multiple years and take opportunities to upgrade equipment with PF technology when already considering an upgrade (AHDB, 2013b). Interoperability presents potential issues for automated and integrated data collection, the equipment used on the tractor needs to communicate with the GPS logger, or the in-built computer within the tractor. Without this operability, farmers can become constrained to certain companies, or frustrated at complicated data conversion and transfer processes (Williamson, 2014).

The hardware involved is the most costly part of adopting PF and thus investments need to be made over a certain period of time to provide returns (Barnes *et al.*, 2019). Economic analyses have shown which elements of PF methods are most cost effective for farmers, and which are less likely to be taken up due to their cost (Godwin *et al.*, 2003; Awan, 2016).Economic reasoning often only presents part of the complicated story behind the uptake of PF methods.

2.4. How, and by Whom, is PF Used

The adoption of PF systems, and particularly the technologies or techniques most commonly used by farmers, have been evaluated by multiple sources, at different times throughout the last two decades and in different countries (Sylvester-Bradley *et al.*, 1997; McBratney *et al.*, 2005; Knight *et al.*, 2009; Khosla, 2010; Defra, 2013a; Parliamentary Office of Science and Technology, 2015; Awan, 2016; Paustian and Theuvsen, 2017). The main reasons for adoption are undoubtedly the economic benefits from reducing inputs and adoption tends to be by larger farms, and by younger farmers. The key focus in the England appears to be based on GPS guidance systems, and variable N management, with uptake levels at around 22% of all holdings by 2012, but over 50% of arable farms (Defra, 2013a). Unfortunately this survey data is now seven years out of date, so the increases in use of GPS, soil mapping, variable rate technology and yield mapping are likely to be significantly higher (Professional Nutrient Management Group, 2018). Although a percentage of farm holdings using PF systems might be around a quarter in 2012, the area of land managed under those farm holdings might be a considerably different percentage of the agricultural land in England. The uptake is seen as more beneficial for larger farms >300ha and is greatest in the arable sector, meaning the arable east and central parts of England will be most likely adopters. Higher value crops, such as vegetable and root crops, have high nutrient requirements and the most potential benefit from PF systems. The other key adoption factors also include farmer perceptions, age, attitude to risk, time restraints and technical confidence, as well as cost barriers, presence of soil variability, use of farm advisers and peer to peer networks (Barnes *et al*., 2019).

Despite the economic drivers for PF, there are both direct and indirect environmental reasons for using PF systems that have developed over time, but increasingly within the last decade. Awareness of the indirect impacts of adopting PF systems is common amongst researchers, farmers and governments: the targeting of inputs leads to less fertiliser use, and more accurate applications mitigate diffuse pollution. Yet there is only limited quantitative evidence of this positive environmental effect from PF practices. This raises questions whether this is just a theoretical perspective that is marginal in its environmental impact, and could in fact be encouraging farmers to use more fertiliser in other places producing the same or worse environmental impacts (Joint Research Centre (JRC), 2014; Barnes *et al*., 2019).

There are record keeping and traceability benefits to PF that are of direct benefit to the farmer (AHDB, 2013b: p.57). For example PF systems can help farmers to automatically create risk maps where soil run-off into watercourses is likely, or where organic manures are stored, and aid the creation of nutrient management plans for compliance with government legislation or farm assurance schemes. These types of benefits of PF can save farmers time, which is increasingly an important factor for farm management.

The structure of the PF industry within the UK is made up of several large companies. These companies are often parts of wider agricultural supply businesses and agronomy services, and have been involved with PF for at least a decade, or two. They have developed a wide range of PF services (for example see https://www.soyl.com/, http://www.precisiondecisions.co.uk/ and http://www.ipf-uk.com/ accessed on 01/02/19). Further smaller, recently developed, companies have also seen an increasing place on the UK market within the last five years, often focusing towards more specific elements of a PF system, for example software development (http://www.ag-space.com/ accessed on 01/02/19), drone applications (https://droneag.farm/ accessed on 01/02/19). Farmers tend to usually use one particular company's approach and the available technologies within that package, rather than picking and choosing elements from multiple systems. This is due to simplicity and time restraints. Whereas some farmers, and especially early adopters, experiment with different PF approaches.

PF systems have significant value for researchers and governments. Much research surrounding PF systems by researchers (outside of the technical application of PF technology) and governments, relate to the adoption of PF systems. Interest is increasingly focusing towards the use of PF systems for land management policy, environmental sustainability and farm agronomy, showing the malleability of PF systems and how they are/should be used (Addicott, 2016; Balafoutis *et al.*, 2017; Sylvester-Bradley *et al.*, 2017; Barnes *et al.*, 2019).

2.5. Future Directions

2.5.1. Automation (Drones/Robotics) in Agriculture

In the UK, future directions of PF appear to be heavily influenced by the automation of PF processes (Williamson, 2014). This has been seen in two specific contexts over the past few years, drone-based techniques, and the development of robotics in agriculture (Jarman *et al.*, 2016; Duckett *et al.*, 2018).

The development of drone base sensing systems has been a technology that has influenced many areas of society, but within agriculture it has been particularly significant. Drones have been developed for imaging and mapping crops and soils in a variety of ways, but are also moving into automated precision agrochemical application. The number of companies has drastically increased in the last few years and the ease with which farmers and advisers have assimilated the data collection process and the hardware has been impressive. Drone-based applications, with automated flight patterns, take-off and landing, has also encouraged the development of other automated agricultural applications with potential for future development.

Basic agricultural robotics has a history of development in the UK, but has recently had more attention. For the first time in the world, one hectare of land was prepared, planted, managed and harvested completely by robots in 2016 (http://www.handsfreehectare.com/ accessed on 02/02/19). Alongside this, the level of automation within existing tractor designs has developed to allow driverless tractors for minimising time spent on repetitive tasks. The potential of farming with swarms of small agricultural robots (Albani *et al.*, 2017) and electric tractors (Scurlock *et al.*, 2017), although still in early phases, is coming closer to reality. With increasing pressure to de-carbonise agriculture while mitigating environmental degradation and produce food efficiently, these trends towards automation are likely to continue (Scurlock *et al.*, 2017; Duckett *et al.*, 2018).

2.5.2. Agri-Tech Data

As the collection of field relevant data continues, the potential of long term farm records, that are spatially and temporally detailed, will become increasingly valuable. This value may be for the farmer themselves, but also for researchers, private companies and governments in aggregating this data for their own use. This is already starting to be shown by examples such as the 'Precision Soil Mapping' project led by Cranfield University (https://gtr.ukri.org/projects?ref=NE%2FP008860%2F1 accessed on 13/10/19). This intends to bring together a PF software provider as well as other research organisations to evaluate how high resolution satellite imagery, using a 'Soil Brightness (SOB)' index, can be combined with existing soil property maps across the UK to improve the accuracy of soil maps. This project highlights how, alongside the integration of better agronomic on-farm trials, researchers can access larger and more detailed datasets in collaboration with PF companies, enhancing the multi-disciplinary approaches to data between agriculture and other subjects on scales previously not possible.

Another example of this is the term 'Agronōmics' (Sylvester-Bradley *et al.*, 2017). With increasing ability to accurately record yield and crop health in PF systems, it opens up the possibility of moving agricultural trials (traditionally based in laboratories) out into the field. This is said to be transforming the understanding that researchers gain from trials by placing them in the wider environment, as well as helping farmers to use the engage with and use the results of trials, promoting knowledge exchange and experience-based learning. It is, however, not without its challenges due to the accuracy of measurements necessary and the management of less controllable factors in the environment, such as inherent soil variability.

‘Agrimetrics’ is one of four Agri-Tech centres in the UK (along with Crop Health and Protection, Animal Productivity Welfare and Health, Engineering and Precision Technologies) aiming to boost innovation in the agriculture sector by collaborations between government, industry and academia (https://agrimetrics.co.uk/home accessed on 13/10/19). ‘Agrimetrics’ aids research into the aggregation, analysis and exchange of large datasets in the agri-food industry, providing independent skills, informatics expertise to help projects. These centres have already helped link national datasets such as field boundaries, with soil types, geochemical information and agricultural information. It is anticipated that the collection and connection of landscape data will only increase as digital agriculture is embedded further within the government, academia and industry.

2.5.3. Future Agricultural Policy

Agricultural policy, at the EU level and the UK level, is at a point of directional change with the renewal of the CAP which has dominated agricultural and land management practices in the EU over past decades, and for the UK due to its intention to leave the EU in 2016 and preparations for a new domestic agricultural policy. Both policy directions are shifting towards focusing on higher ambitions to tackle environmental problems while encouraging a healthier agricultural system with fair incomes for farmers, more sustainable food chains, and increased focus on preserving rural landscapes (Defra, 2018c; European Commission, 2019). PF approaches have already had impacts on the development of the current CAP 2014-2020, with increasing studies looking forwards to the next period of the CAP development and how PF could be more directly linked to environmental benefits (Joint Research Centre (JRC), 2014; European Parliamentary Research Service, 2016; Kritikos, 2017). However currently, in both the UK and the EU, PF methods are not included within direct payments to farmers, but instead are included under productivity schemes in the European Agricultural Fund for Rural Development allowing the purchase of capital items such as GPS equipment to enhance productivity. The value of PF systems is yet to be fully integrated within future agricultural policy, but there appears to be much overlap between the benefits of PF and the challenges of future agricultural policy.

2.6. Concluding Remarks

With a continued emphasis and drive for PF to contribute not only to farm economics, but also environmental policy, better understanding of agronomy and ‘field to fork’ traceability for food production (Gebbers and Adamchuck, 2010), it is likely that PF processes will become normal practice. Although variability between different methods and techniques exist, and variation of farmer adoption will be a constant, as the underlying drivers increase so will adoption across many developed and developing countries, not just the UK.

Chapter 3

3 Archaeology on Agricultural Land

Methods of archaeological investigation and management may seem like common knowledge to many, yet this is not the case for PF communities, and a key objective of this thesis is to promote shared understanding of these processes. Simultaneously, it is worth comparing the archaeological and the PF backgrounds together in the same format, exhibiting the similarities and differences. This chapter will give an overview of archaeological field methodologies, the technologies and techniques used and by whom, as well as the approaches to heritage management with a focus in the UK. The intention is for this chapter to cover methods and background relevant for archaeological sites on agricultural land and specifically buried archaeological sites

3.1 Archaeological Investigation Techniques

The following Sections will demonstrate the approaches, often in the order that they might be used in, for investigating archaeological sites. Not all of these approaches will apply to every archaeological site and some approaches may be combined in a multi-method approach to a site. How some of these investigation techniques differ between development-led archaeological investigations and independently-led (e.g. academic research or community projects) will also be discussed. This is an important distinction that has been described in more detail by Darvill *et al* (2002).

3.1.1 Desk-Based Assessment (DBA)

The beginning of any archaeological investigation will normally involve a DBA. The purpose of a DBA according to the Chartered Institute for Archaeologists (CIfA) is to "…determine, as far as is reasonably possible from existing records, the nature, extent and significance of the historic environment within a specified area…." (CIfA, 2014b: p.4). When approaching any site, especially on agricultural land, a DBA will determine how much previous archaeological work has been done at a site (geophysical surveys or excavations etc.). It will also examine historical documents, maps, photographs and the local historic environment records for the site and its surroundings, as well as the likelihood for preservation of archaeological deposits.

The history of DBAs, and of a standardised approach to archaeological investigations, has been driven by development-led archaeology. This has occurred since 1990 when the investigation of archaeology was required within the planning system through Planning Policy Guidance Note 16 (Darvill *et al.*, 2002). Since then development-led archaeology has dominated the total number of archaeological investigations taking place within England, and a similar situation more widely across northern Europe (Webley *et al.*, 2012). A DBA is the first step that authorities use to gauge whether further archaeological investigation is necessary before development takes place, and what sort of investigation might be most appropriate (geophysical survey, trial trenching, full excavation etc.).

Although DBAs are more rigidly applied in development-led archaeology, there is a parallel process in independently-led archaeological investigations. Independent investigations might include for example; university departments, museums, local societies, individuals and community groups. Each of these will need to consider the existing archaeological evidence for an area before planning further investigations. The format and level of reporting may be different to that of a development-led DBA due to specific requirements, funding or time restraints, but invariably any research project will include relevant background and the archaeological significance or potential of a site.

3.1.2 Aerial Photography and Remote Sensing

One of the key 20th century innovations in archaeology was the development of aerial reconnaissance for recording, interpreting and managing archaeological sites. Several books and articles discuss the impact that aerial surveys have had on archaeological understanding (Wilson, 1975; Maxwell, 1983; Bewley, 2003). From the first aerial photographs taken of archaeological monuments by individuals such as O.G.S Crawford (Crawford and Keiller, 1928) and J. K. St Joseph, to the regularly planned aerial sorties by the Royal Commission on Historical Monuments in England (RCHME), the importance of spatially observing archaeology has been critical for the understanding and characterisation of archaeological sites. Typically photographs are either taken at an oblique angle to the ground surface, or vertically above the surface. Obliques can be useful for highlighting topography, but are less useful for spatially plotting the exact locations of crop marks.

While individual photographs are of benefit to archaeologists, the value of large scale analysis of multiple photographs over time, combined with other data (such as airborne laser scanning and satellite imagery), is substantial. This has been demonstrated in England by the National Mapping Programme (NMP) (Bewley, 2003; Ingle and Saunders, 2011; Evans, 2019). More than 120,000 new archaeological sites have been discovered through 100 individual projects covering around half of England (Evans, 2019: 1–12). These digital records now contain accurate spatial locations and morphological depictions as well as archaeological descriptions that help heritage managers record, interpret and monitor the historic environment as well as direct future research. Large scale projects such as the NMP transform our understanding of landscapes and fill gaps in evidence in between archaeological sites, showing how useful continuous, accurate, data across the landscape is.

Despite large coordinated projects such as the NMP, Bewley (2003) states that aerial survey could, in cases where there has been changing agricultural practice, complicated geologies, or past restrictions, take up to 50 years to begin to understand the landscape from its cropmarks. Traditional aerial reconnaissance is targeted at specific times of the year when crops are stressed (early summer) and flying conditions are suitable, meaning that sometimes there is a narrow window for data collection. Data interpretation can also be costly and demand extensive experience for effective and standardised interpretation (Wilson, 1982; Evans, 2019).

With technological advances of cameras and aerial platforms, traditional aerial surveys are now regularly complemented with other remotely sensed data from drones and satellites (Bewley, 2003; Lasaponara and Masini, 2007; Verhoeven, 2009; Campana, 2017). This combination means data can be gathered at the correct times (some satellites having daily re-visit timings) and higher spatial resolutions than previously possible, allowing for greater coverage and more ephemeral archaeological remains to be observed (Campana, 2017; Cowley *et al.*, 2018; Moriarty *et al.*, 2018). In addition, cameras recording different parts of the spectrum (multispectral and hyperspectral) have begun to be tested more routinely in archaeological investigations within the last decade (Verhoeven, 2009). These cameras allow not only visible light in the red, green and blue bands to be recorded, but Red Edge, NIR, and thermal parts of the electromagnetic spectrum. These can be used for sensing cropmarks and soil variations where subtle changes in reflectance occur as a consequence of archaeological remains and enhance what can already be seen in the visible parts of the spectrum (Lasaponara and Masini, 2007; Verhoeven, 2009; Moriarty *et al.*, 2018).

3.1.3 Topographical Survey

Archaeological survey has a long tradition of recording the surface topography of archaeological sites and landscapes. Topographical survey is a method for recording sites, for contextualising those sites in the wider landscape, and for monitoring the preservation of sites (Aston and Rowley, 1974; Bowden, 1999; Historic England, 2017c). Topographical survey can take many forms, from contour plans of fields to detailed hachured drawings of Iron Age hillforts. Surveys aim at understanding the landscape in 3D, by taking measurements of the grounds surface, interpreting what is seen on the ground, and producing graphical representations of sites (Opitz and Cowley, 2013).

In the 19th and 20th centuries, before digitisation, methods for surveying did not change greatly (Historic England, 2018a). Measuring tapes, plane tables, and optical devices such as theodolites and levels were core equipment for the experienced field surveyor. Since the 1970s, development of Differential GPS systems, Total Station Theodolites and computers with GIS software, mapping of archaeological sites has become increasingly more digital, as have topographical survey. Today, techniques such as LIDAR (Light/Laser Detection And Ranging) scanning and photogrammetric analysis of images are frequent (Opitz and Limp, 2015).

LIDAR allows analysis of landscape topography even if covered by woodland or buildings (Historic England, 2018c). In England data has been gathered by the Environment Agency initially for flood mapping. This data has now been made freely available, opening up the use of LIDAR data for archaeological investigations.

Photogrammetry is a method for stitching multiple individual photographs together and accurately rectifying and georeferencing them (Bewley, 2003: 282–4; Historic England, 2017b). In conjunction with the rise of drones, photogrammetry provides a more cost effective and quick process for creating high resolution 3D models and Digital Terrain Models (DTM) in a whole variety of archaeological situations (from buildings to objects and landscapes).

In Figure 8, image A shows LIDAR data alongside the River Severn displayed as a DTM, below the trees a past river channel can be seen, while in the grass field it is less visible. In image B, the channel can clearly be seen in the grass field from photogrammetric analysis of drone imagery, yet trees obscure the other half of the channel. Between these two images one can see the immediate benefits and limitations of these two techniques.

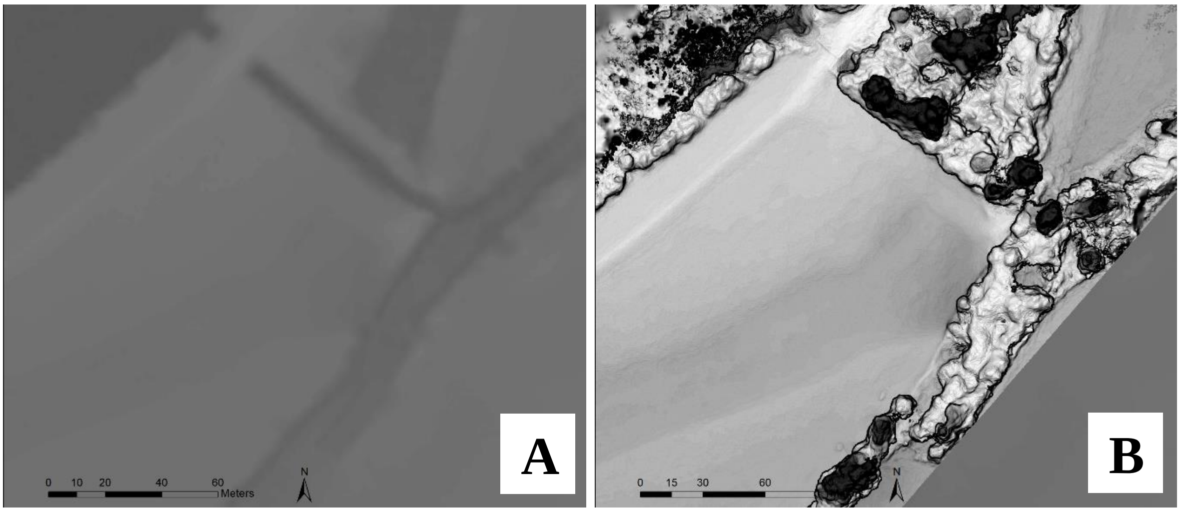


Figure 8: Airborne LIDAR data with 50cm pixel size (A), in comparison to a DTM produced by drone imagery and photogrammetry with 13cm pixel size (B)

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The advantages of digital approaches enable much higher data collection speeds, increasing levels of accuracy, as well as enabling multiple ways to interrogate and graphically present data. Instead of contour lines or paper-based hachured earthwork surveys, GIS programs can turn measurement points into a DTM for 3D viewing, combined analysis with satellite imagery or geophysical data, and allow the production of 'hillshade' models that artificially light the DTM to show centimetre level depressions or raised areas of ground. Something that is clear, however, is the importance of a skilled surveyor, whether taking a traditional or digital approach to topographical survey (Halliday, 2013).

3.1.4 Fieldwalking and Metal Detecting

While many archaeological methods have developed into increasingly digital and non-invasive approaches that have sped up data collection, certain methods have not developed in quite the same manner. Fieldwalking is the process of systematically covering a field, or wider area, collecting artefacts that might be on the surface and recording positions of those artefacts (Foard, 1977; Haselgrove *et al.*, 1985; Connolly, 2008). This helps to map areas of fields relating to an archaeological site, or a type of archaeological artefact within a site, such as coins, pottery or metal working waste. Aside from the influence of GNSS positioning systems and GIS systems to process and produce distribution maps, the process of fieldwalking is relatively unchanged, but is still popular on sites difficult to survey, where archaeological sites have few structural features or where access to expensive geophysical or geochemical equipment is not available.

Metal detecting has become a very popular hobby over time, drawing mixed responses from archaeologists, yet it has an important role to play in the identification, recording and interpretation of archaeological sites and artefacts (Connolly, 2008; Haldenby and Richards, 2010). From detecting for missed metal objects in the spoil heaps of excavations, to the identification of unknown archaeological sites, detecting has a place in many areas of archaeological investigation. The significant increase in detected finds across the UK has influenced the start of the Portable Antiquities Scheme (PAS), with over 1 million archaeological finds recorded in an online database that can be used by historic environment teams to protect heritage, researchers, and by members of the public (Portable Antiquities Scheme, 2015).

3.1.5 Geophysical Prospection

Modern archaeologists aim to understand as much as possible about a site non-invasively, before evaluating archaeological sites through destructive coring or excavations. This approach has led to a whole range of geophysical techniques that can be used to evaluate physical contrasts between archaeological sites and the medium (most commonly the soil) surrounding them (Clark, 1990; Gaffney and Gater, 2003; Linford, 2006; Schmidt *et al.*, 2015). Importantly, geophysical methods are the main methods for directly measuring subsurface physical anomalies, rather than remote sensing data or topographical survey, which are direct surface observations.

The most widely used geophysical method for archaeological prospection is magnetometry, or magnetic gradiometry. This method relies on subtle variations in the earth’s magnetic field created by various magnetic anomalies having different intensities or directions than the background (Fassbinder, 2015). Naturally occurring iron minerals in the soil, soil bacteria and the underlying geology produce local contrasts to the wider earth’s magnetic field (Linford, 2006). These magnetic contrasts can be altered by human activity such as a ditches, walls, or areas of burning. For example buried walls displace soil that often have a higher magnetic intensity (producing a negative contrast). Inversely buried ditches can be filled with material of a higher magnetic intensity to the surrounding soil (producing a positive contrast). Large ferrous anomalies such as pipes, metal objects, or burnt areas, will produce significant magnetic anomalies. There are two main types of sensor, the Fluxgate magnetometer (most common), and the Caesium Vapour magnetometer (less common but has greater sensitivity) (Linford, 2006: 2226ff). Data has traditionally been collected by hand held sensor systems, however increasingly, cart-based sensor arrays are used for covering larger areas and at higher resolutions than before (Trinks *et al.*, 2010; Gaffney *et al.*, 2012).

Another magnetic technique is magnetic susceptibility (MS). This measures the susceptibility of a material (i.e. soil) to be magnetised and is often used in conjunction with geochemical surveys or other magnetic surveys (Dalan, 2008; Gaffney, 2008: p.326; Gerrard and Aston, 2017). There are multiple ways to measure MS, one is using a small coil that is held to the ground and applies an alternating current to a shallow depth (Bartington MS2). Another is via the use of electromagnetic induction (EMI) techniques that can simultaneously measure conductivity and MS. EMI does not require contact with the ground and so is suited to large area surveys, hence its use in both archaeological surveys, PF surveys and soil mapping (De Smedt *et al.*, 2013; Gheyle *et al.*, 2016; Trinks and Pregesbauer, 2016).

Another key group of techniques used in archaeological prospection are electrical methods. Earth Resistance (ER) is a commonly used technique, involving an electrical current being passed between two metal electrodes in the ground, and a comparison between these two electrodes and a second pair of electrodes set in another location (Clark, 1990; Gaffney and Gater, 2003). Resistance measurements can vary depending on soil moisture and soil porosity, often being used to find buried ditches and walls (Cuenca-García, 2012). Traditional surveys involve wooden frames with pairs of electrodes, spaced appropriately according to the depth of investigation. These methods do require ground contact which can limit the areas covered in a day, but cart systems have been developed to make the method more efficient. (Dabas, 2009). Electrical Resistance Tomography (ERT) is similar to ER but uses multiple incrementally spaced probes to measure resistance at various depths along a transect (Gaffney, 2008). ERT tends to be used more commonly on targeted features rather than across the area of a site, where ER is often used to create spatial maps.

Another technique, Ground-Penetrating Radar (GPR) involves a shielded antenna pulsing electromagnetic radiation of a particular frequency down into the soil, with a receiver that ‘listens’ for reflections (Gaffney and Gater, 2003). Certain changes in soil moisture content, structure, stone content, air porosity, as well as texture, all relate to the soils dielectric permittivity and can affect how radar waves travel through the soil and reflect from anomalies or changes within it (Conyers, 2016). GPR has become easier to use due to advances in computer processing that is necessary for the large amounts of data GPR can produce, especially in relation to depth information and 3D processing allowing 2D depth slices to be visualised (Trinks *et al.*, 2010; Zhao *et al.*, 2015). GPR has become increasingly popular because it can be used in a wide variety of environments; such as built-up areas, inside buildings and in motorised configurations (Figure 9). As well as its accurate depth estimations that can range depending on the frequency of antenna used (often a range of 160-500MHz is used in archaeological investigations). Similar to other techniques, new developments include the motorisation of the technique, allowing multi-channel GPR systems fitted onto rough terrain vehicles to cover larger areas with increasing spatial resolution (Trinks *et al.*, 2010).

Ultimately the type of archaeological site, the geological background, the surrounding environment and the exact aims of the archaeological investigation will determine which choice, or mix of choices, of geophysical methods might be necessary. Geophysical surveys are also commonly carried in both development-led archaeological investigations as well as in research or community spheres, making geophysical survey one of the most common approaches to archaeological investigation after traditional archaeological excavation (Gaffney, 2008).

Figure 9: The versatility of GPR, A = surveying inside Deerhurst Church, UK, B = surveying cave sediments in Zanzibar, C = motorised survey in Virginia US (© M. Horton)

3.1.6 Geochemical Prospection

The impacts of humans on the landscape, in terms of habitation, activity and wider land use, can leave geochemical anomalies within the soil. Since the early 20th century this has been recognised, particularly relating to soil phosphorus (from the work of Arrhenius, a Swedish agronomist in the 1930s) (Middleton and Price, 1996). Since then, numerous studies have built on the work around soil phosphorus, and ventured into the multi-elemental analysis (Eidt, 1977; Middleton and Price, 1996; Aston *et al.*, 1998; Entwistle *et al.*, 1998; Historic England, 2007: p.33; Holliday *et al.*, 2010). This has increased within the last decade with the advent of cheaper and more accessible laboratory (and field) techniques for quantifying elemental concentrations of samples via Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and pXRF methods (Wilson *et al.*, 2008; Dungworth *et al.*, 2013; Frahm and Doonan, 2013; Hunt and Speakman, 2015).

The evidence from geochemical surveys has shown on multiple occasions that elements such as P, Ca, Mn, K, Mg, Cu, Pb, Zn can be enhanced due to archaeological activities, and that certain elements are connected with certain types of archaeological activity. For example phosphates are often connected to areas of habitation due to long term organic deposition (Holliday and Gartner, 2007; Stijn Oonk *et al.*, 2009). Confidence in applying geochemical techniques more widely and routinely, as geophysics is currently, has been limited by gaps in understanding of the taphonomy of elements in archaeological soils, the ability to establish a baseline of background natural variations in elements, and how modern effects have impacted archaeologically induced geochemical signatures (Stijn Oonk *et al.*, 2009; Holliday *et al.*, 2010; Historic England, 2015b).

Geochemical surveys can be used for a variety of reasons within archaeological investigations: prospecting for new sites, delineating existing sites, understanding more about land-use around existing sites, and evaluating specific archaeological deposits. Out of all of these, and in light of the above limitations, geochemical analysis of specific archaeological deposits, such as fill deposits of pits or ditches, building floors, or metal working sites is most common from the literature. There has been comparatively little (Aston and Gerrard being most notable (2017)) work using geochemical mapping as a prospection technique, especially in combination with geophysical surveys (Cuenca-García, 2012). This is especially so in development-led work in comparison to independent spheres (B. Urmston, pers. comm.).

3.1.7 Geoarchaeological Survey

Geoarchaeology is described as the “application of earth science principles and techniques to the understanding of the archaeological record” (Historic England, 2007: p.1). It includes geophysical and geochemical approaches, but this Section will elaborate on wider methodological approaches. Due to the characteristics of how landscapes develop, and how human societies have interacted with those landscapes, geoarchaeological methods are required to deal with the macro-scale (landscape), the meso-scale and the micro-scale (human settlement and individual deposits) fluidly and simultaneously (French, 2003, 2015). At the landscape scale, it is not possible to observe and record entire landscape profiles. This means that proxy datasets (geological maps, topographical maps, soil maps, and opportune observations) and targeted coring or small excavations are most commonly used. These approaches can be used to define the form and drivers (colluvial, alluvial, aeolian, modern actions etc.) behind the current landscape’s development, and identify where there is greater potential for buried archaeological soils, palaeosols, to survive *in-situ*. Excavations, whether for geoarchaeological or other purposes, can allow better descriptions of the meso/micro-scale stratigraphy and allow for more sampling to take place for laboratory analysis. In some cases stratigraphic description can provide the evidence necessary to answer the research question, however, this is most often combined with further analytical techniques (Historic England, 2015b).

There are a considerable number of analytical techniques that can be used on geoarchaeological samples to chronologically date, compositionally analyse and assess the microstratigraphy or structure. For a more detailed list see Historic England’s geoarchaeology guide, French’s handbook, and Rapp and Hill (Rapp and Hill, 2006; Historic England, 2007: 30–42; French, 2015). Undoubtedly some of these techniques require specific sampling methods to be used (such as block sampling for micromorphology) and certain skillsets, these can limit their use. Especially so across independent and development-led archaeological investigations where either time or money is under pressure. Despite this, developer-led archaeological projects, and many independent projects, will often include, where necessary multiple geoarchaeological approaches to provide contextual information to archaeological sites and landscapes. This is likely to continue in the future (Canti and Huisman, 2015: p.105).

3.1.8 Archaeological Excavation

The origin of archaeology began with the excavation of archaeological sites to retrieve important material artefacts to interpret the past. Since its beginnings, the aims and methods of archaeological excavation continue to change (through both theoretical debate, technological change and external factors) but are certainly more standardised than half a century ago (Tilley, 1989; Barker, 1993; CIfA, 2014a). Excavations, including less extensive cores or test pits, remain central to the majority of archaeological investigations. In most cases excavations cause the destruction of archaeological deposits in the hope that the evidence collected can answer archaeological questions or at least rescue deposits from unrecorded destruction. As a consequence, archaeological excavations are generally considered single events and cannot be re-evaluated if archaeological deposits have been totally removed, unless evidence still survived in the side sections of a trench or within the re-deposited topsoil of a previous excavation. Many excavations tend to be small in area, due to the time and costs involved. Yet in some cases, where big development projects, or large scale research projects occur excavations can be much larger and involve total topsoil stripping of the site.

3.1.9 Publication and Archiving

The last phase in the investigation process is the publication and reporting of the investigation, and the dissemination of the results. Whether the investigation involved only a DBA, or whether it was a multi-phase investigation with DBA, geophysical survey, geoarchaeological work, excavations and post-excavation analysis, it is important to present, interpret, publish and archive (CIfA, 2014c). Archaeologists have been consistently aware that the development of the future archaeological record depends on the reporting and publishing of the results, and methods of investigation (Trow, 2018).

Standardised ways of recording archaeological investigations have been developed over time. In the past, recording investigations related to specific types of archaeological resource (e.g. the Historic England managed Excavation Index, records of particular archaeological societies, or bulletins of aerial reconnaissance missions each year). They now focus on bringing all types of archaeological resource together into accessible repositories and signposting to where information can be accessed across the whole of the UK (Historic Environment Record (HER) Offices, Archaeology Data Service (ADS), Online AccesS to the Index of archaeological investigationS (OASIS)). These repositories can be accessed to a certain extent by the public, and aim to enable people from all different archaeological backgrounds to engage with the data and the interpretations made. The 'Know Your Place' project in the West of England is a prime example, where a web application delivers Ordnance Survey (OS) maps, historic maps, along with photographs and linked information, as well as the opportunity for people to contribute their own memories and heritage (http://www.kypwest.org.uk/ accessed on 22/10/19) . This long term and engaging emphasis, while seeing better uptake over the past decade within the sector, still has challenges in ensuring consistent, accessible and engaging ways of archiving and disseminating work (Trow, 2018).

3.1.10 Future Directions

Archaeological investigations, while grounded in materiality by their nature, are becoming increasingly digital. The collection of data, storage of data, publication of data and exchange and re-use of data all benefit from digital approaches. This allows the greater integration of evidence in multi-technique, multi-spatial, multi-temporal situations. While there is place for much more advanced non-invasive prospection in the future, excavation will remain a key tool for investigating archaeological sites in the future, but perhaps in a more limited way. It is the diversity of techniques (borrowed from many other subjects) and multi-disciplinary approaches that characterise archaeological investigations.

3.2 Heritage Management on Agricultural Land

In July 1870 an article written by Colonel Augustus Lane-Fox, for *The Saturday Review*, acknowledged the damage of agricultural practices from arable agriculture on archaeological sites (Trow, 2010: p.129). The value of turning grassland into arable during the nineteenth century encouraged landowners to destroy or neglect archaeological monuments. Barrows were flattened, the rich organic soil being used to fertilise other fields, and standing stones removed for building or to stop obstruction to ploughing (Chippindale, 1983: 2–3). It was these scenes of destruction that invoked a need for something to be done.

Eventually in 1882, the Ancient Monuments Protection Bill became law, ensuring maintenance was carried out on a limited number of designated ancient monuments and appointing inspectors of ancient monuments to oversee their condition (HM Government, 1882). Following this pioneering piece of legislation, a series of Acts amended and extended heritage legislation in Great Britain, with the most recent (The Archaeological Monuments and

Archaeological Areas Act 1979), still based substantially on the 1882 Act (Chippindale, 1983). This sets the basis for the framework of heritage protection in the Great Britain. Focusing on nationally important, designated monuments and areas, but lacking the ability to protect archaeological heritage that is less critical, less well understood, yet still at risk from land management practices (Trow, 2010: p.131).

On the international front, despite each individual nation having its own history of tackling the destruction of rural heritage (Chippindale, 1983: 3–4), attempts to manage heritage did not occur until the 20th century. Throughout the 18th, 19th and 20th centuries the word 'heritage' was used in many different situations and with many different meanings, mostly relating to the cultural property of an entity (Ploska, 2009; Vecco, 2010). During the 1970s the, by then, well-used term 'cultural heritage' was defined in the United Nations Economic Social and Cultural Organisation (UNESCO) World Heritage Convention and focused on the common concept of humanity's cultural (monuments, buildings and sites) and natural heritage, and the dangers of its loss or degradation to the world (UNESCO, 1972). At the European level 'archaeological heritage' is used more frequently when meaning the practical management of archaeological sites and monuments. It was based on the Valletta Convention's definition and implicitly included within the European Landscape Convention, embedding the contributions that archaeological heritage makes on a landscape (Council of Europe, 1992; European Landscape Convention, 2000; Fairclough *et al.*, 2002). It is these two conventions that provide the wider framework within which heritage protection works.

From early monitoring and survey projects such as the Monuments at Risk Survey in 1995, the extent and the risks of degradation to rural archaeological heritage, and especially buried remains, were highlighted in England (Darvill and Fulton, 1998). Now it is evidenced by Historic England that 84% of scheduled monuments are situated in agricultural land, and a third are impacted by agricultural practices and natural processes (The Heritage Alliance, 2017). This shows the limitations of the current legislative framework for mitigating or preventing agricultural damage even on nationally important sites, let alone the hundreds of thousands of undesignated sites. To recognise and manage these threats better, it has been essential to continually develop ways to identify and characterise archaeological heritage, and to conserve and monitor that heritage despite legislative gaps.

3.2.1 Identifying and Characterising Archaeology on Agricultural Land

Over time archaeologists have used investigation techniques to build up records of artefacts, sites and landscapes. These records exist in various stages of evaluation and publication, y*et al*l contribute to the archaeological record. This record provides the basis for identifying what is and what is not archaeological, as well as assessing the character of remains. For example a geophysical survey might delimit anomalies that look like a common Iron Age field system as well as geological patterns. Excavation of those anomalies might find that these field systems instead date to the Bronze Age, and these field systems aligned to geological changes showing past awareness of different soils benefiting or limiting certain land uses. Investigations help to build a picture of the spatial extent, the temporal span and the surviving condition of archaeological remains. While identifying the remains present and the condition of those remains, initial investigations do not provide enough information to fully consider the 'value' of that site. It is only through situating that site within the context of the surrounding landscape or within other sites of a similar type or time period, that allow a better characterisation of how 'valued' that site is within the wider archaeological record. Continuing the same example, it could be that that Bronze Age field system is unique in a certain area and therefore archaeologically more important.

As the concepts of archaeological heritage have developed over time, the identification and characterisation of archaeological heritage has similarly changed. Early identified sites, such as Stonehenge, tend to be visually identified because of their above ground remains and are easily accessed and engaged with by the public. Whereas the buried remains such as a Roman villa may not be discovered until finds are ploughed to the surface and noticed by someone. Developments in non-invasive techniques, increasing numbers of archaeological projects and a simultaneous increase in the amount of development that might prompt archaeological discovery, has meant the number of buried archaeological sites known today is far greater than the number known 50 years ago. Examples such as the Hidden Landscapes Project at Stonehenge, and the West Heslerton Research Project in the Vale of Pickering, provide examples of how the knowledge surrounding particular sites has grown over time especially from the use of non-invasive techniques (Powlesland *et al.*, 2006; Gaffney *et al.*, 2012).

In the England, there are nearly 20,000 scheduled monuments with the highest level of legal protection and of the highest priority for management (DCMS, 2017). Those numbers increase with the inclusion of the National Heritage List (estimated at 600,000 in 1993), and other types of designated heritage (Parks, Gardens, Battlefields etc.) (Darvill and Wainwright, 1994). Today, with all Historic Environment Records, both designated and undesignated heritage (such as find spots or crop marks), there are likely to be millions of records and an equally large number yet unknown (Trow, 2018). This presents significant challenges to people managing the historic environment, especially with regard to how resources are allocated to manage these sites and records (Trow, 2018). Characterisation has therefore been a way to identify archaeological heritage that is most at risk, or most significant, and is able to be managed in a better way to address loss or further degradation. An example of this is the Selected Heritage Inventory for Natural England (SHINE) in England (Defra, 2013b). This was created as a single, nationally consistent dataset of designated and undesignated historic environment features in rural areas, that could benefit from measures within agri-environment schemes as part of the CAP funding for farmers.

3.2.2 Conserving and Monitoring Archaeology on Agricultural Land

Managing buried, undesignated, archaeological heritage, has been a challenge to historic environment specialists for over 50 years. After early recognition of the impacts of agricultural improvement on archaeological sites from the 19th century, and renewed impetus to protect and preserve sites in the post-war period (in reaction to the Digging for Britain campaign) (Lambrick, 1977), it was not until the 1990s when attention was again focused on monitoring how archaeological sites were continually being affected by agricultural practices, rather than just plough damage more specifically (Trow, 2010).

In 1995, the then English Heritage (now Historic England) commissioned the Monuments At Risk Survey (MARS) to provide up to date information on the condition and survival of archaeological sites in England (Darvill and Fulton, 1998). It aimed to systematically quantify England's archaeological resource, its changing state and the implications of degradation for different monument types by surveying a 5% transect of all known sites (Darvill and Wainwright, 1994; Trow, 2010). This 'single point in time' exercise showed that:

- on average one archaeological site had been destroyed every day since 1945, including some scheduled monuments;
- 21% of rural sites protected as scheduled monuments were still under arable cultivation;
- 60% of monuments in arable areas were at medium or high risk of damage (Darvill and Fulton, 1998; Oxford Archaeology, 2002).

This work was followed up in 2003, 2008 and 2018 by Historic England ('Ripping up History', 'Scheduled monuments at Risk' and 'Heritage At Risk' respectively). These studies developed the 1995 baseline data and aimed to update and evaluate a 100% sample of designated archaeological heritage in order to establish baseline information on risk, and to revisit it at regular intervals (now annual updates inform the HAR National Statistic). The latest 2018 assessment highlighted improvements; with 12.2% of England's scheduled monuments listed on the register in comparison with 21% in 2008 (Heritage, 2009; Historic England, 2018b). Despite this loss and damage from arable cultivation, agriculture remains the second largest risk to scheduled monuments, affecting 40% of entries on the register (Figure 10). These percentages only apply to scheduled monuments, and the risks surrounding undesignated archaeological sites are likely to be far higher.

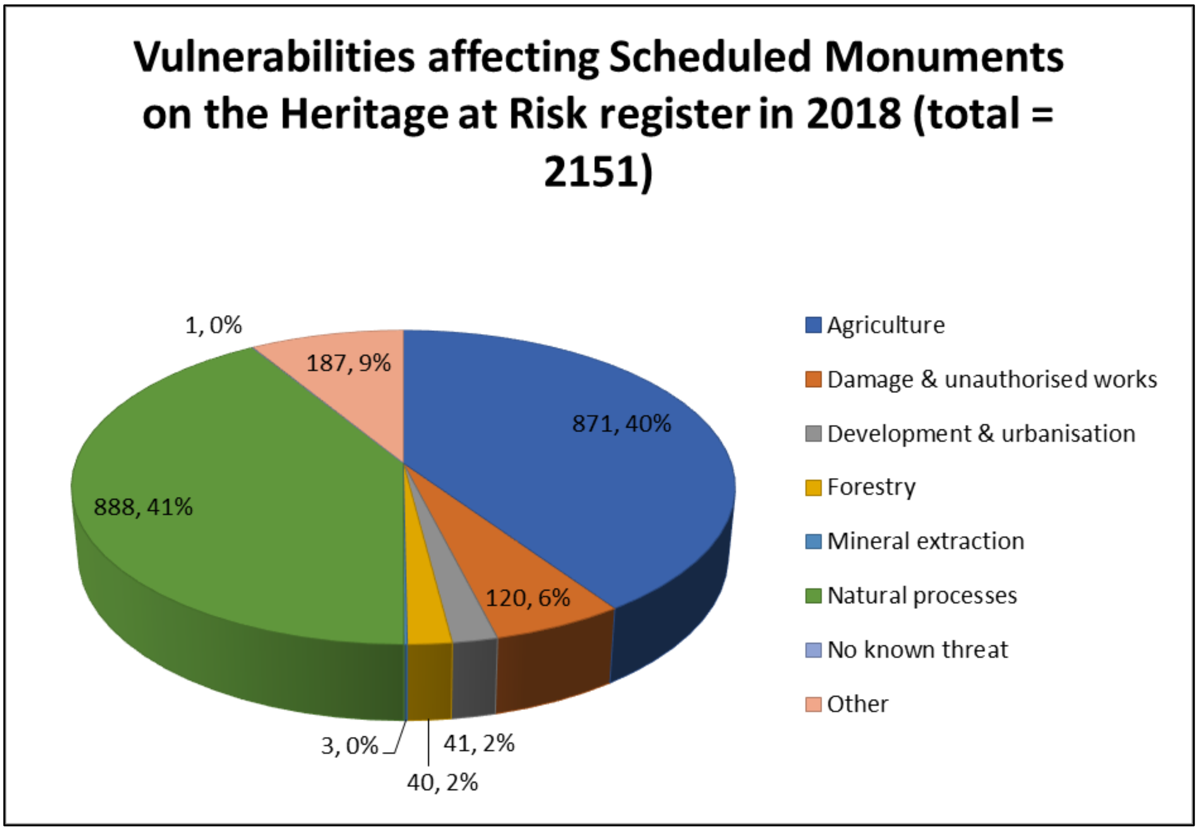


Figure 10: The range of vulnerabilities affecting scheduled monuments in England (courtesy V. Holyoak)

The risks from intensive agriculture, which in the context of this research will focus on arable (and to a limited extent grassland) land use, have mainly centred on the physical damage to archaeological sites by cultivation (Lambrick, 1977; Oxford Archaeology, 2006). The work by Oxford Archaeology (2002) showed that many different types of damage could occur to archaeological sites directly and indirectly from arable land use: soil erosion, repeated cultivations, soil drainage, ancillary farm works, animal damage, physical abrasion of smaller artefacts and the changing soil geochemistry on archaeological sites. It also identified surrounding issues that can be site intrinsic and to do with past land management practices, such as the nature of the archaeological site, soil characteristics, topography, crop rotation, cultivation implements and farm economics.

Further work followed to provide a methodology for heritage managers to assess the risk of cultivation damage on archaeological sites, and to provide evidence that mitigating measures were benefiting that monument as well as potentially minimising the impact on the farmers practices. The Conservation of Scheduled Monuments in Cultivation (COSMIC) set the baseline for the methodology. COSMIC 2 piloted this methodology in the East Midlands and COSMIC 3 looked at the national implementation (Oxford Archaeology, 2006, 2014). An important outcome of this work highlighted that archaeological sites could be preserved by techniques that simultaneously helped the farmer save costs and maintain yields. This was a new perspective in managing rural heritage, in contrast to removing land from arable cultivation all together. At many sites assessed, continued cultivation was recommended as the risk of damage was low. In other cases, a range of options were considered such as minimum tillage (where the soil is not ploughed or inverted and cultivation is limited to 15cm), direct drilling, a change of crop type (therefore reducing the cultivation needs by removing root crops for example) and buffer zones. This advice was taken on board by farmers, making both the risk assessment simpler for heritage managers and the decision making process more transparent for Government (Jackson and Miller, 2010; Oxford Archaeology, 2014). Under the CAP in the UK, heritage management options for farmers within previous Environmental Stewardship schemes and current Countryside Stewardship schemes, have proven fully or over-subscribed in past years, delivering positive management to over 24,000 heritage assets covering 355,000 hectares (The Heritage Alliance, 2017).

3.2.3 Future Rural Heritage Policy

Lambrick (1977: 7–8ff) discussed how archaeological heritage management in arable landscapes depended on two things: economic basis for compensating the loss of income for a farmer from having to implement some form of archaeological (or agricultural for that matter) policy; and goodwill from farmers and mutual understanding. This was during the early stages of the CAP, which was started in 1962 to support farmers and improve agricultural productivity. Today the CAP still exists and continues to be re-evaluated for its effectiveness in modern day society (European Commission, 2019). The future CAP beyond 2020 has nine key objectives and places far more emphasis on environmental challenges and societal problems than food production. Within this framework however, rural heritage policy relies on the same drivers as in the 1970s. Economic compensation is necessary to aid the conservation of archaeological heritage. Although further work on producing 'win-win' situations through direct drilling and shifts in agricultural practice as well as mitigation of risk to archaeological sites, has been attempted. It still remains essential to engage and build better relationships with the farming community to share views and promote awareness of archaeological heritage than solely rely on funding farmers to do things differently.

In the UK, the future of policy is currently uncertain as a result of the exit of the UK from the EU. However there is a clear drive towards the use of any agricultural subsidies for the delivery of 'public goods' (Bateman and Balmford, 2018; Defra, 2018c) rather than to directly support food production. The current theme of public goods can be incredibly broad and is heavily focused towards the natural environment, meaning that the historic environment can be neglected in the wider policy arena.

This is also shown in another framework that underlies both the EU's and the UK's future policy drivers: the term '**ecosystem services**'. This term has developed throughout the 20th century but is now a common underpinning framework for understanding and valuing how ecosystems contribute to humanity through a number of 'services'(UK National Ecosystem Assessment, 2014), as well as how the historic environment fits into that framework (Fluck and Holyoak, 2017). This framework of ecosystem services encompasses a number of complex environmental, social and economic systems within which heritage and the historic environment can be part of. The challenges of future heritage policy lie in clearly integrating and emphasising the historic environments relationship with other ecosystem services and their methodologies. By feeding into the relevant parts of this framework and therefore into future policies, archaeological heritage should be part of the core land management strategies (Fluck and Holyoak, 2017; NCC, 2019).

3.3 Concluding Remarks

Archaeology is an inherently multi-disciplinary subject as is shown by the wide variety of technologies and techniques for the prospection and management of archaeological sites alone. This brings with it a requirement for archaeologists to draw together expertise and data from multiple different sources, digital and non-digital, to question where archaeological evidence exists, and how to manage it in the future. At this level there are many similarities with PF approaches outlined in Chapter 2.

Chapter 4

4 Soils, the Binding Material

Soils are continuously formed and altered by both natural and cultural processes (Limbrey, 1975; Avery, 1990; French, 2003; Rapp and Hill, 2006). These processes can change over time, being in some cases radically altered by short-term events (erosion) or by more gradual processes over much longer periods of time (break down of minerals). The combination of these processes has created the wide ranging and variable soil types present in the UK (Avery, 1990). Having described the development of technologies and techniques used to map soils in archaeological and agricultural contexts, this chapter will highlight soil as the central part of this thesis, that stitches together archaeological and agricultural worlds. The development of soils, the history of their use, as well as the impacts that humans have had on soils over time, are fundamental questions for both archaeologists and PF specialists/farmers.

4.1 Soil Development

Fundamentally, soil is formed at the earth’s surface from the products of physical processes altered by, and combined with, the chemical and biological products of the atmosphere (air), hydrosphere (water) and biosphere (plants and animals including humans). Development of the soil depends on a number of factors, including (i) the primary minerals themselves, (ii) the weathering of those minerals, and formation of secondary minerals, (iii) the addition and cycling of OM and other minerals, (iv) transport processes, and (v) time. These fundamentals of soil science and how they relate to archaeology are covered by Limbrey (1975).

As a result of the fundamental factors above, soils (the biologically active parts) and sediments (the biologically in-active parts) (Rapp and Hill, 2006: p.39) can become layered in various horizons that can be strikingly different from each other. It is these soil horizons that make up the soil profile, which allows soils to be classified into soil types through observation and interpretation. Broadly, soils are divided into an A horizon (mixed mineral and organic surface layers), an E or eluvial horizon (where products of weathering have been lost down the profile), a B horizon (where an accumulation or alteration of mineral or organic remains occurs from upper layers), and finally a C horizon (that denotes the parent material or bedrock undergoing alteration but recognisable as parent material) (Limbrey, 1975: 76–87).

There are a number of key processes that can disturb and alter the soil profile (Limbrey, 1975: 88–94; French, 2003: 20–35; Rapp and Hill, 2006: 25–59), but the key aspects are drawn out below. **Erosion**, **colluviation, alluviation** are landscape processes that can cause the breaking up/loosening and movement of soils and sediments down slopes or along watercourses. **Leaching** can cause movement of materials downwards through a soil profile in solution, either leading to accumulations or entire loss from the soil profile. **Translocation**, differs from erosion and colluviation (which are movements across soil profiles), is the movement of particles within a soil profile, both up and down, due to processes such as biological activity, hydrological conditions and physical effects. The local **climate and weather** can alter rainfall and temperatures, affecting plant growth and microbial activity that contribute to soil cycling processes. Humans can contribute to all of these factors directly or indirectly.

Figure 11: A typical rendzina with a stone free organic A horizon, Overlying a stone accumulation horizon (A/C) produced by earthworm sorting. Scale 10cm divisions, taken in Bishopstone, Sussex, UK (courtesy of M. Bell)

The soils assessed in each case study of this thesis are all lowland soils over chalk or limestone geologies. They have all been in agricultural use for a substantial period of time and have all been cultivated to a certain extent. These soils are typically called rendzina soils, characterised by a very organic black calcareous humus (A horizon) formed mainly via worm activity, lying on a relatively unaltered calcareous rock (C horizon) as seen in Figure 11 (Limbrey, 1975: 128–130). Generally rendzinas are very shallow soils, because erosion of surface layers removes material more quickly than it is produced and there is little mineral material that aids the formation of a deeper B horizon. However, deeper soil profiles can develop if other sediments are deposited above the bedrock leading to variable profiles between rendzinas and profiles containing CwF above the calcareous bedrock for example (Limbrey, 1975: p.176).

4.2 The Formation and Character of Plough Soils

In agricultural landscapes, or landscapes that have previously had intensive agricultural management in the form of arable crop production, plough soils are a defining feature. They are generally characterised pedologically by the appearance in the soil profile of a homogenous, consistently deep, uppermost horizon that often has a number of different soil characteristics in comparison to the typically developed soil profile, and can be classified within the A horizon as Ap, a ploughed A horizon) (Limbrey, 1975; Hodgson, 1978). From an archaeological perspective, plough soils are characterised by their lack of *in-situ* preservation of archaeological remains due to complete physical mixing by cultivation. In most cases, plough soils are treated as a material to be disregarded before an excavation can begin (the practice of “topsoil stripping” using machines). In other cases it is still monitored by metal detection or sieving, if archaeological evidence is suspected within the plough soil. There has been some work on surveying plough soil assemblages by systematic field walking, which was popular in the 1980s and 1990s, but receives less attention in most archaeological evaluations today in favour of other less labour-intensive survey techniques such as geophysics, test pitting or metal detecting (Haselgrove *et al.*, 1985; Haldenby and Richards, 2010). Archaeologically, plough soils cause issues by the fact that artefacts or structures are not only disturbed from their original context, but also can be vertically and laterally spread considerable distances by cultivation and by soil fauna such as earthworms (Yorston *et al.*, 1990; Boismier, 1997; Oxford Archaeology, 2002; Canti, 2005). While in an agricultural sense, plough soils represent the crucial layer of soil that has to be managed for seed germination and plant growth, nutrient levels, drainage, compaction, weeds and pests, contamination etc.

The formation of plough soils is due to the regular cultivation of the upper layers of the soil profile, not just the ‘ploughing’ of a soil. There are many cultivation techniques used on farms in the UK and, with a large agricultural manufacturing industry, an almost unlimited combination of implements sold to farmers (Figure 12). These can be divided into two major types; inversion (ploughing or baulking with a mouldboard) and non-inversion (tine, disc, or pre-mouldboard ploughing). Early evidence for cultivation in Britain comes from a number of sites where preserved palaeosols have been with plough marks cut into the geology beneath a dateable archaeological feature (such as at South Street Long Barrow), dating from the 4th to the 3rd millennium BCE (Fowler and Evans, 1967). This means cross-hatched grooves, measuring only a few centimetres in depth, represented single, and in some cases multiple, periods of past cultivation (Fowler and Evans, 1967: p.290).

Before the mechanisation of the agricultural industry in the late 19th and early 20th centuries, cultivation techniques relied on horse-power and often single-furrow ploughs that had little weight to force them to ‘bite’ into the soil (Figure 12, C), even with the addition of metal points/ploughshares from the late Bronze Age onwards. Horse- or oxen-drawn ploughing meant that they could not turn around onto the same furrow and therefore created ‘rig works’ that are known as ‘ridge and furrow’ patterns today (Hall, 2001). This is where plough soils become higher in the main ridges and lynchets (on the headland of the field), allowing better drainage/water retention in the furrows. As steam power began to be harnessed, some of these techniques could plough to depths of 0.35-0.45m even in heavy clay soils previously not able to be ploughed (Lambrick, 1977; Gascoyne, 2006).

After the Second World War, significantly more powerful tractors and multi-furrow reversible metal ploughs were engineered to achieve depths of between 0.2-0.4m (Figure 12, D). This modern ploughing was also practiced over a far larger area in this period, driven by the need for domestic food production post-war (the ‘Dig For Victory’ campaign), and the physical capabilities that modern engineering made available to every farmer, and especially affected lowland areas suitable for conversion to arable production (Gascoyne, 2006). This has meant that in the majority of situations all plough soils, and soils only cultivated by tine or disc, have been physically mixed to the consistent modern depths of around 0.25m on average.

There are other cropping types (root crops or vegetables) and soil issues (compaction for example) that require deeper non-inversion cultivation such as sub-soiling (Figure 12, A) and mole draining, which again have only been possible in the past 50 years with mechanisation. These methods can disturb sub-surface soil layers to depths of 0.4-0.7m, but with wider spacing than ploughing (Oxford Archaeology, 2002). These means soils can be disturbed at a wider spacing, but at a greater depth than the normal plough depth.

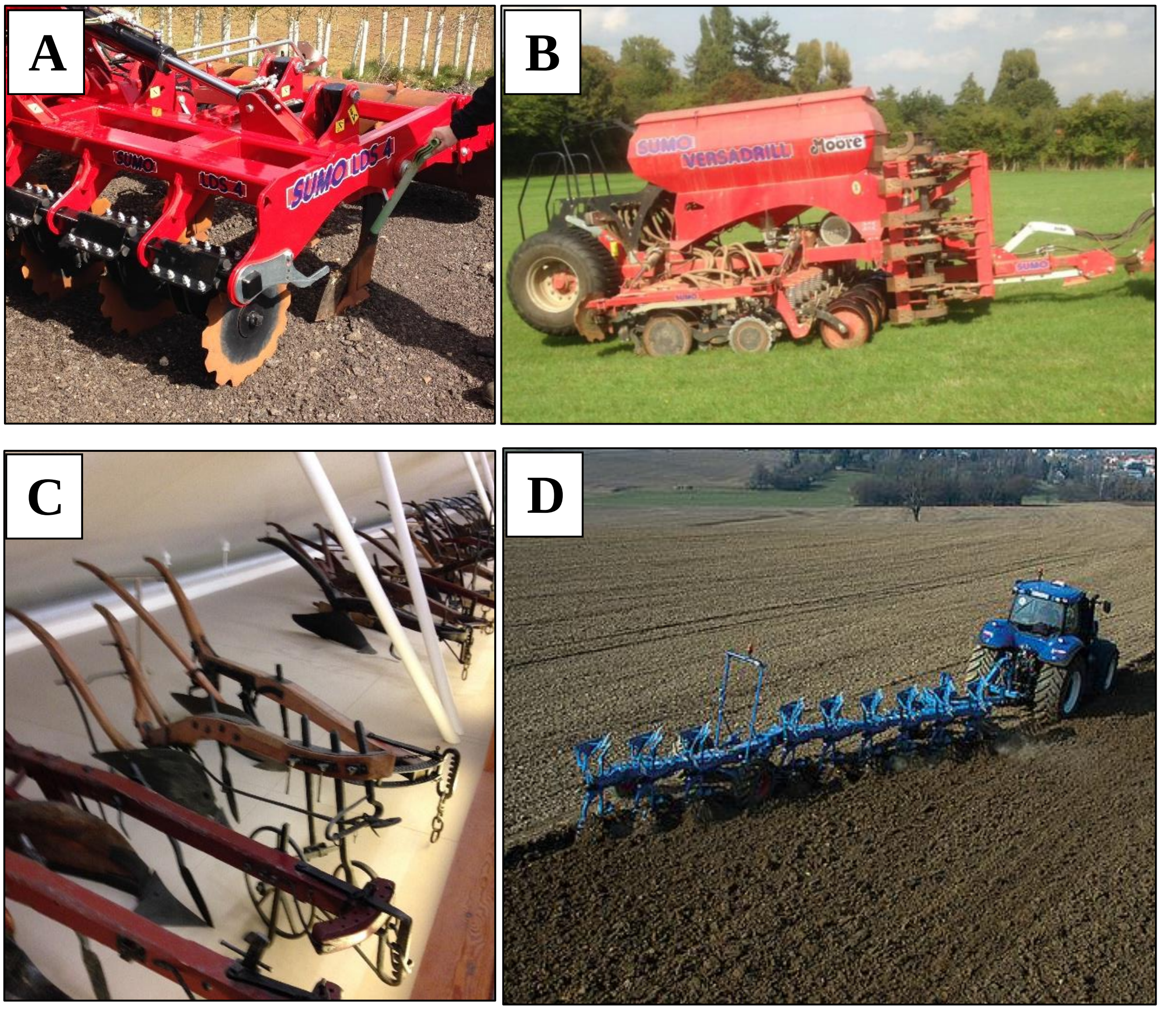


Figure 12: Variations of cultivation equipment A=disc and subsoiling legs, B=direct drill with discs for minimum disturbance, C=selection of 19th century ploughs at MERL Museum in Reading, D=large modern plough. (all © author apart from D taken from https://lemken.com/en/lemken-news/news/detail/detail/new-titan-for-ultimate-acreage-performance/ © Lemken)

The physical mixing and breaking-up of plough soils introduces a very different soil structure, with greater porosity for air and water to infiltrate the upper soil layers, greatly altering the oxidation state, and fluctuations of oxidation, as well as the microbiological activity in the soil profile, affecting the preservation of certain archaeological materials (Oxford Archaeology, 2002; French, 2015). It also changes the structure of soils, depending on the soil texture, cultivation methods and conditions during cultivation, from larger peds to finer well sorted aggregates. It can change the composition of that soil by introducing material from below, whether that is fragmented chalk on shallow rendzina, or influxes of clay from a chalky boulder clay. This can often occur if cultivation is deeper than normal, or where erosion/compaction reduces the depth of plough soil, and is affected by the type of cultivation method. Non-inversion methods are likely to mix the lower boundary between the Ap and the A/B horizons, whereas inversion methods would move that additional material to the top of the plough soil where it may be further eroded/weathered and mixed into the whole Ap horizon.

Other practices such as fertilisation, agrochemical application, liming and storage of bulk materials can all cause changes to the composition of plough soils over time. Manure is one of the most common types of fertiliser, with the longest history of use (since the early Neolithic) within agricultural systems that rely on animal husbandry as well as crop production (Bakels, 1997; Bull *et al.*, 1999; Bogaard *et al.*, 2013). Manure is primarily made from animal and human excreta, perhaps mixed with other organic remains of plant material or additional soils and sediments. Its composition is dependent on the materials available in a locality at the time and it is used to provide short- and long-term release of macronutrients, as well as major supplies of micronutrients, required for crop growth (Shepherd *et al.*, 2002; Bhogal *et al.*, 2011; AHDB, 2017). Manure also increases the quantity and diversity of OM fractions, plant seeds and microbiology within the soil that increases its structure and depth, which can be noticeable archaeologically in the stratigraphy of palaeosols (Bakels, 1997; Jones *et al.*, 1999; Bhogal *et al.*, 2011). Manure is one of the most significant additions to plough soils, in terms of quantity and over time, being one of the mains reasons why ploughing exists: to enable the burial and mixing of manures or crop material within the soil.

However, since 19th century, nutrients necessary for plant growth have been increasingly provided by mineral and inorganic fertilisers, either manufactured or mined. Nitrogen fertilisers are mainly produced from the Haber-Bosch process of fixing nitrogen from the air, phosphorus and potassium are instead mined from various geological deposits (Yara International, 2018). Manufactured or mined fertilisers are tailored for specific nutrient contents or to suit a farmers' needs; but as with any mined resources there are also risks of additional inclusions that might be less desirable (Section 4.4). Liming materials, such as the historical use of marl (a clay/limestone mix), or ground limestone are also important additions to plough soils. The use of manures, artificial N fertilisers, intensive crop production and atmospheric deposition can all cause soils to become slowly more acidic. The pH of the soil solution is a crucial factor in the availability and form of nutrients within the soil solution and it has therefore long been recognised that liming materials have long-term benefits for agricultural production by raising soil pH. Industrial by-products are often applied to soils as soil improvers or fertilisers because of the various nutrients or micronutrients they contain, and slow release patterns they have. Historically iron and steel-working slag has been a common by-product, with iron slag appearing in field contexts even in the Roman period (Kaminski, 1995: p.195) and 'basic slag' still being included within fertiliser advice and guidance today (AHDB, 2017).

4.3 What can Soils tell us about Past Agricultural Practices?

Soils contain a great deal of evidence for all sorts of studies, across many different academic disciplines and interests, with some remains such as chemical compounds, lasting only days, whereas other remains such as pottery or stone lasting for millennia within the soil. Soils are delicate resources of evidence for answering questions about the past, and about how they were themselves used in the past.

The origin of agriculture and beginnings of sedentary societies is one of the key questions that challenges archaeologists (Price and Bar-Yosef, 2011). There have been various constructed hypotheses for the expansion of agriculture, from population pushes, habitat pulls, to social manipulations. These continue to be debated as new evidence pushes back dates for the use and domestication of crops and animals, plus their interconnections with societies (Price and Bar-Yosef, 2011; Arranz-Otaegui *et al.*, 2018). For such early periods in human history, the quantity of evidence is constrained and the importance of any new evidence from new archaeological sites is significant. Thus the assessment and recording of soils and sediments at these early sites is of particular importance.

In certain circumstances where seeds and pollen are preserved in soils, the study of these remains can add to the understanding of past land use and management. Archaeobotanical approaches to preserved organic remains at archaeological sites has provided information on past diets, social aspects of food, arable management practices, livestock management, introduction and use of new plant species, and the reconstruction of past environments (Historic England, 2011). Indeed it is also not only archaeologists that benefit from the botanical study of soils, more recently, the awareness of the seed bank held within soils has grown in the agricultural community, especially as a result of significant weed problems such as black-grass (*Alopecurus myosuroides*) in Britain (Metcalfe *et al.*, 2019). Weed seeds can be shown to favour certain soils over others, and have adapted to certain management practices or timings to allow them to successfully complete their life cycle despite human attempts to manage them (Major *et al.*, 2005). It is also recognised that certain plants germinate and thrive in conditions relating to human activity, especially one which is very common today: the stinging nettle

(Taylor, 2009). Therefore areas of soil that have been used differently in the past, agriculturally or non-agriculturally, can have effects on the biological remains that survive today.

The study of cultivated and uncultivated soils by soil micromorphology can highlight the detailed microscopic impacts humans have had on soils and the post-depositional effects on those remains. For example the effects of cultivation on soil microstructures can, in some circumstances, produce alternating laminates of different sized sediments, dusty clay coatings, changes in porosity and compaction, as well as fabric mixing and aggregated fabrics in furrows (Macphail *et al.*, 1990; Carter and Davidson, 1998; Macphail, 1998; French, 2002: 47–53). In addition micromorphological approaches to settlement sites have demonstrated aspects of daily life of prehistoric people through identification of routines such as cooking, cleaning and preparation areas, as well as building life cycles, origin of materials and post depositional actions from weathering, bioturbation and chemical processes (Matthews *et al.*, 1997; Shillito *et al.*, 2011; Banerjea *et al.*, 2015).

Soils that have received attention in the past few decades have been a group of anthropogenic soils including ‘Dark Earth’, Amazonian *terra preta* (Portuguese for ‘black soil’), African ‘Dark Earths’, *Plaggen* (literally ‘sod’) soils and even Nordic ‘Dark Earths’. Although the term ‘Dark Earth’ seems to be applied quite liberally to many soils, originating out of mainly urban contexts during the post-Roman period in Europe, the term is often used for soils that have been significantly transformed by anthropogenic action (Macphail *et al.*, 2002). They all share similarly characteristic soil properties such as very high, and stable, organic carbon contents (Fairhead and Leach, 2009; Schmidt *et al.*, 2014; Wiedner *et al.*, 2015). These soils have drawn interest from archaeological angles due to their varied formation processes and the fact they can contain substantial amounts of evidence relating to past human occupation or use of a site. Their longevity of use in certain areas such as the Amazon, Africa and Europe where the these soils are still prized by modern communities for their fertile properties is notable (Arroyo-Kalin, 2010; Schmidt *et al.*, 2014). This has meant that a wider community of researchers interested in anthropology, environmental change and sustainable agriculture are also keen to learn more about how these soils were created, how they have been sustained, and how studying them can help future soil management practices (Solomon *et al.*, 2016; Isendahl and Stump, 2019a).

One of the fundamental concepts of agricultural production is the management of nutrients within soils to produce higher yielding crops and repeated crops year after year. Throughout the past, and still today, this is done through the addition of fertilisers to the soil that provide nutrients and OM to the soil and the plants growing on it. This addition can leave traces for archaeologists to detect and learn about fertilisation practices in the past. Methods for detecting past fertiliser or manure production, and use, have developed over the past 50 years. From unexplained scatters of abraded Romano-British pottery within old field systems (Guttmann *et al.*, 2005); ratios between organic and inorganic fractions of soil phosphorus (Nielsen and Kristiansen, 2014), analysis of soils in thin section micromorphology (Davidson and Carter, 1998), to methods such as soil lipid analysis (Bull *et al.*, 1999), concentrations of thermophilic microorganisms (Chernysheva *et al.*, 2017) and use of stable nitrogen isotope ratios (Fraser *et al.*, 2011).

Archaeologically, it is not only animal manures that are commonly used as fertilisers, but also seaweeds and shell sands in coastal communities, bracken and peaty deposits in moorland and lowland areas, and human waste, domestic wastes, industrial wastes around settlement areas (Guttmann, 2001). In Britain, Neolithic and Bronze Age evidence shows use of domestic wastes as well as available materials, but the penning of animals and increased use of animal manures was not more widely seen until the Iron Age (Guttmann *et al.*, 2005). As industrial processes have become more common, industrial wastes such as iron furnace slags, paper mulch, and various incinerated wastes have also at times throughout history (and prehistory) been applied to soils, sometimes for genuine agronomic needs but sometimes to get rid of waste materials (Davidson *et al.*, 2006; Meharg *et al.*, 2006).

The wide variety of soil studies highlighted here, which is by no means fully representative, has aimed to demonstrate how valuable soils are in preserving archaeological remains. These sorts of remains are not necessarily traditional archaeological artefacts or structures that can be clearly identified, but instead include organic and inorganic remains in various formations that are embedded within soils in unique ways relating to past land management and agricultural practices. They form part of the soils' history and ultimately contribute to the development and fabric of soils today.

4.4 Soil Contamination

The contamination of land is legally defined in the UK where 'substances are causing or could cause: significant harm to people, property or protected species; pollution of surface waters or ground water; harm to people as a result of radioactivity' (*Environmental Protection Act*, 1990;

Historic England, 2017a). Often archaeological and agricultural impacts on soils do not fall within this definition: although particular areas that involve historic mining and smelting are recognised as areas of potential soil contamination (Royal Commission on Environmental Pollution, 1996; Environmental Audit Committee, 2016) as well as the effects of contamination on archaeological sites themselves (Historic England, 2017a). If one takes a wider perspective of soil contamination that includes more ephemeral, local and long-term impacts of the accumulation of certain elements, then we should consider how archaeological sites impact this in lowland agricultural environments, as has been done for some archaeological sites in coastal areas of Scotland for example (Meharg *et al.*, 2006).

Particular agricultural examples come from the accumulation of cadmium (Cd) and arsenic (As) in soils from certain types of fertilisers (Hartley *et al.*, 2013; Six and Smolders, 2014). The cadmium issue has been recognised for a number of years triggering studies to evaluate the accumulation of Cd in agricultural soils from the additions of inorganic phosphate fertilisers, other organic manures, atmospheric deposition and current soil Cd levels in comparison to losses across the EU (Six and Smolders, 2014; Römkens *et al.*, 2017), with similar studies at the UK level (Nicholson and Chambers, 2008). At the field level, the addition of both inorganic phosphate fertilisers, lime, as well as materials such as sewage-sludge and poultry manure are the cause of most Cd accumulation. This accumulation, where it is long-term, could lead to increased health risks for animals and humans (Nicholson and Chambers, 2008).

Large scale metal production and industrial activities have led to large amounts of heavy metals being emitted into the atmosphere and then being redeposited in soils, in substantial quantities (Nicholson and Chambers, 2008: p.4). The proximity of the point source of heavy metal contamination will considerably change the level of impact it has on soils, hence in the last couple of centuries (since the Industrial Revolution) contamination studies have focused in large industrial areas, often next to or within urban areas. Historically, these processes are likely to have been less intensive, but more localised. For example, evidence from Roman Silchester shows non-ferrous metal working that was very localised (Cook *et al.*, 2005). Proximity of a site to the natural ores used for metal production is also important, with evidence of ferrous metal working in the Romano British period on Dartmoor (Carey and Juleff, 2013) and the Weald in Sussex (Kaminski, 1995). Archaeologically, the deposition of heavy metals can be shown nearby to enclosed hearths or fires and repeated burning of materials, not only for perhaps the smelting process, but also association with human use of fires for warmth, cooking and light, production of ashes etc. and the possible impacts this could have had on human health in certain environments (Monge *et al.*, 2015).

Figure 13: Photograph of the soil surface at Perdiswell Farm, pieces of metal working waste and plastic can be seen mixed into the soil from historic fertiliser and digested sewage sludge application (© author)

Other types of land use not normally recognised for their soil contamination is that of game bird shooting. In the UK it is common for farms to run game bird shoots that can mean regular firing of shotgun cartridges filled with hundreds of 2-3mm lead pellets over particular fields or landscapes. Lead deposition from this can build up significantly in soils, in fact being one of the most significant contributions of lead to soils in England and Wales (Nicholson and Chambers, 2008).

Another additional local pathway for soil contamination at the field level is via the emission of particulates and heavy metals from combustion engines, and leakages from, vehicles and aircraft. Various studies have been made assessing the impact of road networks especially on ecosystems and habitats in their vicinity (Nicholson and Chambers, 2008; Natural England, 2016). From these it suggests that heavy metal deposition of Zn, Cd, Cu, Pb, Cr does occur often in proximity of busy roads, and concentrations within soils decline quickly within 10-50m from the roadside logarithmically. The quantities of deposition from aircraft is less well evidenced and is also expected to be more widespread than an individual field unless that is close to a runway. Another factor that is lacking within the literature is consideration of agricultural vehicles such as tractors and combine harvesters, but the relatively short exposure time and the even coverage, may mean impacts are negligible.

An archaeological approach to conflict has begun to consider the impact of modern (20th century generally) conflicts on landscapes (Chapman, 1994; Saunders, 2002). Conflicts of all types can have subtle, as well as disastrous, impacts on the environment and the soil due to the firing of ordnance, bomb damage, structural defences, minefields and other hazardous substances (Morris, 2003). In addition, the effects of military actions are not always only felt on landscapes of conflict, but also in landscapes containing military training areas, as well as contributing to a uniquely preserved (uncultivated) archaeological landscape as at Salisbury Plain (McOmish *et al.*, 2002). Military training areas, for example, can contain many hazardous and accumulative substances, most often heavy metals such as As, Ba, Cu, Cr, Cd, Hg, Pb, but also biological substances such as anthrax and depleted radioactive isotopes (Bricka *et al.*, 1994). Archaeological evaluations have started to investigate these types of landscapes for the purposes of understanding the conflicts' impact on the landscape (Gheyle *et al.*, 2016), but less has focused towards the subtle impacts, especially of heavy metals, on agricultural landscapes and wider diffuse soil contamination from conflicts.

Another example of soil contamination, which is both archaeologically relevant and agriculturally caused, is the issue of so-called 'green waste' and its effect on archaeological geophysics (Gerrard *et al.*, 2015). The increased use of recycled organic materials on farms, generally perceived as a beneficial thing to do for a more circular economy and to improve soil health, has been linked to impacts on the effectiveness of geophysical methods. Particularly on magnetic responses from archaeological deposits, almost totally obscuring multiple types of archaeological feature. Although there are rules and specifications for composts (PAS100 via http://www.wrap.org.uk/sites/files/wrap/PAS%20100_2011.pdf accessed 15/02/19) and anaerobic digestates (PAS110 via http://www.wrap.org.uk/content/bsi-pas-110-producing-quality-anaerobic-digestate accessed 15/02/19), that stipulate nutrient limits, physical, chemical and biological properties and levels of impurities permissible, there are still low quality products containing metal, glass and plastic contaminants being used regularly. Even at the recommended limits, the volume of material has potential, over multiple applications, to significantly affect the levels of magnetic intensity of the soil. This could lead to large areas of agricultural land unable to be surveyed using magnetic prospection techniques such as magnetic gradiometry and also (although it has not been evaluated yet) the same issue could impact PF electro-magnetic surveys for soil mapping.

The focus above has been towards the elemental, more specifically heavy metal, contamination of soils due to the relevance this has for archaeological sites (in both persistence and immobility as well as quantitative effect) and the potentially toxic effects for plants and humans. It demonstrates some of the major impacts that humans can have on soils, and that although some contamination can occur from a single application of a material, there are many more gradual accumulations of materials that are occurring in soils that, in the future, could impact land use and archaeological practice.

4.5 Agricultural Perspectives of Soils

‘Soil health’ has become a topical phrase in the agricultural community (Harvey, 2018; https://ahdb.org.uk/greatsoils accessed 10/07/19). The term was developed in the late 1990s from various aspects of soil quality within agroecosystems research, and describes the need for an emphasis on the general condition of the soil (Kibblewhite *et al.*, 2008). This was in response to the effects of agricultural intensification and previous attention directed at only one or two key soil qualities (often related to yield). More recent research has shown the complexity of soils, in how humans manage them and how they provide functions for the environment and society as a whole; Haygarth and Ritz propose that 18 ecosystem services rely on healthy soils (Kibblewhite *et al.*, 2008; Haygarth and Ritz, 2009). This understanding is now not only common in the academic communities, but also within Government and the wider public, as shown by the House of Commons report on Soil Health (Environmental Audit Committee, 2016). The complexity of managing a network of systems, with an incredible array of variability and controlling factors, via actionable management practices and how to monitor those effects is currently the challenge faced by the agricultural community. Further research is focusing on how to turn the general understandings of various ecosystem services provided by soils (which are reasonably well understood at a theoretical level) into more practical, local decisions and actions, that land managers can take and record (Stockdale *et al.*, 2019).

Traditionally, in agricultural communities and especially amongst farmers who manage land, I have noted explicit perspectives that soils are sometimes thought to be static. “You cannot change your soil, so you need to manage it differently” (I. Beecher-Jones, pers. comm.). In the short-term and even in a life time, there is limited scope to ‘change’ a soil and therefore management tends to focus on altering other practices that can be managed such as drainage, cultivation, cropping etc. This stationary perspective is also conveyed in some literature and the methodology surrounding the classification of land in England and Wales (MAFF, 1988), where physical and chemical soil characteristics for grading land form the basis for economically valuing it, and where it is described that "soil quality….cannot be altered" (Maddison, 2000: p.520). There is a dichotomy here between the principles of PF, the crux of which is to manage the variability within a field (mainly due to soil variation), and the underlying causes of that variability. In a knowledge exchange workshop held to explain PF methods to farmers, it was said that mapping the soil properties is the first step towards managing variation, but later it was mentioned that historic field boundaries should be taken into account due to historical management practices of different fields (I. Beecher-Jones, pers. comm.). This simultaneously recognises that the soil can limit farmers' choices and that farmers can limit the soil. Another example comes from the interpretation that historic fields tend to have different soils and that historically boundaries were placed to delineate different soil types because farmers knew their soil. This, while being true in some cases (such as river meadows following alluvial deposits), is not always the case. Historic fields boundaries can overlie the same soil type, but have drastically different OM levels, structure and depths due to varying management over long periods of time. To the farmer, those two soils are noticeably different.

Agricultural perspectives on soils has changed over the past decade. The steer away from focusing on one or two soil qualities towards a more holistic approach of soil health and its relation to many interconnected services that it provides, has been reflected in changing farming practices (for example the increase in mixed farming practices, cover cropping and use of green manures to improve soil health). With the rise of PF, farmers have begun to realise, and be able to manage, soil variability in a more detailed manner. Shifting attention from managing soils at the field level, to managing them at the smaller 'zone' level.

4.6 Soil Mapping: from Auger to Arc GIS

The reasons for mapping soils can be wide-ranging depending on the particular focus. One focus could be on the agricultural characteristics of the soil for growing a range of specific crops, whereas another might be to map specific indicators of soil health. Mapping can be both quantitative and qualitative, forming numeric datasets showing variation in a particular property and combinations of assessments to provide overall judgements of soil properties. Soil mapping *per se* is not new, having beginnings within the 18th and 19th centuries, but has seen renewed impetus within an increasingly digital world (Minasny and McBratney, 2016). In the UK today, traditional soil survey data has been digitised and combined with new digital data to provide national soil information systems to satisfy demands in environmental science, PF and land use planning (Webster, 1994; Hallett *et al.*, 2017).

PF relies on soil mapping for assessing the soil, one of the key variabilities of crop production. However, the usefulness and accuracy of traditional soil mapping from traditional, hand auger and field inspection, soil surveys for PF applications was recognised as a limitation early on (M. Dafforn, pers. comm.). Due to the high resolution requirements of PF, traditional soil survey maps are often combined with geological maps, satellite imagery and other high resolution data to provide more detailed assessments of within-field variation than previously existed (https://www.cranfield.ac.uk/research-projects/soil-mapping accessed on 25/10/19).

This demand, along with increased computing power over the past 20 years (with GIS systems such as Arc GIS and Quantum GIS), more portable and innovative soil sensors, and the development of web applications for sharing/displaying/accessing data, has meant digital soil mapping has become common place in agriculture, soil science and archaeology (Minasny and McBratney, 2016). It is particularly important for the use and reuse of legacy soil data that may have been collected historically, allowing reinterpretation and evaluation of soil properties and the spatial comparison of soil data.

4.7 Concluding Remarks

This Chapter demonstrates how diverse and interconnected soils and humans are. From the development and formation of soils to the long history of human use, the soil fabric has been altered, reformulated and recycled many times. Soils are a repository of evidence for what has happened in the past, as well as the processes and cycles that will determine how humans and the environment interact in the future.

Chapter 5

5 Methodology

This Chapter will outline the methodology used at each case study site, grouped into four Sections; DBA, fieldwork, laboratory-based and data analysis methods. This thesis aims to question how archaeological and PF data can be integrated; used for mutual benefit, shared and add value to the understanding of archaeological and agricultural soils. The first step is to group together the datasets available at each case study site (DBA). The second is to test how archaeological sites can impact soils, and situate these impacts within PF approaches, by collecting new, cross-site comparisons (fieldwork, followed by laboratory work and finally data analysis).

5.1 Desk-Based Assessment

DBA is a familiar term in the archaeological world, but less recognised in the agricultural world, even though the underlying methodology is used in PF. The majority of data on, and surrounding, each site was not primary data created by this research, but secondary data taken from the results of other surveys and studies, hence collating this information within a DBA is crucial. Each case study Chapter begins with an introduction to the location of the site itself, as well as a short review of existing data and information about the site, from both the archaeological and the agricultural/PF perspective.

5.1.1 Archaeological Sources

Table 1 shows the full list of sources consulted to collate the archaeological DBA at each case study site. This draws on multiple sources of data and information including historical, geological, pedological, archaeological, topographical, spectral, and cartographic mapping together into one synthesis for the relevant area. Although Table 1 goes into the full list of sources checked, not every case study site had available data, or information, for that particular area. In some cases certain records like borehole records and Portable Antiquities Scheme (PAS) finds, were not in locations relevant to the case study site and therefore were not included further.

Name	Format	Source
OS maps (1:10000 + 1:25000)	GeoTIFF	https://digimap.edina.ac.uk/os
OS Topography (5m)	GeoTIFF	https://digimap.edina.ac.uk/os
LIDAR 1m resolution	ASCII	https://environment.data.gov.uk/DefraDataDownload/?Mode=survey
Historic OS maps (1st Edition onwards)	GeoTIFF	https://digimap.edina.ac.uk/historic
Google Earth Images (multiple years)	TIFF	Google Earth
HERs	SHP/PDF	Individual Historic Environment Record Office
Aerial photographs	JPEG/ Hard copy	Online - https://www.britainfromabove.org.uk/ Historic England Search Room in Swindon
Previous archaeological/historical work • Desk-Based Assessment • Archaeological excavation • Geophysical survey • Geoarchaeological survey • Research reports • Historical literature	Hard copy/online / raw data	Search on Archaeology Data Service https://archaeologydataservice.ac.uk/ Historic England Geophysical Survey Database https://archaeologydataservice.ac.uk/archives/view/ehgsdb_eh_2011/ Local archaeological and historical societies Google search for grey literature, historical sources
Bedrock and Superficial Geology	GeoTIFF	https://digimap.edina.ac.uk/geology
Soil maps	Hard copy and GeoTIFF	Soil Survey for England and Wales http://www.landis.org.uk/ - National Soil Resources Institute http://www.ukso.org/ UK Soil Observatory (British Geological Survey) http://mapapps2.bgs.ac.uk/geoindex/home.html
Archaeological finds (PAS)	SHP	https://finds.org.uk/
Borehole records	Online Record cards	https://www.bgs.ac.uk/data/boreholescans/home.html

Table 1: The variety of evidence collected and collated for the archaeological DBA of each case study site, in what format, and from what source.

5.1.2 Agricultural/PF Sources

Similarly to the archaeological DBA, without information on the cultivation practices of a farm, or the types of fertiliser used, for example, it would be hard to provide a background on the soil's management, or how any archaeological impacts may affect that management system. Therefore a baseline of agricultural and particularly PF data and information is necessary. Table 2 draws out the key sources of data and information that were targeted in establishing the agricultural baseline for each case study site.

Name	**Format**	**Source**
Farm Information • Farm ownership • Farm history • Past land use • Crop rotation • Livestock • Fertiliser choice • Cultivation history	Oral	Farmer
PF history (hardware/software/companies used)	Oral	Farmer
Existing PF data • Soil zoning • Soil nutrient mapping • Satellite imagery • Geophysical data • Soil type assessments • Yield maps	Hard copy and digital (PDF and SHP, KML, Excel Spreadsheet)	Farmer/PF company
Historic Weather Data	Excel Spreadsheet	Met Office - https://www.metoffice.gov.uk/datapoint/product/historical-station-obs
Google Earth Images (multiple years)	TIFF	Google Earth
Bedrock and Superficial Geology map	GeoTIFF	https://digimap.edina.ac.uk/geology
Soil maps	Hard copy and GeoTIFF	Soil Survey for England and Wales http://www.landis.org.uk/ - National Soil Resources Institute http://www.ukso.org/ UK Soil Observatory (British Geological Survey) http://mapapps2.bgs.ac.uk/geoindex/home.html

Table 2: The variety of evidence collected and collated for the agricultural/PF assessment of each case study site, in what format, and from what source.

Within the data collected, overlaps could occur between the archaeological DBA and the agricultural baseline, for example, where historic field boundaries might be shown on historic OS mapping in an archaeological DBA, but also recorded by asking the farmer about previous land use of a field, or crop marks shown in satellite imagery. In those situations both will be compiled to test whether the data itself differs, or whether the interpretation of that data differs even when questioning it for similar purposes.

5.2 Data Collation and Visualisation

Tables 1 and 2 show there are over 35 different sources of data and information collected across both archaeological DBA and the agricultural or PF baseline. Any data with a spatial extent suitable for display as an image, was georeferenced, overlaid with other data and visualised in Arc GIS (10.5.1). Others without a useful spatial extent, for example literature or farm cultivation information, were stored in folders either digitally or in hard copy format.

The quality and accuracy of data input into Arc GIS varied depending on the nature of the inputs. Many of those 35 sources were in digital formats already (such as PDFs, JPEG or GeoTIFF image files, ASCII, SHP and KML files) but some were not (hard copies of aerial photographs, documents, paper maps). Each of these file types needed specific attention to convert them into digital formats, and then to input them into Arc GIS. Any hard copies were scanned as image files and georeferenced using as many control points as possible within the image to reference them to already accurately spatially referenced data. Some datasets had originally poor spatial resolution and therefore could be georeferenced at the field level, but were unable to provide accurate comparisons with other high resolution data. Datasets that were in digital format, but with no spatial reference (PDF or JPEG image files for example) were georeferenced in the same way as hard copies. Many datasets were already available in the correct formats, with coordinates and projection files, enabling immediate display within Arc GIS. This variability in the data gathered was more problematic than using only the higher quality (from a visualisation point of view) data, however, certain datasets may be specific to certain moments in time and space, capturing important observations in relation to soils, crops, or past land use, and therefore they were still included within the analysis.

5.3 Fieldwork Methods

The fieldwork aspects of this research aimed to provide one or more consistent datasets across each case study site. The purpose of these was to aid comparisons of existing data and interpretations between case study sites and provide a basis for analysing the difference between the archaeological and PF-based assessments of the soil.

The main fieldwork was undertaken in three stages. Starting with the first case study site, Myncen Farm, Dorset, fieldwork commenced over early spring 2015. The second case study at Wilsford Manor Farm, Wiltshire, began during summer 2015, lasting until spring 2016. The last and largest case study at Perdiswell Farm, Oxfordshire, began in spring 2016 and finished in spring 2017. The staggered nature of the fieldwork allowed for experience to be gained and for this experience to influence the methodology as a whole. During the first phase of fieldwork, laboratory analysis was completed immediately, allowing re-sampling if necessary and evaluation of how to present the data being gathered. Supplementary fieldwork consisted of drone surveys, site visits and crop walking, carried out multiple times each growing season throughout the years of fieldwork at each case study site to inform the evaluation.

5.3.1 Soil Sampling Design

The standard agricultural methodology for soil sampling, as described in Section 2.3.4, can vary quite significantly depending on the requirements of the farmer, the ability or preferred approach by the PF company, the elements being measured, the relative costs and the usefulness of those results over longer periods of time. The general advice by agricultural advisers is for a sample every hectare (100m^2), although in many cases it would be less than this due to costs (AHDB, 2013b). In archaeological soil sampling for similar topsoil surveys, the resolution would be within the range of metres (1-20m for sites, 0.2-0.5m for structures) (Historic England, 2007: p.31). In arable contexts anything more detailed than 10m would be unlikely to yield better results due to soil movement from cultivation. Within excavation areas sampling density could be even higher (centimetre scale rather than metre scale) due to buildings and excavation areas being smaller in scale. To produce a comparative dataset that provides detail to low density agricultural soil sampling surveys, but also effective data for answering archaeological questions in arable contexts, a systematic topsoil grid of 20m squares was designed across each case study site. If necessary on smaller sites, this could include nested sampling to provide extra detail. This grid spacing allowed a large enough area to be covered at the same resolution, making it suitable whether a field was 5ha or 50ha, while providing enough data points for a robust statistical analysis of the data, even at the sub-field level. The grids were created using Arc GIS to produce a north/south orientated grid within each field boundary, which could then be exported to a GNSS system for marking out on the ground.

Although topsoil spatial variability was significant for this research, an assessment of soil depth and subsoil stratigraphy was also required to various levels. Geoarchaeological and archaeological excavation sampling regimes tend to focus on transects across landscapes, traversing key features and coring to record deeper stratigraphy. Agricultural and PF regimes tend to focus on the upper metre of soil below the surface and would only focus on a couple of representative landscape positions within a field. The sampling design should therefore interconnect these two approaches, by taking regular traverses across the field cutting landscape features if possible, but also with respect to time and resources, focus on the upper metre of soil, or to solid/fragmented bedrock substrate if soils are shallow.

5.3.2 Sampling methodology

5.3.2.1 Topsoil Sampling:

The pre-determined grid set out in Arc GIS was laid out on the ground using a Topcon Hiper-V base and rover system (Figure 14) with RTK corrections to sub-centimetre accuracy. The original base-station position for each site was recorded, marked physically with a peg and returned to each time entering the same base station coordinates for exact matching across different survey days/years. The base-station was positioned in a location with as much ‘sky view’ as possible without being inside the field, where any physical marker would be disturbed by agricultural operations throughout the year. At each sampling point, the point marked the centre point in relation to the sampling methodology below.

Every topsoil sample comprised a bulk sample from five sub-samples in a 1m^2 area, as shown in Figure 14. This was necessary to reduce the variability of the sample, especially microvariation at the metre scale which could produce background ‘noise’ in the resulting data (Oliver, 2010). Samples were taken from the upper 0-15cm of soil as is consistent with most agricultural soil sampling for arable land (Rowell, 1994: p.14). Samples were collected with a hand gouge corer (a smaller gouge was used for topsoil sampling only, larger 25mm gouge was used for soil cores). The bulk samples approximately came to 300g each, providing enough soil for all analysis necessary, as well as to save portions of original samples if later analysis or inspection was necessary.

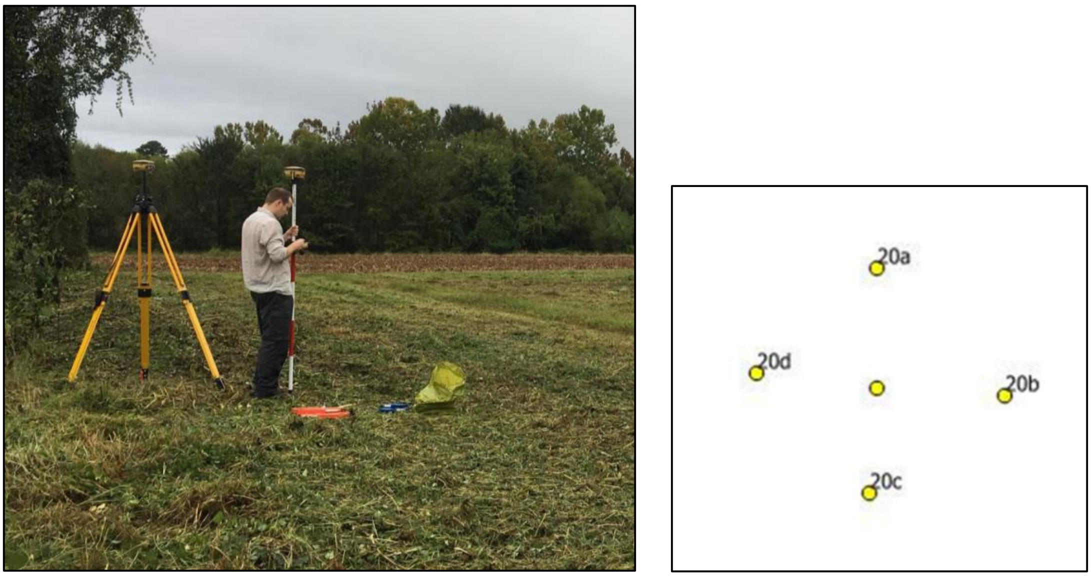


Figure 14: shows the author setting up the GNSS system (left) and the topsoil subsampling design for 1m^2 around the central sample location (right) (© author)

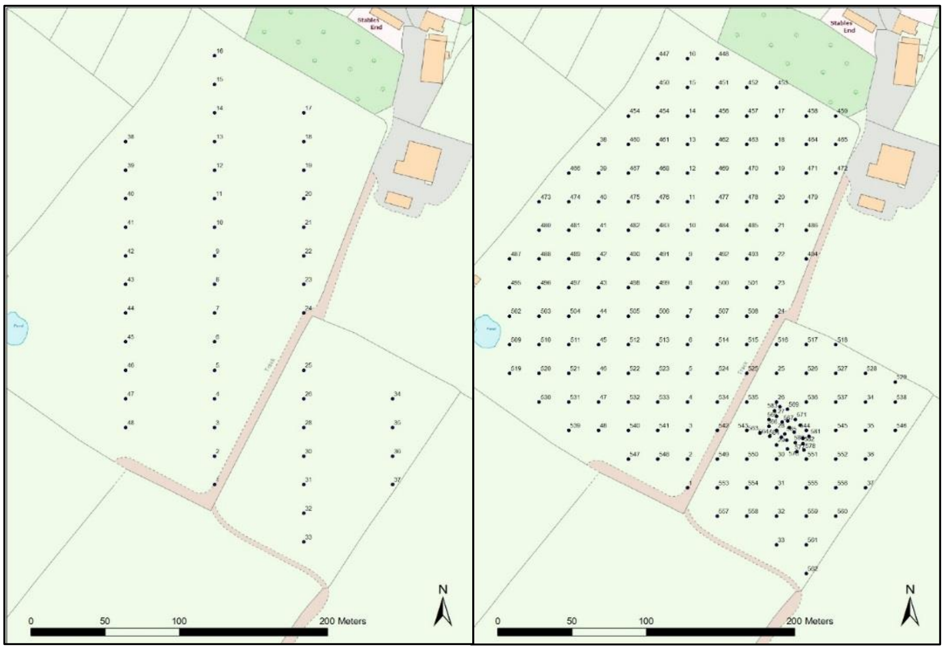


Figure 15: Example core transects (left) and further topsoil sampling (right) at Myncen

(contains OS data © Crown copyright and database right 2019)

5.3.2.2 Soil Coring:

Core transects were aligned to the existing topsoil sampling grids (Figure 15). It was intended that transects 40m apart, with cores spaced at every 20m, would give a several transects to compare soil stratigraphy across the sites. Samples were taken using a 25mm gouge corer to achieve depths of approximately 1 metre, or until clear indication of bedrock geology. In the majority of cases it was possible to extract complete cores, but in some cases the core was unavoidably split into two or more sections due to the texture, stone content and moisture content of the soils. Each core, or section of a core, was photographed, assessed and described, as is set out in Hodgson (1978), on recording sheets in the field. The sub-sampling of each core was semi-systematic, any stratigraphic layer greater than 5cm in depth was sampled separately, and in the case of layers thicker than 20cm, samples may be split into upper and lower to characterise within that layer.

Figure 16: Gouge corer (25mm diameter) with a core (right) and the recording sheets used (left) (© author)

Further directed sampling may be necessary to target particular archaeological features or enclosure areas and details for these situations is included in each case study Chapter. The sampling design was left flexible to allow for additional samples to be taken if thought necessary in the field, or to take opportunities of other events occurring on the site (for example at Wilsford fieldwork coincided with the University of Reading's field school and excavation, allowing samples to be taken within archaeological features and the sections exposed by archaeological excavations).

5.3.3 Drone Surveys

Drone surveys were conducted across each case study site, whether in addition to existing drone data or for new data, to provide comparisons between PF satellite imagery (low resolution) and higher resolution drone imagery. As a result of an opportunity to borrow a multispectral camera (MicaSense RedEdge), multispectral imagery could be evaluated in comparison to RGB images. Hyperspectral imagery was also available at one case study site (Wilsford) due to another opportunity to compare airborne hyperspectral data, with drone and satellite-based imagery.

Drone surveys were conducted with a DJI Phantom 3 Advanced, with a 12.4 Megapixel RGB camera, or a MicaSense RedEdge camera retrofitted to the drone for multispectral imagery (5 separate lenses collecting five different wavelength bands: 1=blue, 2=green, 3=red, 4=NIR and 5=Red Edge). All surveys were completed at a height of 110m above ground level, on a parallel path, guided by the drone's own GNSS receiver, with at least 70% overlap between swathes for accurate photograph matching. Drone surveys were planned in advance with the relevant permissions necessary (this included permission to fly next to London Oxford Airport at Perdiswell Farm in addition to general landowner consent). RGB surveys were processed via the online Drone Deploy service to produce orthorectified GeoTIFFs that could be downloaded and input into Arc GIS. Multispectral camera surveys additionally required a calibrated reflectance panel to be imaged before every flight to correct for different light intensities. Imagery was processed through MicaSense's own online service (ATLAS) to again produce multiple orthorectified GeoTIFFs for each band (1-5) for input into Arc GIS.

5.3.4 Crop Walking

An important aspect of this fieldwork was to join together surveys, completed at various stages of crop growth, from satellite, aircraft and drone imagery, with visual inspection on the ground. In all PF services, field inspection is essential to ground any interpretations from aerial imagery due to the multiple causes of poor crop growth or soil variability. As part of a funded training opportunity through this Doctoral Training Partnership, I was able to become a fully qualified agronomist, enabling more effective crop walking and identification of common pest, weed, disease or soil issues while on fieldwork. Therefore every time field visits occurred, whether for soil sampling or for drone surveys, the crop and soil at the time was visually inspected and notes of any abnormalities or inspection of poor areas were kept in a notebook. Inspection involved walking across a representative area of the field checking the growth stage of the crop, visual inspection of the crop itself to check for diseases or nutrient deficiencies or weed infestations.

5.4 Laboratory Techniques

Laboratory work was conducted throughout the three years as sampling was completed. Initially the first six months of laboratory work was focused on the first case study site to test the proposed methodology and amend it before continuing onto case study sites two and three. In a similar approach to the fieldwork methodology and the sampling regime, the key aim was to provide a consistent analysis across all samples that could provide a balance between agriculturally relevant soil analysis as well as archaeologically relevant analysis.

Soil geochemistry has been identified in Chapters 2 to 4 as a notable link between archaeology and PF. Agricultural analysis of soils usually takes the form of plant-available nutrient analysis whereas archaeological analysis often focuses on a broader range of extraction methods depending on the questions being asked. These can range from total elemental concentration to plant-available levels of nutrients. Archaeological studies often involve assessment of heavy metals and other elements that have been shown to relate to various types of archaeological activity (P, Ca, Mn, K, Mg, Cu, Zn) (Holliday and Gartner, 2007; S. Oonk *et al.*, 2009). When taking both approaches into account, a technique was needed that could provide multi-elemental analysis covering:

- a mixture of agriculturally and archaeologically relevant elements
- results that allow a certain level of comparison between elemental and plant-available nutrients
- a relatively quick sample preparation time to aid a greater number of samples to be analysed for assessing the soil's spatial variation.

pXRF was chosen because it represented a balanced fulfilment of these needs. It is a flexible technique that can be used in the field, or in the laboratory, and access to equipment was available through the University of Reading. It allows analysis of a wide range of agriculturally and archaeologically relevant elements within a single analysis. It does not allow analysis of plant-available nutrients, but due to the collection of existing plant-available nutrient analysis and pH from farms, it was decided that the time and cost required for specific extractions of certain plant-available nutrients was not necessary and a focus on total elemental values would be sufficient.

Other methods for total elemental analysis such as ICP-MS or laboratory-based X-Ray techniques, although potentially more accurate, require more lengthy sample preparation, therefore would limit the number of samples analysed and cost more in supplementary materials. Previous use and research in pXRF has been carried out in geoarchaeological investigations, soil pollution mapping, artefact analysis as well as in other geological and pedological investigations (Frahm and Doonan, 2013; Hayes, 2013; Weindorf *et al.*, 2014; Lubos *et al.*, 2016). Its general lack of use in commercial agriculture, and especially PF, provided an opportunity to test its use within this context as well as re-evaluating the value of rapid multi-element topsoil surveying for archaeological investigations. It's flexibility for use in the field, and in the laboratory, was also an advantage that was tested during the early stages of this research.

5.4.1 Sample Preparation

All samples were homogenised and split into smaller, approximately 100g, representative samples for oven drying. They were dried at 110 degrees C for 12 hours, weighed and then dried for a further 12 hours to determine moisture content. Moisture content was measured for an initial batch of samples to assess how moisture effected pXRF analysis, soil moisture was not measured after this initial test and samples were oven dried overnight. Samples were then sieved to < 2mm and placed in small analysis cups, with approximately 10g of soil in each covered by polypropylene film 12µm thick to protect the nose cone of the analyser from being punctured by soil particles (Figure 17).

Figure 17: shows the 100g soil samples prepared for oven drying (left) and 10cl sample pot for pXRF analysis (right) (© author)

5.4.2 Portable X-Ray Fluorescence (pXRF)

A Thermo Niton XL3t GOLD+ portable X-Ray Fluorescence analyser was used in a lead-lined test stand in the laboratory (Figure 18), to reduce exposure to myself and others. The test stand provided for more consistent analysis of samples than using it by hand, due to effects from small movements while analysing for over 2 minutes. The pXRF was ‘System Checked’ before every use, as recommended in the manual. It was used in Mining mode, a mode often used for soils when looking at a mixture of lighter elements as well as heavy metals. The pXRF has four filters (Low/Medium/High/Light) that are usually set to 20s each. For focusing on lighter elements and improving count accuracy, measurement times were adjusted to 30:30:30:60 respectively giving a total measurement time of 150 seconds per sample.

The graph (Figure 19) shows the pXRF results for phosphorus plotted against the standard analyser error results. There is a clear positive relationship between the concentrations of phosphorus in the calibration samples in comparison to the error values recorded. This is due to the instrument calculating the standard deviation (SD) of the counts collected per energy peak, and translated into parts per million (ppm) using an internal algorithm. Thus generally, the higher the peak (higher concentrations) the higher the SD of results were. This can be defined as the ‘count error’.

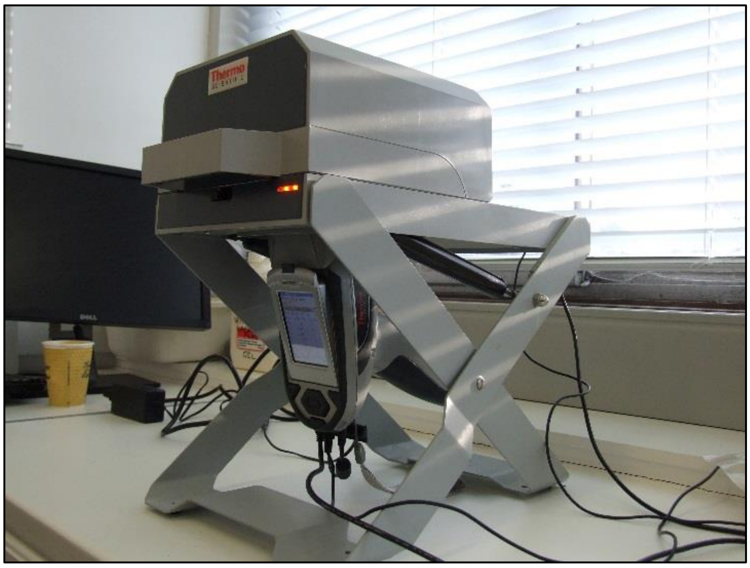


Figure 18: The pXRF in its test stand (© author)

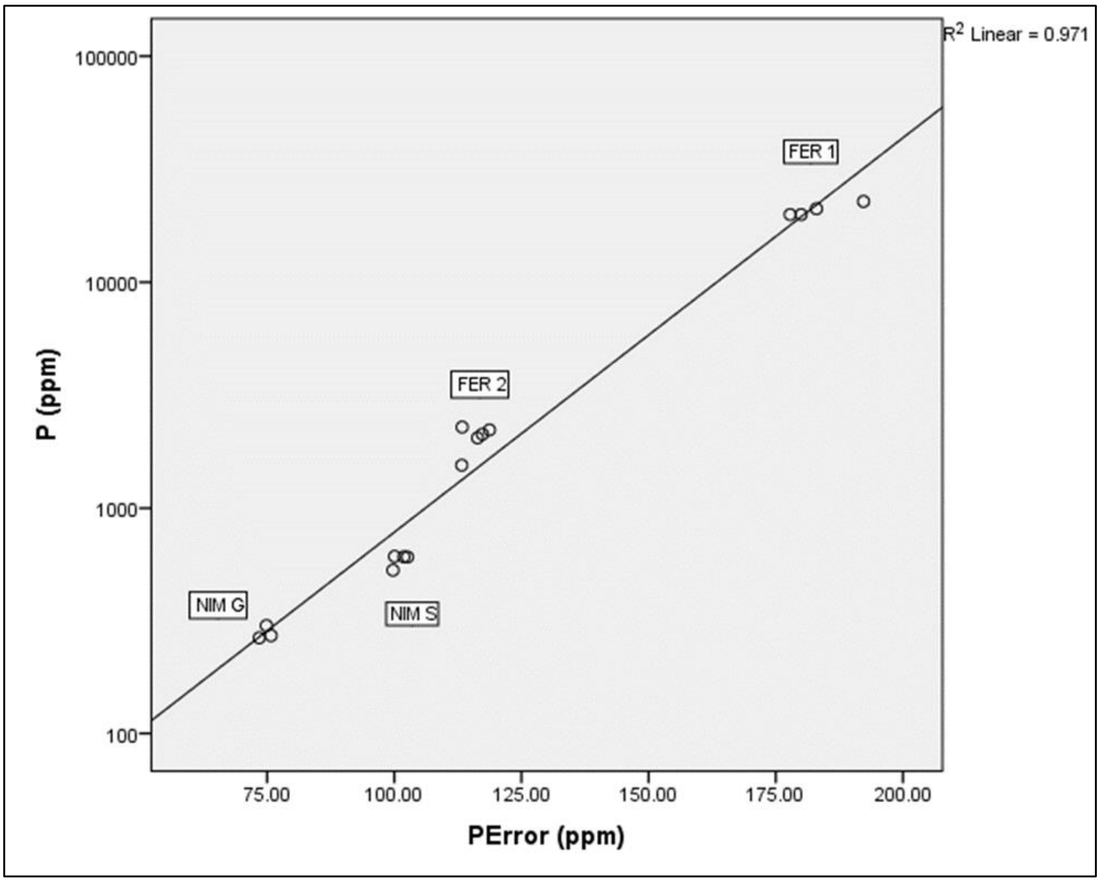


Figure 19: Graph of P concentration vs error values calculated by the instrument for 4 calibration samples (© author)

In addition to the count error, the instrument's accuracy can vary over long periods of time, or between different analysis sessions, due to internal shift. Therefore at the beginning, and sometimes at the end, of each analysis session reference standards were analysed to test intra- and inter-session variability. Multiple reference standards were used (FER2, FER1, NIMS, NIMG) that had pre-determined compositions by laboratory-based XRF, and elemental concentrations similar to the soils being analysed. Periodic checking of the stability of the values was undertaken every couple of sessions to ensure if any change did occur, it could be evaluated and action taken if necessary.

Further to the count error and the stability of the pXRF measurements, sample heterogeneity will have effects on the robustness of the results. For the most accurate homogenisation, soils can be milled to a fine powder, then set into resin to ensure particle matrices stay the same and are consistent. This however requires significant preparation and was not possible for the quantity of samples needing analysis across three case study sites and the large area of those sites. Instead the measurement of bulk <2mm samples was used.

To gain an idea of the sample heterogeneity over Myncen Farm, four samples were analysed in triplicate. Each time the sample was poured back into the bulk sample bag, mixed and then poured back into the analysis pots. Taking the mean and the SD of each sample, a Coefficient of Variation (CV) was calculated, and averaged, to give indications of the variability within the sampling and analysis methodology.

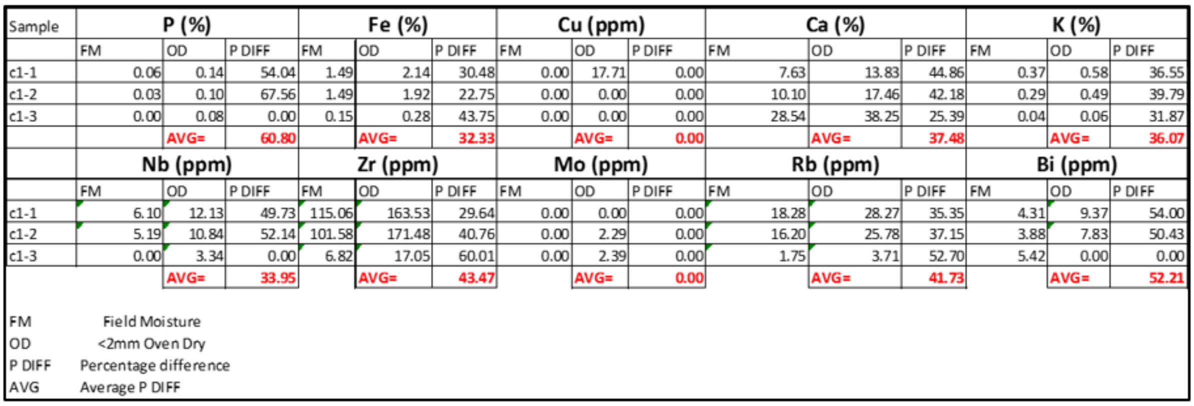
Coefficient of Variation (%)	Zn	Cu	P	K	Fe	Ti	Ca	Average Core CV (%)
Core 1	8.9	-	13.4	1.5	0.7	0.2	0.6	4.2
Core 40	8.1	20.9	6.1	2.1	2.6	3.2	1.8	6.4
Core 43	6.6	12.8	6.2	3.9	3.8	2.9	4.5	5.8
Core 47	12.5	10.2	3.6	2.8	8.6	4.4	10.1	7.5
Average Elemental CV (%)	9.0	14.6	7.3	2.6	3.9	2.7	4.3	6.3

Table 3: The results from replicate analysis of samples, examining the variation among different elements as well as the variation among different cores (© author)

Table 3 shows that the mean CV across the four cores is 6.3% (based on Zn, Cu, P, K, Fe, Ti and Ca). The variability between cores ranged from 4.2% to 7.5%. The average CV for each element also varied (between 2.6% and 14.6%), with Cu being most variable (this is most likely because levels of Cu were close to the Limit of Detection (LOD)). These values give some idea of the variability to be expected from the sampling (field sampling and sample preparation) as well as pXRF analysis for certain elements (elements in quantities close to the LOD will be more variable).

Moisture has a significant effect on the detection of elements by pXRF analysis due to water molecules absorbing X-Rays and dissipating the energy (Ge *et al.*, 2005; Stockmann *et al.*, 2016). This was a major concern within this methodology, since one advantage of the pXRF was its portability, that meant it could be used out in the field and save time spent on sample preparation. Yet if analysis was affected significantly by ‘normal’ (and the variability in ‘normal’) soil moisture levels, this would restrict the accuracy of the data.

Therefore a comparison of three samples at field moisture (sampling was done in autumn/winter due to cropping and accessibility) which ranged from 25% to 28%, with samples that had been dried, ground and sieved to < 2mm was made. The results (Table 4) suggest that there was a significant difference in elemental concentration of particular elements between field moisture content and prepared samples. The difference varied due to each element, but phosphorus, a particularly important element in this study, was found to be 60% lower on average than the prepared sample. Other elements reliably within detection limits were on average 30-40% lower. There were five occurrences where at field moisture elements were not below LOD, where they were detectable in the oven dried samples. As a consequence of these results, all samples were prepared (dried, homogenised and sieved) to ensure detection improved and reliable data was gathered across the three case study sites.



Sample	P (%)			Fe (%)			Cu (ppm)			Ca (%)			K (%)		
	FM	OD	P DIFF	FM	OD	P DIFF	FM	OD	P DIFF	FM	OD	P DIFF	FM	OD	P DIFF
c1-1	0.06	0.14	54.04	1.49	2.14	30.48	0.00	17.71	0.00	7.63	13.83	44.86	0.37	0.58	36.55
c1-2	0.03	0.10	67.56	1.49	1.92	22.75	0.00	0.00	0.00	10.10	17.46	42.18	0.29	0.49	39.79
c1-3	0.00	0.08	0.00	0.15	0.28	43.75	0.00	0.00	0.00	28.54	38.25	25.39	0.04	0.06	31.87
		AVG=	60.80		AVG=	32.33		AVG=	0.00		AVG=	37.48		AVG=	36.07
	Nb (ppm)			Zr (ppm)			Mo (ppm)			Rb (ppm)			Bi (ppm)		
	FM	OD	P DIFF	FM	OD	P DIFF	FM	OD	P DIFF	FM	OD	P DIFF	FM	OD	P DIFF
c1-1	6.10	12.13	49.73	115.06	163.53	29.64	0.00	0.00	0.00	18.28	28.27	35.35	4.31	9.37	54.00
c1-2	5.19	10.84	52.14	101.58	171.48	40.76	0.00	2.29	0.00	16.20	25.78	37.15	3.88	7.83	50.43
c1-3	0.00	3.34	0.00	6.82	17.05	60.01	0.00	2.39	0.00	1.75	3.71	52.70	5.42	0.00	0.00
		AVG=	33.95		AVG=	43.47		AVG=	0.00		AVG=	41.73		AVG=	52.21

FM	Field Moisture
OD	<2mm Oven Dry
P DIFF	Percentage difference
AVG	Average P DIFF

Table 4: The average differences between dry, sieved soil samples and field moisture samples for a number of elements (© author)

Whilst Section 3.1.6 outlined the increased use of pXRF as a tool for geochemical analysis of archaeological materials and especially soils, as is shown above, it is not without its limitations. These relate to the stability of the instrument over time, and especially for the analysis of soils, the moisture content of the samples and sample preparation used. For the objectives within this thesis, the core aim was to compare within field variability at each particular site. Therefore analysis of each site can take place within a short period of time to save issues over comparing long term analysis. In addition, while some other archaeological investigations might rely on interpretation of pXRF data to analyse minute differences between different archaeological objects or deposits which may be affected greatly by the above accuracy issues, this thesis uses pXRF to detect major variations across soils, and any significant archaeological variations. Where subtle variations occur it may not be possible to detect these without adding in extra constraints into the sampling and analysis methodology.

5.5 Data Analysis and Visualisation

5.5.1 Statistical Analysis

The pXRF analysis software (Niton Data Transfer) outputs data into Microsoft Excel spreadsheets for further data analysis. These spreadsheets of raw data were then compiled across multiple analysis sessions. Following this the spreadsheets were input into the statistics software package SPSS 24, where basic descriptive statistics was used to provide a quick overview of the mean, median, standard deviation, range, minimum and maximum values and a frequency histogram.

Due to the large number of elements measured by the pXRF (usually around 25), it is hard to identify trends in the multi-element dataset. Principal Components Analysis (PCA), a factor reduction technique, was used to reduce the number of variables for further analysis and to identify consistently correlated variables (Drennan, 2009; Jolliffe, 2014). PCA requires that there are assumptions made about the data used in the analysis (https://statistics.laerd.com/spss-tutorials/principal-components-analysis-pca-using-spss-statistics.php accessed on 17/04/17). These include that data should:

- be measured in continuous variables
- have a linear relationship
- have a large enough sample size
- be suitable for data reduction
- have no significant outliers

In most datasets, outliers would be removed before PCA is applied. While this may be suitable in many situations, in this case outliers and variance from the normal distribution are important and should not be removed, since correlation of only one single soil sample could provide evidence of archaeological activity. As a result, there is potential for this to influence the results of PCA. Another assumption is the need for linearity between datasets. In relation to the pXRF data, elemental variables will naturally have different bivariate relationships, and will lack linearity. So although this can limit the usefulness of the output components in explaining the variance of the dataset due to less linear correlations, it can still provide results that show which elements do have stronger linear correlations in comparison to others.

The PCA analysis was completed in SPSS Statistics Package 24, iterating 25 times on a varimax rotation to extract the top number of components based on Eigenvalues above 1. These components could then be used to explain the cumulative variance of the dataset, and from this, major quantitative relationships could be described: observing which elements have consistently higher or lower values in relationship with other elements.

While PCA is a well-used technique, it does have a number of limitations when it comes to dealing with spatial data (Demšar *et al.*, 2013). Therefore the initial PCA analysis was done with non-spatial data (using the analysis measurements only). These were graphically plotted against each other, usually components 1 and 2, representing the largest proportions of variance. After this the PCA analysis was re-run within Arc GIS with spatial attributes included to provide spatial maps of the distribution of PCA results alongside the graphical plots. These results were then used to distinguish different groupings of elements. These groupings were then evaluated with the spatial maps of particular elements to question whether variability originates from either geological, pedological or archaeological variations.

5.5.2 Geospatial Analysis and Visualisation

In this research, geospatial data is important for visualising, analysing and interpreting relationships between different data. It is a method that is inherently used within both archaeological and PF approaches. Using Arc GIS 10.5.1, all spatial data were input into a geodatabase, allowing many different types of data (both raster and vector) to be displayed and georeferenced.

Once compiled into Microsoft Excel, the pXRF data required spatial coordinates to be added from the pre-determined grid, as set out in the sampling design. After being merged, the table could then be directly imported and displayed in Arc Map. This process was the same for some raw yield data at Perdiswell Farm. In Arc Map, the point locations of soil analysis, or yield data, could be interpolated using a simple Inverse Distance Weighting (IDW) to estimate values in between known point values. This was used to produce topsoil maps, and at sites where enough samples from subsoil horizons existed, some interpolated depth maps were created. Other methods of interpolation exist, and have quite significant differences in their levels of accuracy, especially the use of kriging and evaluation of the semi-variogram as noted by (Kerry and Oliver, 2003; Oliver, 2010; Tamba, 2012; Salisbury, 2013). Due to the relatively high density sampling grid, and the cultivation mixing of the soils reducing meaningful interpretation below 10m resolution, it was decided that other more advanced interpolation methods would not be relevant in this analysis, instead retaining a simple approach was most suitable.

Various types of satellite imagery were collated throughout the DBA stages of each case study site. Depending on the source and the original format of the data, the processing flow and end images differ. Satellite images from the IPF Toolbox were input into Arc Map for display by converting them from KML files into layer files and preserving their original colour displays. For any analysis of the actual data, however, those KMLs had to be converted into raster data and had a default (blue/low-red/high) colour ramp applied to them to match the default colour scheme for the pXRF data. By converting them to raster data, it enabled a weighted sum analysis to be undertaken. This takes the value of every pixel, and calculates it in comparison to another pixel that is in exactly the same location but from a different image capture. Thus for averaging satellite data over a whole year, it was possible to use a number of images, weighting each pixel with a 1:1 weighting, and adding them all together. This produced a layer that contained elements of variation from all images originally added to the analysis.

The drone-based data, once processed into an orthorectified GEOTIFF image, could be displayed straight in Arc Map. The multispectral data, that produced individual images per wavelength band, required some calculations to be made while in Arc Map to produce the vegetation indexes required. The equations for working out the two most common vegetative indexes for plant health/variation, Normalised Difference Vegetative Index (NDVI) and Normalised Difference Red Edge Index (NDRE), are shown below:

$$NDVI = (NIR - Red) \div (NIR + Red)$$

$$NDRE = (NIR - Red\ edge) \div (NIR + Red\ edge)$$

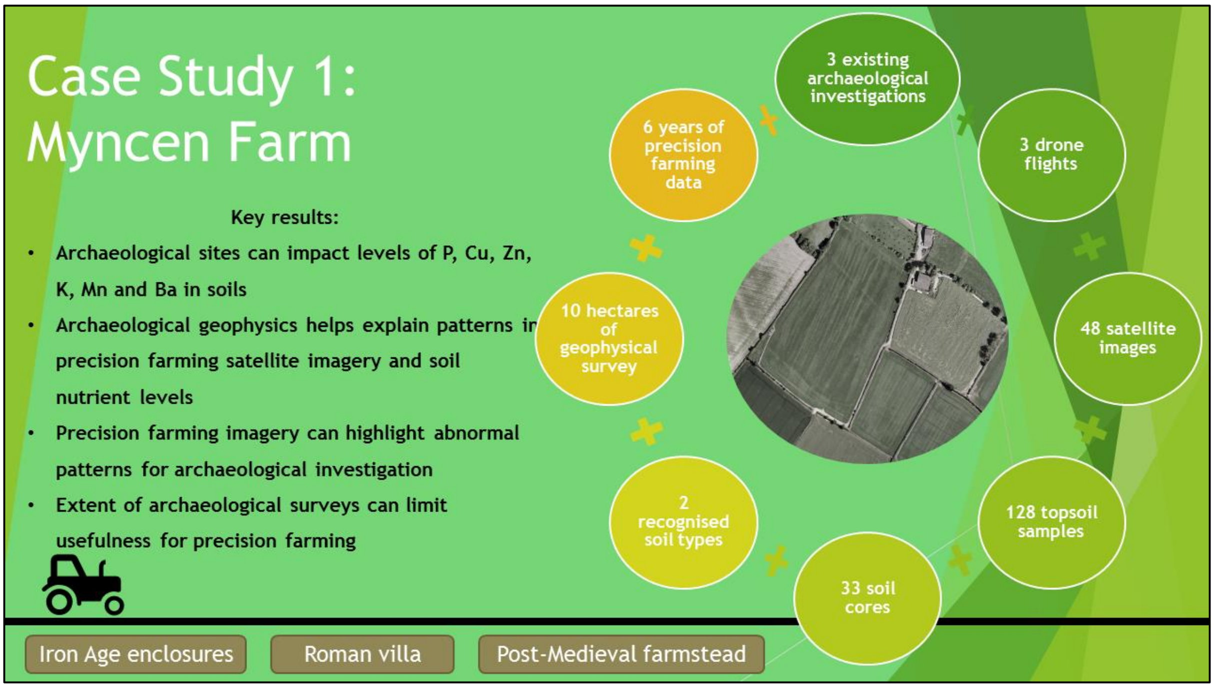
These were processed using the raster calculator tool in Arc Map to produce an image of each index that could then be visualised.

All visualisations of data analysed and created in Arc Map were contrast enhanced to two standard deviations, rather than minimum/maximum, unless otherwise stated. This enabled a consistent approach to be taken to many different datasets (with varying quantitative ranges) while providing better visualisation of the variation within a dataset.

Results

Chapter 6

6 Myncen Farm



Case Study 1:
Myncen Farm

Key results:

- Archaeological sites can impact levels of P, Cu, Zn, K, Mn and Ba in soils
- Archaeological geophysics helps explain patterns in precision farming satellite imagery and soil nutrient levels
- Precision farming imagery can highlight abnormal patterns for archaeological investigation
- Extent of archaeological surveys can limit usefulness for precision farming

3 existing archaeological investigations

3 drone flights

48 satellite images

128 topsoil samples

33 soil cores

2 recognised soil types

10 hectares of geophysical survey

6 years of precision farming data

Iron Age enclosures

Roman villa

Post-Medieval farmstead

Figure 20: Summary of data and results from Myncen Farm (© author)

6.1 Site Introduction

Myncen Farm, Minchington, in East Dorset is an average sized arable farm (104ha) that encompasses many common features of a family run farm in the UK. With a mix of small diversified businesses alongside the main arable enterprise; such as cider production and camping. The farm has been a host for numerous archaeological investigations in the past (Bournemouth University, the East Dorset Antiquarian Society and the Time Team) and been using PF approaches for seven years.

6.1.1 Location

Myncen Farm is 6km SW of Sixpenny Handley, in East Dorset, and lies S of the well-known landscape of Cranborne Chase (NGR- ST 96891431). The farm consists of one ringfenced block of land, with two fields considered within the study area, ‘Mushroom Ground’ and ‘Middle Long Ground Top’ (MLG Top) (Figure 21).

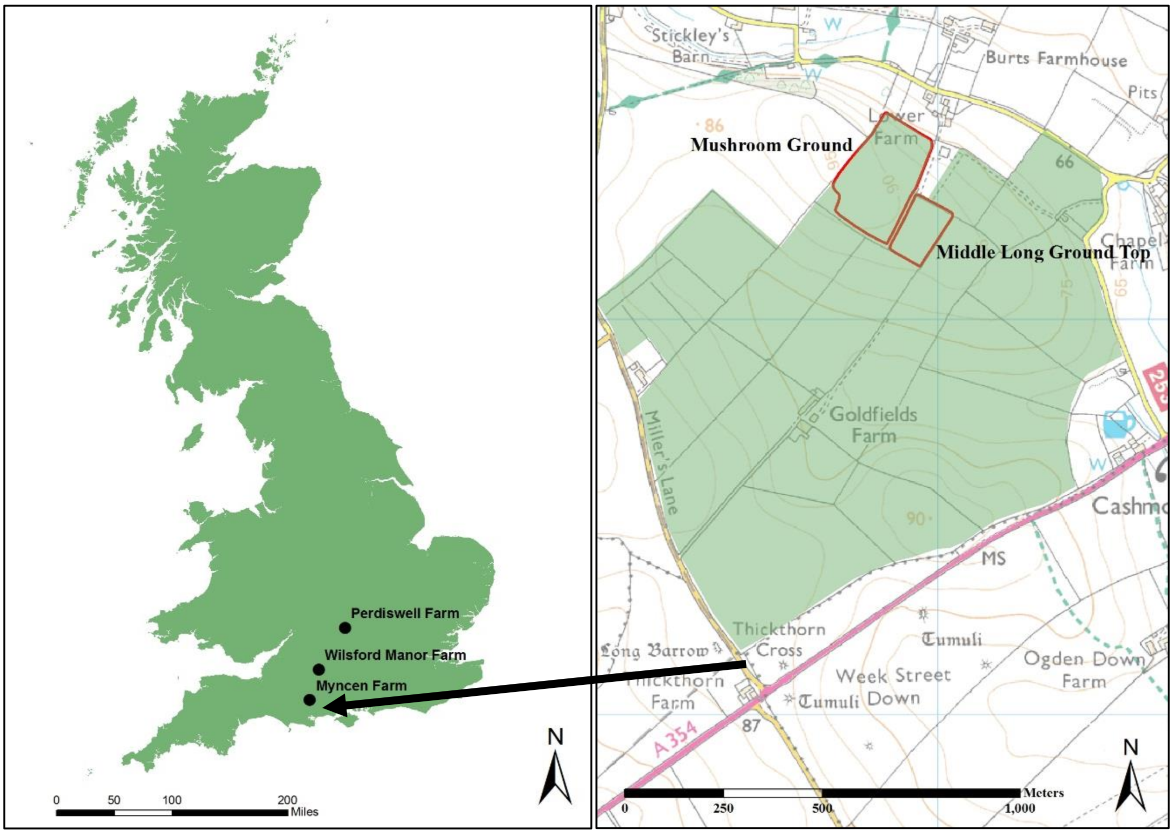


Figure 21: Geographical location of the site, Myncen Farm, with the farm boundary outlined in green, and the fields included in the study area outlined in red

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6.1.2 Geology

The study area lies upon the Upper Chalk Formation that stretches across England. The farm in particular, overlies the boundary between Newhaven and Seaford Chalk Formations (Figure 22) (British Geological Survey 2015). The superficial deposits in the area range from peat deposits and alluvium in the river valley floors, to areas of CwF on higher ground.

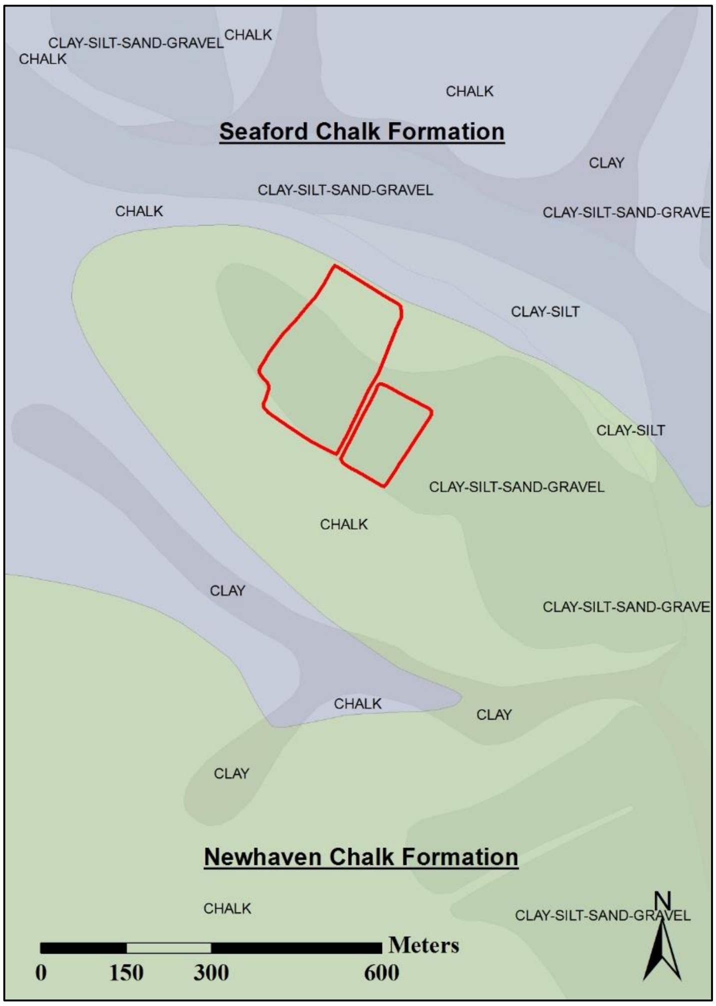

Figure 22: Solid geology and superficial deposits for the study area at Myncen Farm

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6.1.3 Topography

The topography of the study area varies from 94m AOD down to 86m AOD and is on a prominent spur in the undulating chalky landscape (Figure 23). The site overlooks the Gussage valley to the N and E, and also slopes gently eastwards to Cashmoor and the A345.

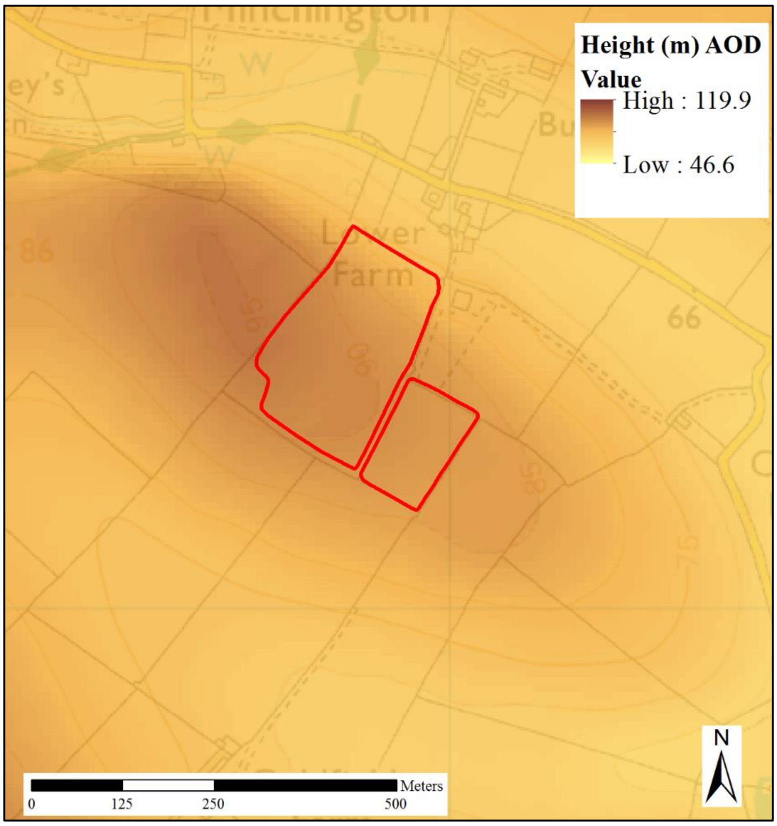

Figure 23: shows location of study area on a Digital Terrain Model (DTM).

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6.1.4 Soils

The soils of the case study area are dominated by the Andover 1 association (343h), described as shallow, well drained calcareous silty soils over chalk, on slopes and crests, with deeper calcareous soils and non-calcareous fine silty soils in valley bottoms (National Soil Resources Institute, 2018a). The deposit on the higher ground running NW-SE is mapped as CwF. This type of clay deposit with flint inclusions is a Quaternary deposit thought to be formed from the dissolution of Late Cretaceous Chalk, leaving behind the insoluble flints, fine clays, some sands and gravels from other sources. They are usually reddish/orange coloured clays, inter-mixed with larger grain sizes (sometimes sandstone pebbles and quartz) and unworn flints. The mineralogy is a mixture of clay, mica, feldspar and quartz and the general soil texture here is a medium loamy clay (http://mapapps2.bgs.ac.uk/geoindex/home.html accessed on 25 September 2015).

6.2 Agricultural and PF Background

6.2.1 The Farm

The farm is managed by Simon Meaden, and his family, the mixed farm covers 104ha in total, the majority of the land being used for arable crop production and only a few hectares of grassland. Livestock have been managed on the farm in the past, but have not been part of the farming operation for decades, other than occasional grazing of neighbouring stock and use of organic manures from local farms. The farm, as well as diversifying into cider production, also run mini-festivals, shepherd’s hut style camping, and have a replica Iron Age round house.

6.2.2 Cropping and Fertiliser

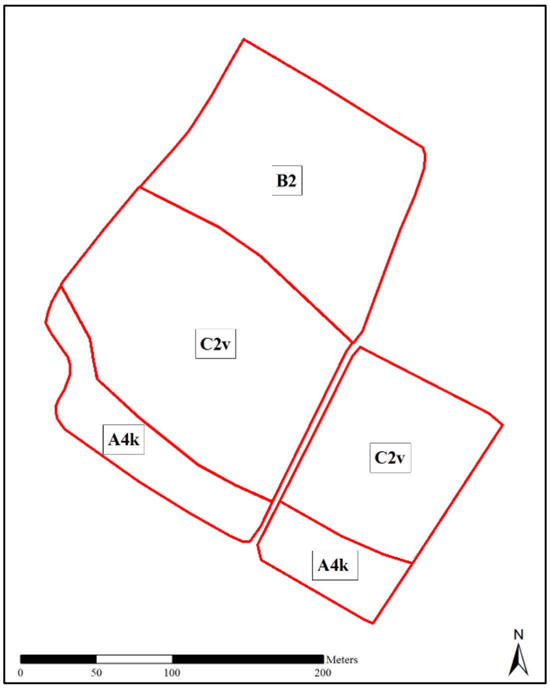
The standard rotation for the farm at present consists of oilseed rape, wheat and spring barley. Annual fertiliser requirements for each crop are planned, using a combination of organic manures (whenever possible), and conventional manufactured fertilisers to ensure levels of nutrients and pH are maintained. Organic manures used vary from year to year depending on availability of poultry litter, cow manure or bio-solids, but all have been used in the past (bio-solids were applied in 2013 and 2016). Fertiliser application is usually on a whole-field basis. Some manufactured straight (containing a single nutrient) fertilisers are applied on a specific zone of a field if soil testing determines that zone is low. The application of manufactured fertilisers is made by a disc spreader that is not fitted with variable rate technology. The application of organic materials is usually via a muck spreader, again with no ability for automatic variable rate. The farm’s combine harvester does not have a yield monitor and so no yield maps are available for the farm.

6.2.3 Cultivations

The cultivations on the farm for the last 5-7 years have consisted mainly of minimal tillage approaches. This means that the fields have not been ploughed (inversion tillage) for a number of years but certainly have been ploughed regularly throughout the last century.

6.2.4 PF

The farm has been using the company Intelligent Precision Farming (IPF), based in Swindon, Wiltshire, for their PF services since 2012/2013. The farm decided to take a desk-based soil zoning approach to divide fields into soil management zones. This did not involve soil scientist evaluation in the field to physically inspect soils, but instead a collation of farmer knowledge, along with satellite imagery of bare soils, and historic imagery, to determine major soil management zones (Figure 24). Since starting in 2012/2013, the farm has input cropping records for each field into the PF software called ‘the Toolbox’. The Toolbox also holds the major records for fertiliser applications since 2012, the field names, the field boundaries and the soil zone boundaries along with soil nutrient information.



IPF Soil Zone Codes
A4k = Shallow soil over chalk, heavy textured, calcareous

B2 = Deeper calcareous soils overlying chalk or chalky drift, medium textured.

C2v = Non-calcareous soils, medium texture, very stony.

Figure 24: Result of the PF soil zoning process for Mushroom Ground and MLG Top (courtesy IPF UK)

The farm has concentrated on using PF techniques that suit the individual circumstances of the farm, both agronomically, economically and socially. For the farm, the benefits of investing in the Toolbox software are for recording purposes and complying with policies like farm assurance schemes or other nutrient related rules that are essential for selling outputs and complying with legislation, rather than for yield mapping and variable rate fertilisation. In addition it provides a historic repository for spatial data such as soil sampling (last completed in 2016, and 2013 before that) and satellite imagery.

Another substantial part of the Toolbox is to provide satellite imagery to the farmer and agronomist. The ‘EyeCrop’ service provides a mixture of satellite imagery (NDVI, CHL and SOB) allowing the farmer and agronomist to look quickly over the farm, identifying areas of good or poor growth and physically inspect certain areas if necessary. This can save time and allow more accurate recommendations of fertiliser in specific areas due to specific growth in that crop.

Total number of satellite images	**48**
NDVI	26
NDVI Early	14
SOB	2
CHL	6
Average number of images per year	**12**
Total number of reliable images	**27**
Number of reliable images per year	**7**

Table 5: Number of satellite images gathered at Myncen Farm from 2013 until August 2017, broken down into types of image, and useful images (images without cloud effect)

6.3 Archaeological Background

Myncen Farm, as a whole, has had extensive archaeological evaluations carried out over the past 20 years and it represents another part of the rich archaeological landscape surrounding north Dorset and Cranborne Chase. The predominantly chalk-based landscapes have hosted the evidence for Britain’s most important and studied prehistoric sites from the Dorset Cursus to Hambledon Hill (Green, 2000). The area has been subject to many archaeological investigations from pioneering British archaeologists such as Colt Hoare (1812) and Augustus Lane-Fox (later General Pitt-Rivers) (1887, 1888, 1892, 1898 as cited in (Wickstead and Barber, 2010)).

6.3.1 20th Century Work

The first investigation of archaeological remains at Myncen Farm began after a brief episode of ploughing in a field named Maidments Meadow (Figure 25) in 1986. This inversion of the soil revealed numerous concentrations of building material, indicative of some sort of underlying structure (Sparey-Green, 1996). With the involvement of the East Dorset Antiquarian Society, and a team from Bournemouth University, a survey was completed and some initial archaeological excavations carried out. These investigations ran from 1996-2001 (Sparey-Green, 1996, 2007).

Initial test pits focused on Maidments Meadow. These investigations resulted in a number of areas of activity, some post-Medieval remains of cottages known as Maidments Cottages, metal finds including Roman coins and a substantial Roman building in the SE of the field. Geophysics within this field using magnetic gradiometry did not report any archaeologically significant results and therefore work focussed on mapping the substantial Roman building by extensive test pits (Sparey-Green, 1996, 2007). Excavations revealed a substantial building range, including a number of intact and disturbed mosaic floors, hypocaust systems within a less conventional villa layout for a site containing such high status decorations. Dating evidence from the excavations suggests a mainly late-Roman period of occupation. Some early-Roman evidence exists as well as potential Iron Age features underlying the building. Post-holes in the middle of one mosaic floor suggests re-use of the buildings after Roman activity on the site (Sparey-Green, 2007).

Other investigations lead by Bournemouth University surveyed the field named East Long Ground. In 1996, some magnetic gradiometry was completed over the field identifying a single ring ditch, a number of linear and curvilinear ditches as well as areas of pits, a possible settlement area and a possible Neolithic mortuary enclosure (Barrett *et al.*, 1991; Hewitt, 1998; Hewitt and Rumsey, 1999). The Neolithic mortuary enclosure, after excavation was exposed as probably a Romano-British rectangular house structure with evident post-holes.

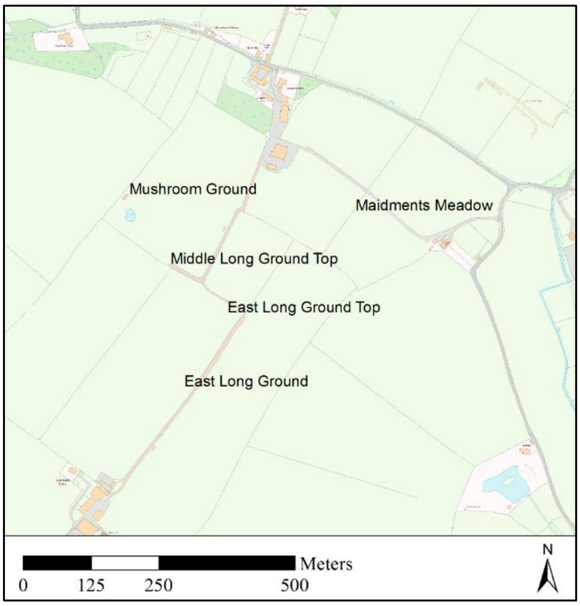


Figure 25: Names of fields at Myncen Farm that have had archaeological investigation

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6.3.2 21st Century Work

Further work continued in 2003 when the site was investigated by the Time Team, along with Bournemouth University and the East Dorset Antiquarian Society (Wessex Archaeology, 2004; Sparey-Green, 2007). The main aims being to enhance the knowledge of the grave groups near Goldfields Farm in East Long Ground, investigate the ring ditch and clarify further the Roman buildings in Maidments Meadow. At the same time more geophysical surveys (Figure 26) covered a number of other areas and specifically concentrated on trying to link the two sites at East Long Ground and Maidments Meadow. Results showed many similar features to what was known previously, one linear ditch seems to run between the two sites but is not continuous or consistent in nature.

Figure 26: Ten hectares of geophysical survey over Myncen Farm gathered by Bournemouth University and GSB from 1996-2012 (courtesy of GSB and Bournemouth University)

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Further excavations over the Roman buildings produced a bath complex with a plunge pool and evidence of mosaic floors within a total of five rooms (Wessex Archaeology 2004). Investigation into the ring ditch in East Long Ground yielded a small amount of evidence of Middle to Late Bronze Age material, however, little other evidence showed further Bronze Age activity. The grave group that totalled 11 probable graves is interpreted as being of a small (extended) family group using the cemetery over a relatively short period of time and date to the late Romano-British period. Further burials nearer the ring ditch were also of similar date. The burials appear to be of a fairly typical small, rural settlement and perhaps formed part of an agrarian community in comparison to the Roman buildings at Myncen Farm which do not have any evidence of agricultural activity or storage. The number of burials is unlikely to represent the whole community of late Iron Age through to late Romano-British period leading to the assumption that further pockets of burials remain unfound (Wessex Archaeology 2004:18).

6.3.3 The Fields: Mushroom Ground and Middle Long Ground Top

The most recent addition, and the most relevant for this case study area, to the Myncen Farm landscape was recorded by aerial photograph in 2005, although the site was certainly photographed earlier than this date but perhaps was not recognised (Wickstead and Barber, 2010). It comprises a cropmark of an enclosure measuring 365 metres by 165 metres and with an area of approximately 5.5 hectares in total. The ditches of the large enclosure on the N and S sides are visible in various satellite images and aerial photographs (Figure 27) and also crosses four modern field boundaries. A rescue excavation took place while a pond was being dug by the Simon Meaden in the field named Mushroom Ground, courtesy of Helen Wickstead who reported the findings in a short report (Wickstead and Barber, 2010). This provided some detail on the southern ditch of the enclosure, being 3.95m wide and 1.91m deep and ‘v’ shaped. There appeared to be three major fills representing the silting up of the ditch but no discernible dating evidence was found to identify the age of this enclosure.

Figure 27: Satellite image from 2009 showing the ditch of the larger enclosure first recorded in 2005 (© Google)

Later in 2012, Bournemouth University completed a magnetic gradiometry survey within and to the SE of the enclosure to gain information about any features lying within it (Figure 28). The results concluded that there was little evidence of activity in the larger enclosure, but a smaller enclosure, interpreted as an Iron Age 'banjo' enclosure, to the SE of the site was further evidence of occupation on the site.

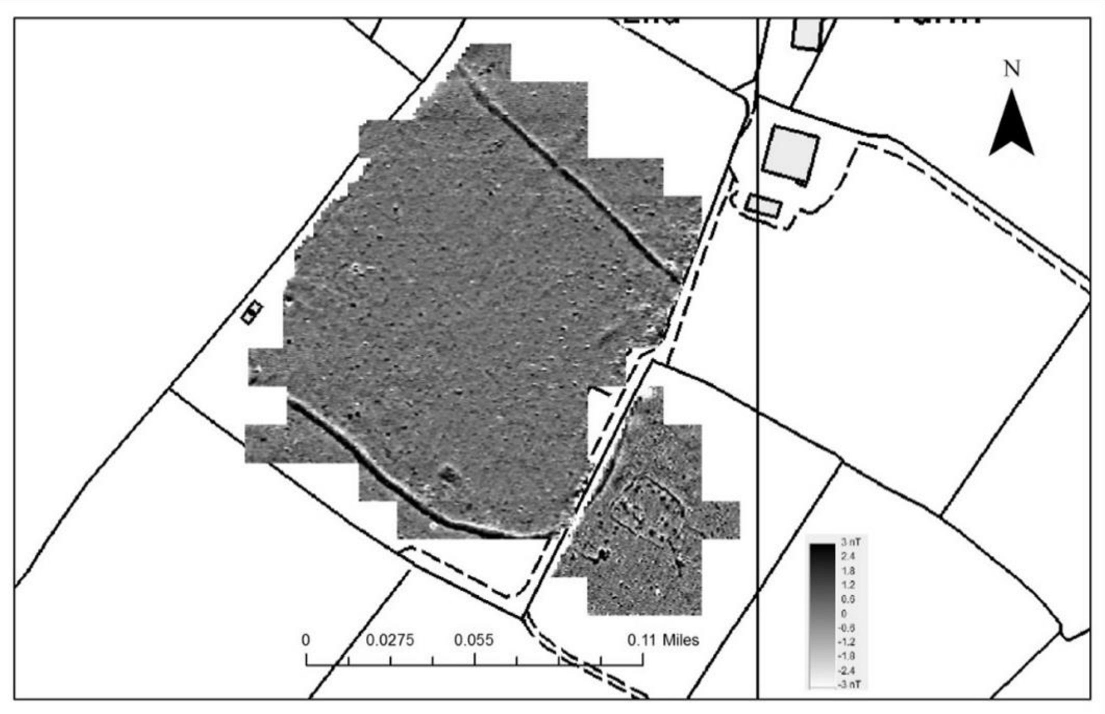


Figure 28: Results of the magnetic gradiometer survey by Bournemouth University in 2012 (Courtesy of Bournemouth University)

The archaeological sources show that the wider landscape surrounding the study area has successive periods of archaeological activity, especially of burials, small isolated agrarian settlement and more significant Roman occupation. The study area itself contains an Iron Age enclosure and a larger enclosure with seemingly little physical evidence of use and of unknown date.

6.4 Fieldwork Results

Here the results of the targeted soil sampling and coring will be discussed in advance of presenting results of how various archaeological datasets fit into a PF context. Although soil coring and geochemical analysis could be part of an archaeological data at a site, this is infrequently the case and therefore this data will be dealt with separately to the genuine archaeological data collected as part of existing investigations into the site (Section 6.5).

6.4.1 Soil Geochemistry

At Myncen Farm, across both fields in the study area, 234 soil samples were taken from 33 cores and 128 topsoil samples (Figure 29). These samples were analysed by pXRF and a total of 21 elements were detected, having discarded elements that were below the limit of detection of the instrument. Copper although being intermittently below the level of detection, was retained due its potential to link to archaeological activities, but caution should be taken when interpreting this element.

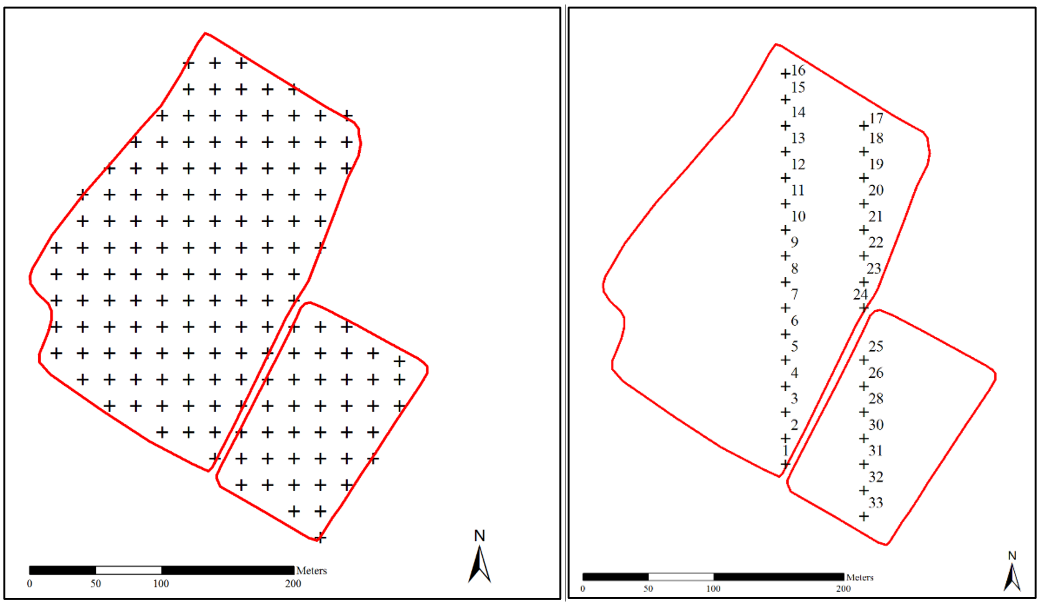


Figure 29: Topsoil sampling locations based on a 20m systematic grid (left) and cores (right) (© author)

The principal components analysis, concluded three components cumulatively summing to 77.0% of the total variance. The first component making 61.1% and the second component making up 10.1% of the total variance in the dataset. These two most significant components were plotted against each other (Figure 30) to show the initial elemental correlations across all samples (topsoil, subsoil and bedrock). From both this graph, and the graphs showing the elemental loadings for each of the three principal components (Figures 30 and 31) it is clear that there is a very strong correlation between Ca and Sr (group A), with a secondary, equally as strong, correlation between a large group of elements (group B). A third, more subtle group (C), contains Zn, Mn, As and Pb, with elements P, S, Ba and Cu distributed widely in the middle of the graph with no particularly strong correlations to other elements.

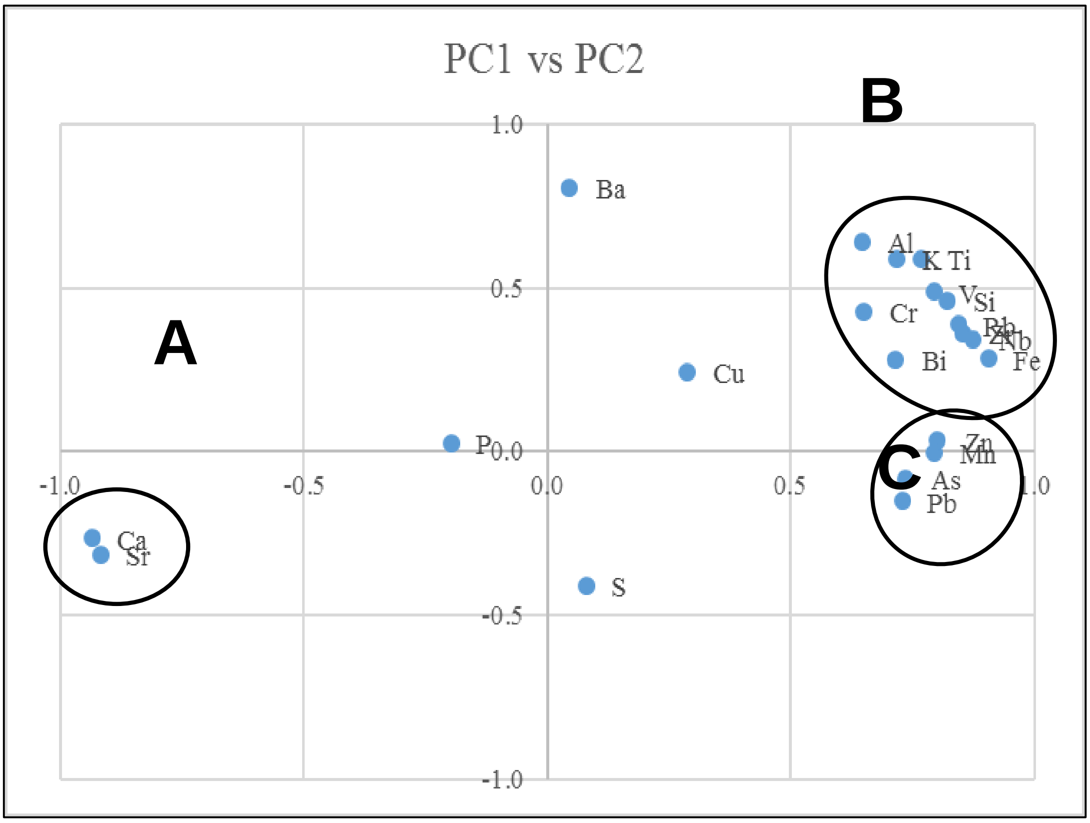


Figure 30: Graph plotting the value of principal component 1 against component 2 for each element detected by pXRF (© author)

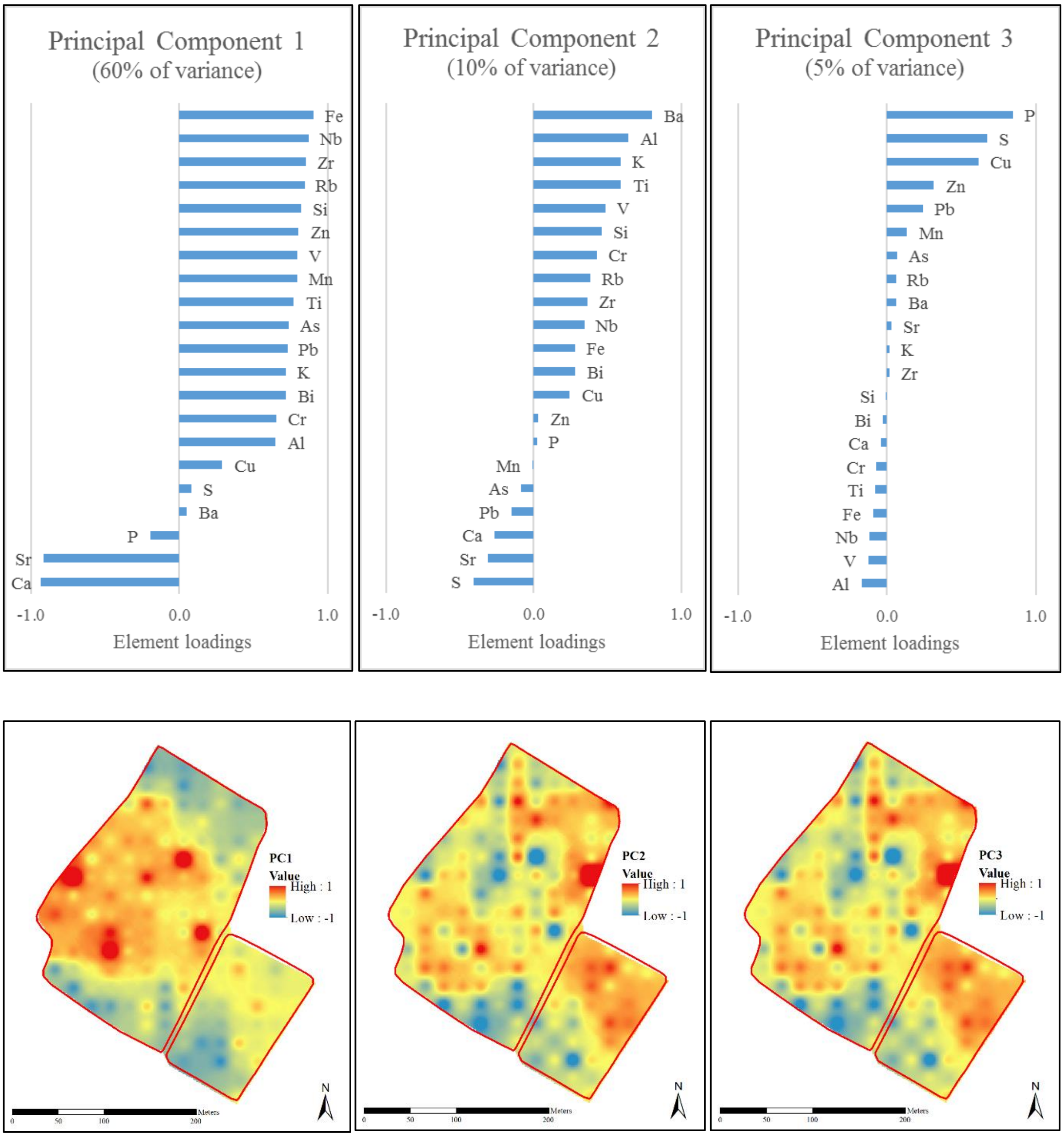


Figure 31: Elemental loadings of each principal component (top), with the corresponding spatial representation of those components across the two fields (bottom) (© author)

Groups A and B explain the most significant differences between the two soil types found on the case study site, as shown on the geological map (Figure 22). With Ca and Sr both correlating with the shallower chalk-based soils. In contrast the CwF-based soils, as is normally expected with clay-rich soils, are correlated with a range of other elements such as Al, Si, Fe and Rb (group B). Both these distributions can be seen most clearly on the map of PC1. The graphs of PC2 and PC3 show less contrasting loadings, but still a similar grouping of elements from the positive to the negative. The elements that are much more variable (P, S, Ba, Cu), do not have strong relationships with either of the background soils.

This initial analysis provides a useful and clear division between the two soil types on the site. These strong relationships, especially strong between Ca and Fe, can be mapped spatially to provide a clear view of where the boundaries between the two soil types lie in comparison to the existing datasets such as the geophysical survey and the established PF soil zones (Figure 32). From this it seems the PF soil zones are slightly misplaced in comparison to the geological mapping, topography, and interestingly the archaeological ditch that defines the larger enclosure. The smaller Iron Age enclosure incidentally lies on the boundary between the Ca and Fe soils, rather than clearly within the 'C2v' PF soil zone. Although Ca and Fe could both differ due to archaeological activities, it is very unlikely that any archaeologically caused variation would create differences in comparison to the total concentrations within these soils.

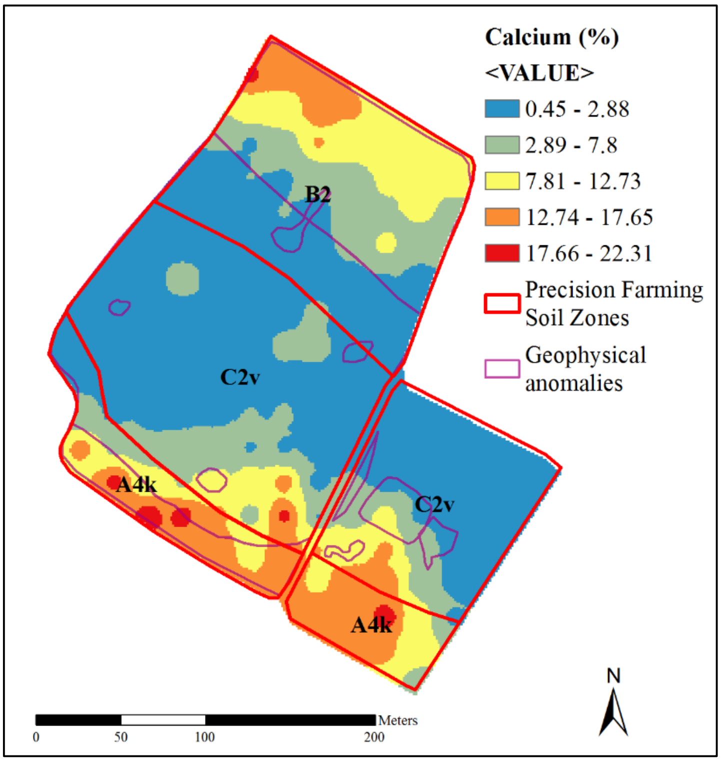
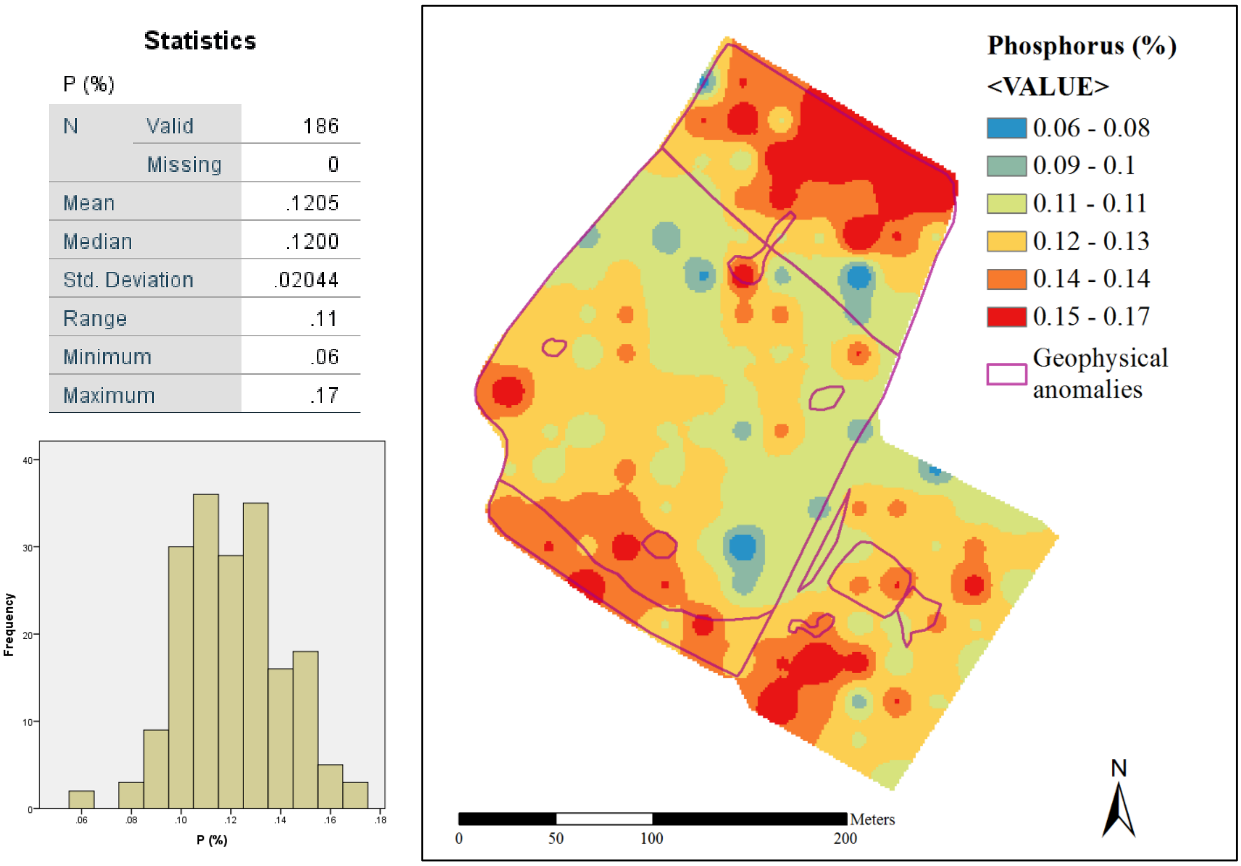


Figure 32: Variation of calcium overlaid with the PF soil zones, and the geophysical anomalies (© author)

Moving to elements that lie uncorrelated to any of the existing elemental groups (and therefore potentially of archaeological interest), there is an enhancement of P to the N and S of the site. Both these areas correspond well with the chalk-based soils on the slopes, but do not always match in the intensity in comparison to the intensity of Ca. For example in the N, Ca is highest to the NW, whereas the high P levels are in the N to NE. This is again shown in Figure 30 and 31 which demonstrates P is more closely linked to Ca and Sr than other elements, but still somewhat different in intensity. Within the main enclosure in Mushroom Ground, it was anticipated that there may have been some P variation due to the use of this enclosure, not necessarily from human habitation due to the lack of any evidence for this, but from livestock use. Yet there seems to be very little, other than a small elevated level that aligns with a geophysical anomaly by an entrance to the enclosure shown in the geophysical data (Figure 33).



Statistics

P (%)

N	Valid	186
	Missing	0
Mean		.1205
Median		.1200
Std. Deviation		.02044
Range		.11
Minimum		.06
Maximum		.17

Figure 33: Basic statistics for P in the topsoil (left top), frequency histogram (left bottom) and map of P variation in relation to magnetic anomalies (right) (© author)

The Iron Age enclosure in MLG Top has a slightly more complicated elemental background. Figure 32 shows the Ca boundary spur out northwards into this enclosure, meaning that this enclosure sits on the boundary between the underlying chalk geology and the superficial CwF deposit. Due to the areas with high Ca/Sr generally being higher in P (average of 0.128%) in comparison to the Fe/Rb areas (average P values of 0.112%) this makes interpretation of whether there is any P enhancement difficult. There is certainly no significant enhancement, but the enclosure is also relatively small (30x25m) with only two or three topsoil sampling points within the enclosure. Therefore some additional, nested sampling was undertaken to confirm this (Figure 34). A further 25 samples, taken randomly from the area of the enclosure, showed that this enclosed area does have a higher average than the chalk-based soils, and the CwF, with an average of 0.136%. While this is quantifiable difference, it is not a significant difference amongst the wider variation. The lack of geophysical evidence hampers any possible archaeological explanations to the other high spots of P in the field.

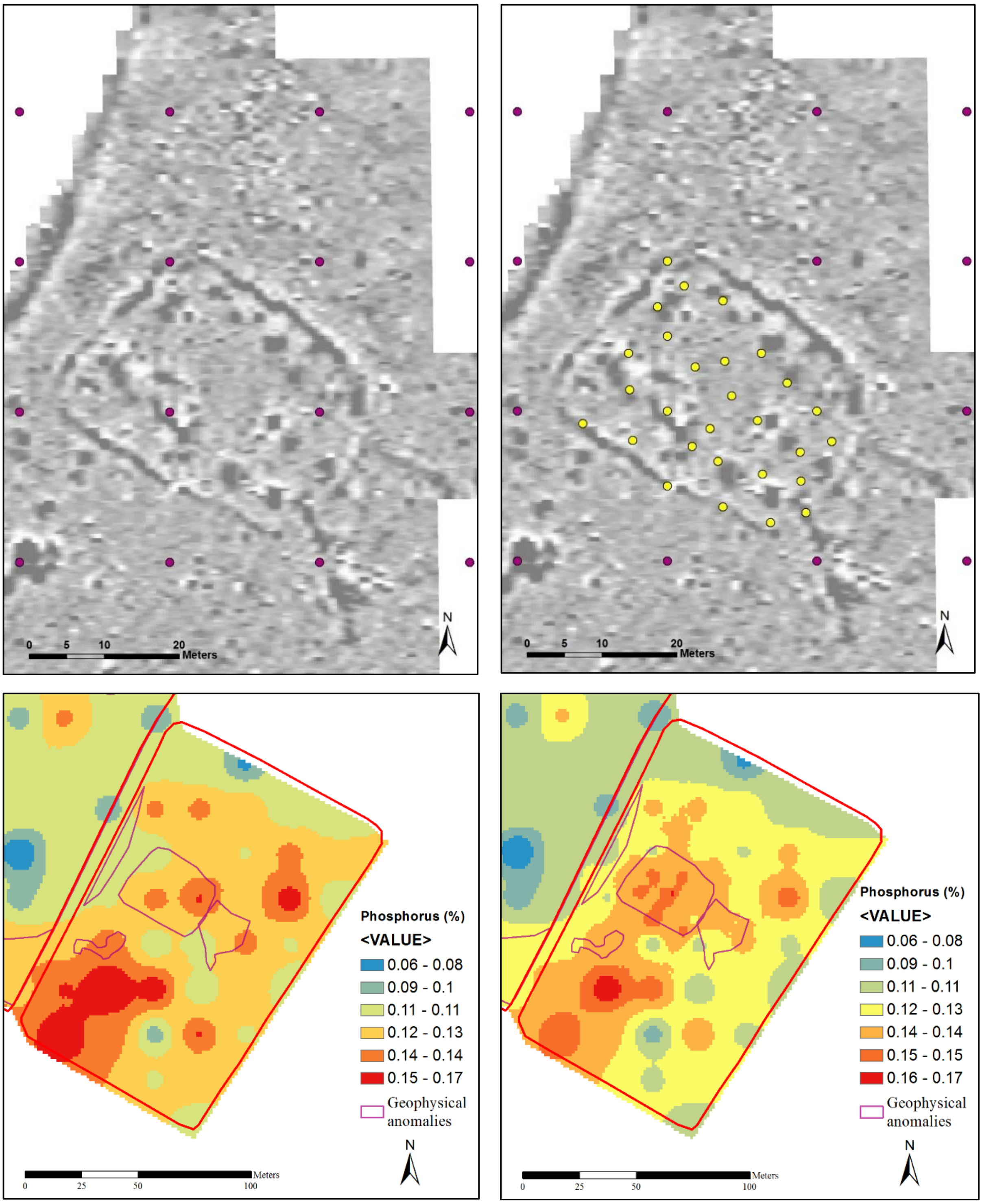


Figure 34: 20m grid sampling and P map (left top and bottom) and random nested sampling and P map (right top and bottom)

Ba values are slightly above average for the area according to the 5km^2 National Soil Inventory (NSI) (135ppm), most likely due to its agricultural use through phosphate fertilisers particularly, but also possibly from affiliations with mineralogy (Kabata-Pendias, 2011: p.143), but shows little variation (Figure 35) associated with the geological background. There are a number of anomalously high areas (>250ppm), that sit on the higher ground, within the CwF deposits. These do not show any variation that is interpretable as archaeological variation or that are at levels of significance for agricultural production.

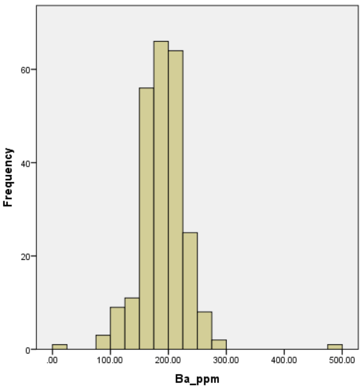
Cu was not reliably detected across the whole study area. Where levels of Cu were detected, the variability was similar to Ba, with more consistent detection within the CwF deposits in comparison to the chalk-based soils (Figure 36). In the CwF soils, there were isolated high values, running across both fields (notably in the NE of MLG Top and at an entrance to the larger enclosure), but few in relation to any known geophysical anomalies, or other visible soil changes.

The S distribution across the site (Figure 37) shows a similar variation to the general geological background, with little that distinguishes it apart from one very high value in the NE of the study area. Concentrations are slightly lower on top of the ridge, the CwF soils, running across both fields. The range of values is quite large (125-1471ppm), with low values on the CwF soils, and higher values downslope on the chalk-based soils. The majority of S in soils (95%) is bonded to organic compounds, with only a small fraction available to plants (Eriksen *et al.*, 1998). Soils with higher concentrations of organic compounds, possibly in conjunction with colluvial build-up downslope (such as the chalk-based soils in the case study area) are therefore likely to have higher S values. Considering the growing agronomic interest in applying S as a fertiliser (Section 2.3.4) this variation in total S could be relevant if the variability of plant available S, and the dynamics of S supply, correlate with the total S content.

Statistics

Ba_ppm

N	Valid	246
	Missing	0
Mean		189.8165
Median		189.2500
Std. Deviation		40.15338
Range		476.18
Minimum		.00
Maximum		476.18



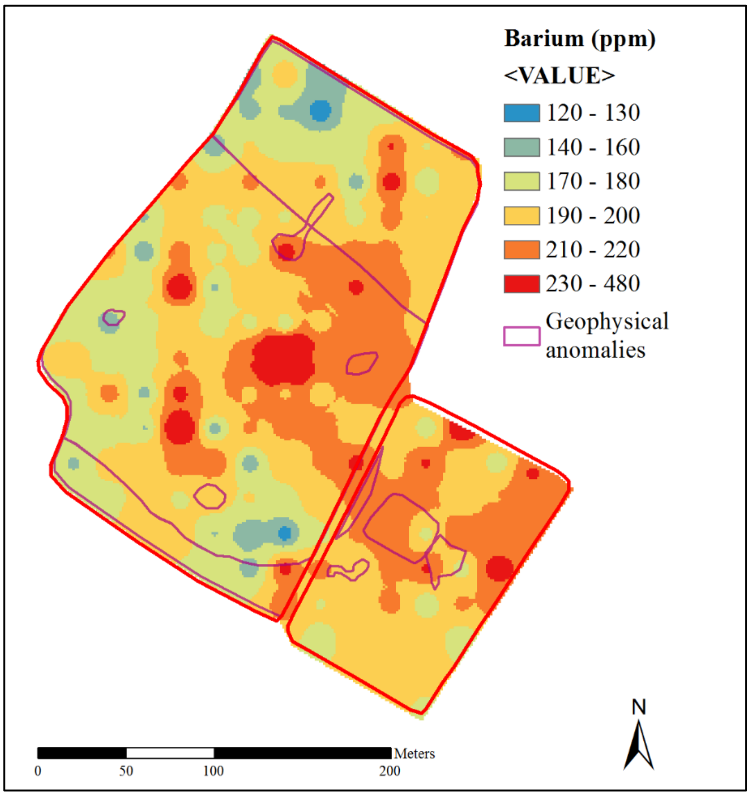
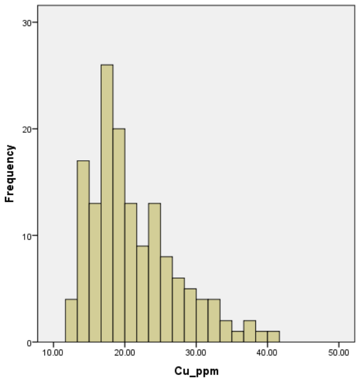


Figure 35: Basic statistics for Ba in the topsoil (left top), frequency histogram (left bottom) and map of Ba variation in relation to magnetic anomalies (right) (© author)

Statistics

Cu_ppm

N	Valid	149
	Missing	97
Mean		21.2056
Median		19.3100
Std. Deviation		6.08192
Range		27.73
Minimum		12.40
Maximum		40.13



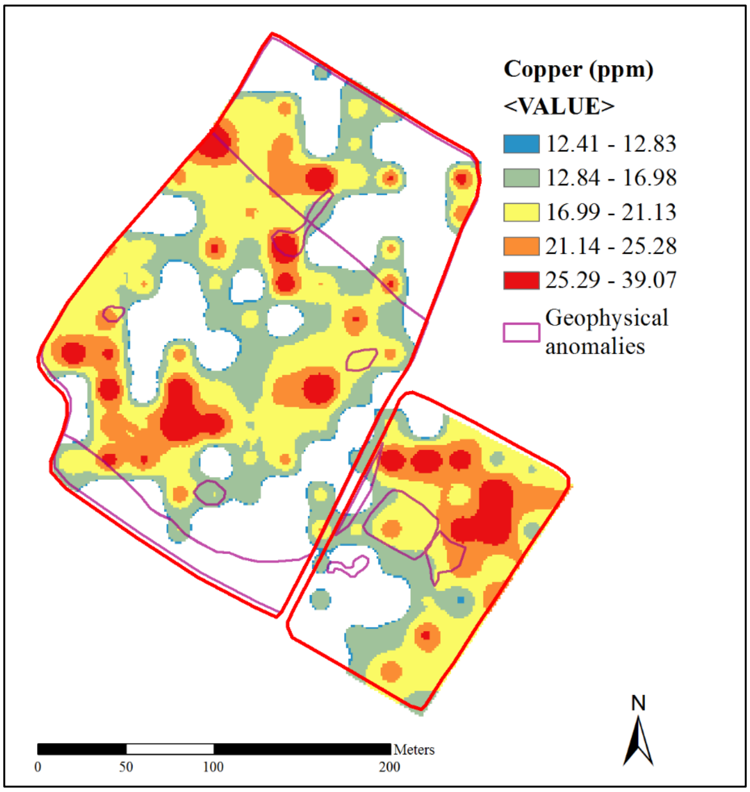
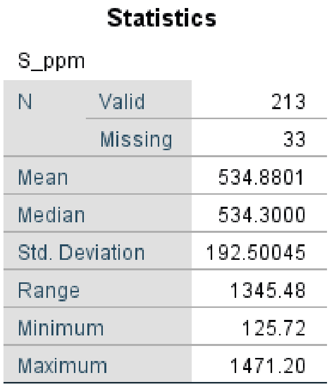


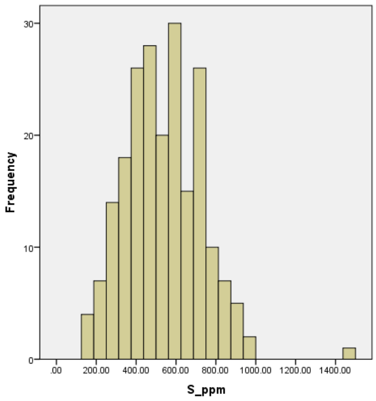
Figure 36: Basic statistics for Cu in the topsoil (left top), frequency histogram (left bottom) and map of Cu variation in relation to magnetic anomalies (right) (© author)



Statistics

S_ppm

N	Valid	213
	Missing	33
Mean		534.8801
Median		534.3000
Std. Deviation		192.50045
Range		1345.48
Minimum		125.72
Maximum		1471.20



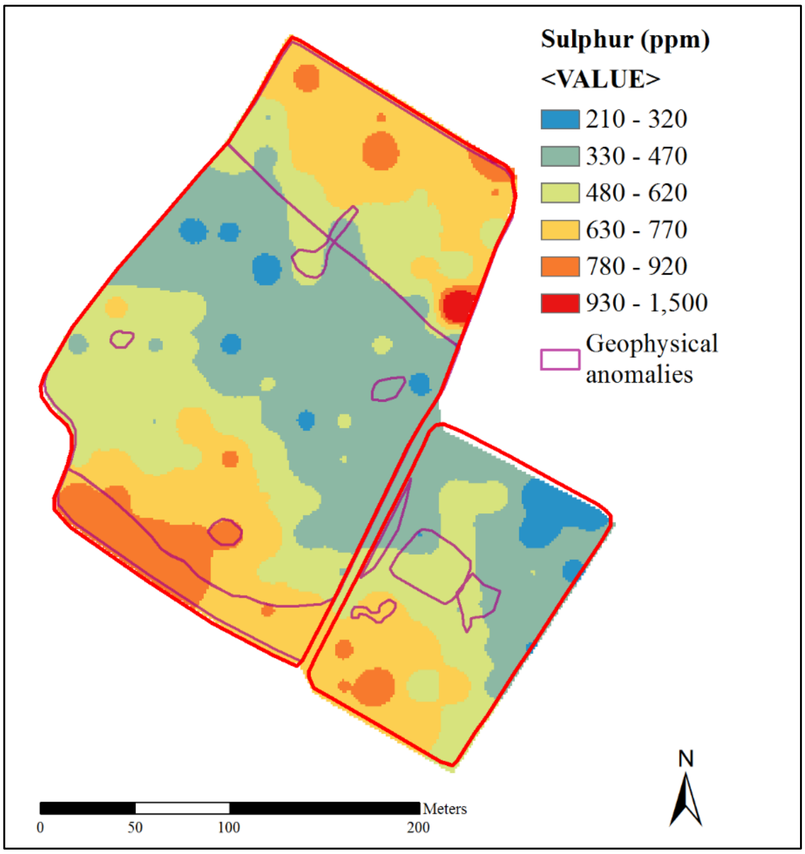


Figure 37: Basic statistics for S in the topsoil (left top), frequency histogram (left bottom) and map of S variation in relation to magnetic anomalies (right) (© author)

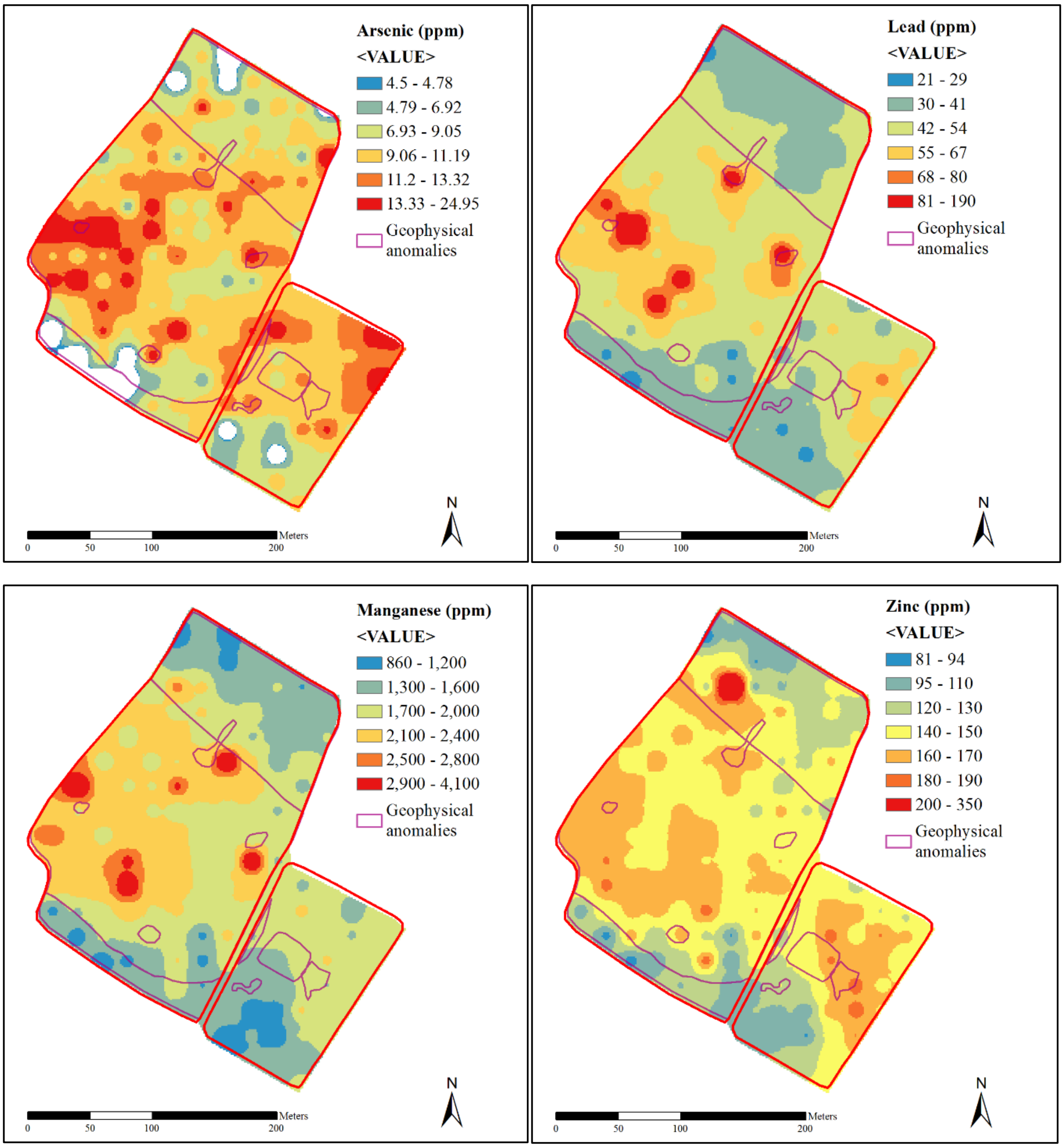
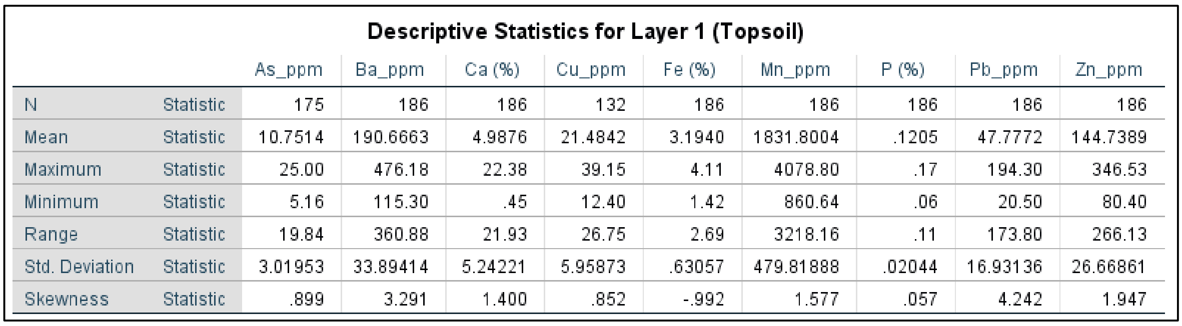


Figure 38: Map of As (top left), Pb (top right), Mn (bottom left) and Zn (bottom right) variation in the topsoil (© author)

Group C, the other significant group of elements not relating to either Ca/Sr or Fe/Rb soils, is made up of As, Pb, Mn and Zn. These are elements that have been known to appear in archaeological deposits for a number of reasons (Section 3.1.6). Figure 38 shows that all four elements share some similar variations. Across all four maps, the general trend is for higher values in the CwF soils on higher ground (except one high Zn value), with lower values, or < LOD, at each slope. Within this trend, there are sharp isolated anomalies that generally occur in the larger enclosure (Mn and Pb). The sharp isolated values are certainly above soil levels indicated by the NSI baseline (As=7.9, Pb=33, Zn=60, Mn=1100). Three of the Pb anomalies are within 5m of separate geophysical anomalies. The Mn anomalies are very similar in distribution, however, not exactly related to the same topsoil samples interestingly. The cause of these high values is not discernible from any spatial relationship to soil changes or archaeological anomalies detected by the geophysical, aerial or satellite surveys. It is therefore likely that these are points of contamination from a very isolated activity, but unlikely to be caused by land use relating to the ditched enclosure.

The As values are interesting since they indicate a broader spread than the other elements. Two areas, the W quarter of the large enclosure and the E corner of MLG Top, have equally elevated levels of As within the topsoil. This distribution is broadly similar to the Cu variations, especially in the E side of the study area. A geological explanation is unlikely, given the variation does not relate to geological patterns, but an archaeological explanation is not possible, without further work to determine the origin of these enhancements.

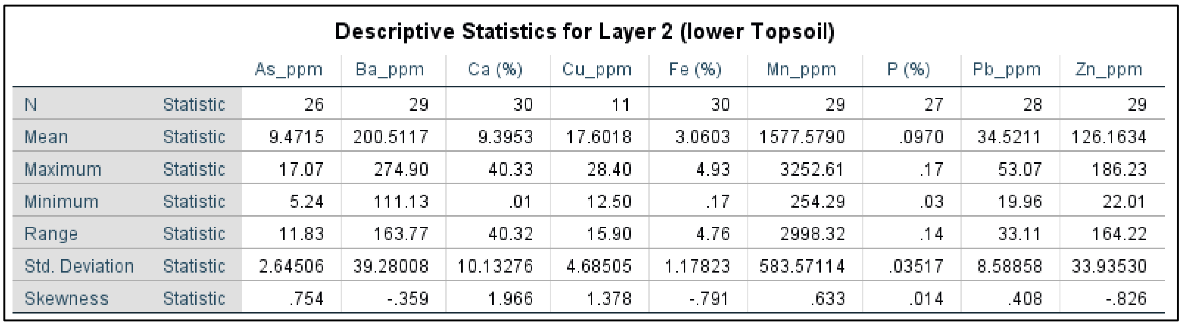
The subsoil sampling was grouped into layer sequences that represent approximately similar stratigraphic horizons, enabling a comparison between the major vertical variations in the soils across the study area (rather than particular cores). The average differences between the topsoil layer one, two and three are summarised in Tables 6, 7 and 8.



Descriptive Statistics for Layer 1 (Topsoil)

		As_ppm	Ba_ppm	Ca (%)	Cu_ppm	Fe (%)	Mn_ppm	P (%)	Pb_ppm	Zn_ppm
N	Statistic	175	186	186	132	186	186	186	186	186
Mean	Statistic	10.7514	190.6663	4.9876	21.4842	3.1940	1831.8004	.1205	47.7772	144.7389
Maximum	Statistic	25.00	476.18	22.38	39.15	4.11	4078.80	.17	194.30	346.53
Minimum	Statistic	5.16	115.30	.45	12.40	1.42	860.64	.06	20.50	80.40
Range	Statistic	19.84	360.88	21.93	26.75	2.69	3218.16	.11	173.80	266.13
Std. Deviation	Statistic	3.01953	33.89414	5.24221	5.95873	.63057	479.81888	.02044	16.93136	26.66861
Skewness	Statistic	.899	3.291	1.400	.852	-.992	1.577	.057	4.242	1.947

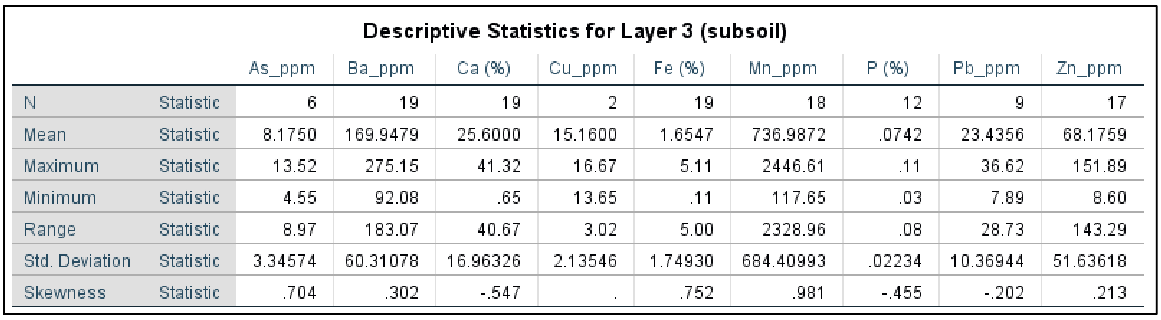
Table 6: Statistics for As, Ba, Ca, Cu, Fe, Mn, P, Pb and Zn in the topsoil (approximately 0-15cm) (© author)



Descriptive Statistics for Layer 2 (lower Topsoil)

		As_ppm	Ba_ppm	Ca (%)	Cu_ppm	Fe (%)	Mn_ppm	P (%)	Pb_ppm	Zn_ppm
N	Statistic	26	29	30	11	30	29	27	28	29
Mean	Statistic	9.4715	200.5117	9.3953	17.6018	3.0603	1577.5790	.0970	34.5211	126.1634
Maximum	Statistic	17.07	274.90	40.33	28.40	4.93	3252.61	.17	53.07	186.23
Minimum	Statistic	5.24	111.13	.01	12.50	.17	254.29	.03	19.96	22.01
Range	Statistic	11.83	163.77	40.32	15.90	4.76	2998.32	.14	33.11	164.22
Std. Deviation	Statistic	2.64506	39.28008	10.13276	4.68505	1.17823	583.57114	.03517	8.58858	33.93530
Skewness	Statistic	.754	-.359	1.966	1.378	-.791	.633	.014	.408	-.826

Table 7: Statistics for As, Ba, Ca, Cu, Fe, Mn, P, Pb and Zn in the lower topsoil (approximately 15-30cm) (© author)



Descriptive Statistics for Layer 3 (subsoil)

		As_ppm	Ba_ppm	Ca (%)	Cu_ppm	Fe (%)	Mn_ppm	P (%)	Pb_ppm	Zn_ppm
N	Statistic	6	19	19	2	19	18	12	9	17
Mean	Statistic	8.1750	169.9479	25.6000	15.1600	1.6547	736.9872	.0742	23.4356	68.1759
Maximum	Statistic	13.52	275.15	41.32	16.67	5.11	2446.61	.11	36.62	151.89
Minimum	Statistic	4.55	92.08	.65	13.65	.11	117.65	.03	7.89	8.60
Range	Statistic	8.97	183.07	40.67	3.02	5.00	2328.96	.08	28.73	143.29
Std. Deviation	Statistic	3.34574	60.31078	16.96326	2.13546	1.74930	684.40993	.02234	10.36944	51.63618
Skewness	Statistic	.704	.302	-.547	.	.752	.981	-.455	-.202	.213

Table 8: Statistics for As, Ba, Ca, Cu, Fe, Mn, P, Pb and Zn in the upper subsoil (approximately 30-50cm) (© author)

The results show a broad declining trend in elemental concentration of the displayed elements with depth (from topsoil, lower topsoil to subsoil) with the exception of Ca, which increases with proximity to the parent material on shallower chalk-based soils. P has a decreasing mean between the topsoil and the subsoil (0.12% > 0.09% > 0.07%), but has an increased range in the lower topsoil (0.11% < 0.14% > 0.8%). This could be caused by variations in P distribution in the upper 30cm due to natural plant and soil processes, but could be due to archaeological disturbances, such as pits and ditches, present in the soil horizons immediately below the plough soil.

This can be tested in two cores (21 and 27), showing how variation in P can be both positive and negative with depth, and that different archaeological features can have different elemental profiles. Core 21, located on the N section of the large enclosure ditch, had a greater depth of soil (1.7m) before chalk than the surrounding soils (0.3m and 0.8m either side of core 21). The pXRF results show P levels decrease to 0.03% between layers 2 and 4 (Figure 39), before increasing back to average levels *c.* 0.11%. Ba, K, Mn and Zn appear positively enhanced between 0.7-1m deep. Core 27 (Figure 40), shows a 1m deep profile through one of the pits in the small enclosure, displaying a gradual decline of most elements with depth, apart from P, Mn, Zn and Cu. These all have abnormal peaks at around 0.7-0.8m deep, where significantly mixed horizons are noted in the core description.

These cores show that elemental distributions can vary between different archaeological features. With regards to the increased range of P in the lower topsoil, these cores do not show high P levels immediately underneath the topsoil as suggested. Instead P variation happens below this layer and can be at much greater depths. This does not necessarily mean these high range values could not come from other archaeological features, but also suggests that other processes are more likely to contribute to those results. The complexity of considering calcium-bound P, with archaeologically enhanced topsoils, or truncated P rich archaeological deposits, as well as other causes of variation in P, make it difficult to discern where more subtle enhancements come without more detailed analysis.

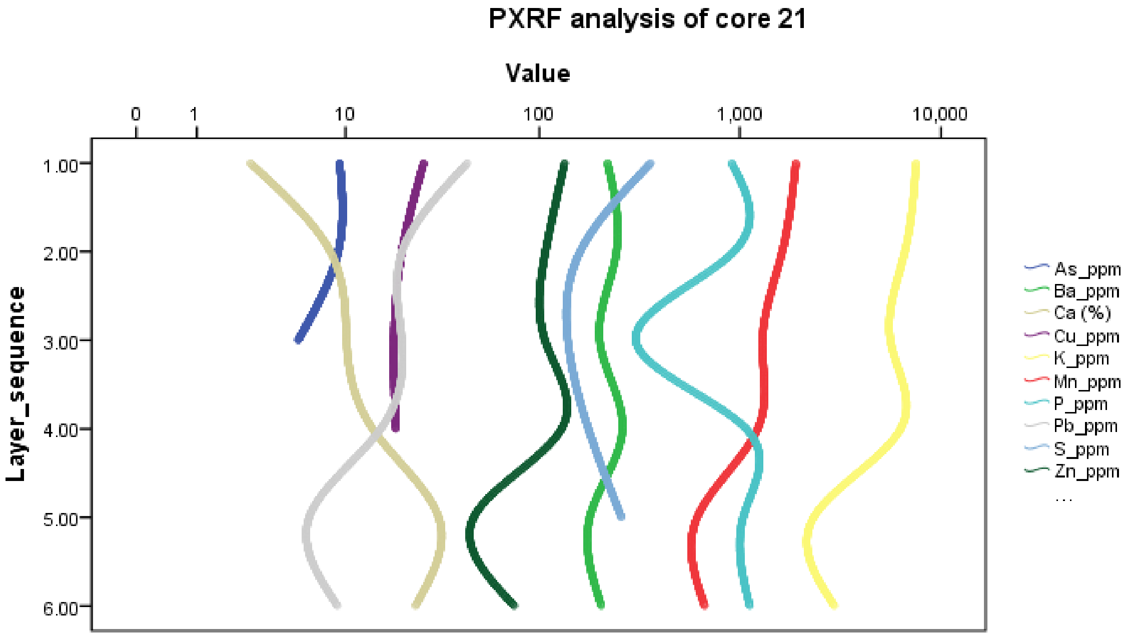


Figure 39: Graph of pXRF results for core 21 (© author)

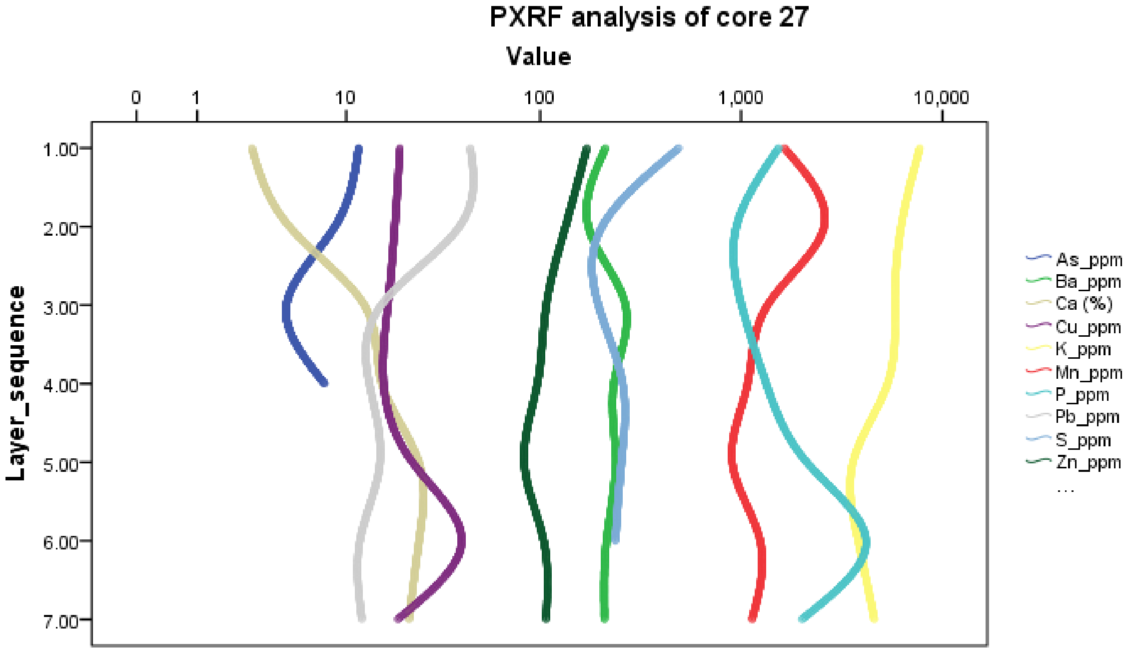


Figure 40: Graph of pXRF results for core 27 (© author)

6.4.2 Soil Stratigraphy

There are two pieces of existing archaeological data that can be used to inform awareness of soil depth and changes in soil stratigraphy across the two fields. This can then be compared with the systematic coring to test how accurate and relevant these are for PF soil approaches.

The first piece of archaeological evidence was from a small excavation of a part of the larger enclosure in Mushroom Ground (Figure 41). The fills of the ditch were generally skewed towards the SE of the ditch section, as well as evidence from previous aerial photographs, suggesting possible evidence for a bank (Wickstead and Barber, 2010). No other evidence of a bank was found, although due to the change in land use to arable cultivation, truncation and spreading would leave little evidence behind. The deepest part of the ditch (1.9m) contained a deposit of chalk blocks that seemed likely to have come from the surrounding bedrock, rather than being actively deposited. Above this was a series of silting episodes mixing chalk and flints along with lenses of brown silt. Some of the upper-fills contained cattle bones and a single flint flake but nothing further that would enable dating of the ditch.

Figure 41: Archaeological geophysics (left) and excavated section drawing for the case study site (right) (© Damerham Archaeology Project)

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The second piece of evidence is the geophysical survey. This provides spatial data for the majority of the study area, although there is a significant portion of East Long Ground not covered, due to resources being focused on the cropmarks spotted from aerial photography, rather than interest in the whole field. The geophysical data from the magnetic gradiometer survey confirms the cropmarks of the large enclosure ditches that cross Mushroom Ground, and that the enclosure ends alongside the modern field boundary. Inside the enclosure there is very little magnetic variation and suggests little evidence of human habitation within this enclosure. This is in contrast to the much smaller enclosure to the SE which has multiple small pits and ditches associated with it.

How can this information help understand the soil depths and stratigraphy of the field? The results show that in the limited area of the ditch, the soil is far deeper and has more complex stratigraphy than the surrounding soil profile. Inside this ditched enclosure, which is now well spatially defined due to aerial photographs, Google Earth imagery and geophysical survey, the geophysical data does not indicate many pits, and does not show any background variation that might suggest soil depths are changing across this area. This however must be caveated by the potential that the magnetic responses may slightly differ because of the background geology (CwF). In MLG Top, interpretation can only be made on the extent of the geophysical data, thus the extent of the geophysical survey hinders consideration of the wider field.

Although originally 48 cores were planned (Figure 42), due to equipment damage in the field, only cores 1-33 were completed and recorded. These two transects are presented in Figure 43 and 44. Cores 27 and 29 (not labelled on Figure 42) were taken at 10m intervals in between cores 26-28-30 due to greater detail needed over the smaller area of the Iron Age enclosure.

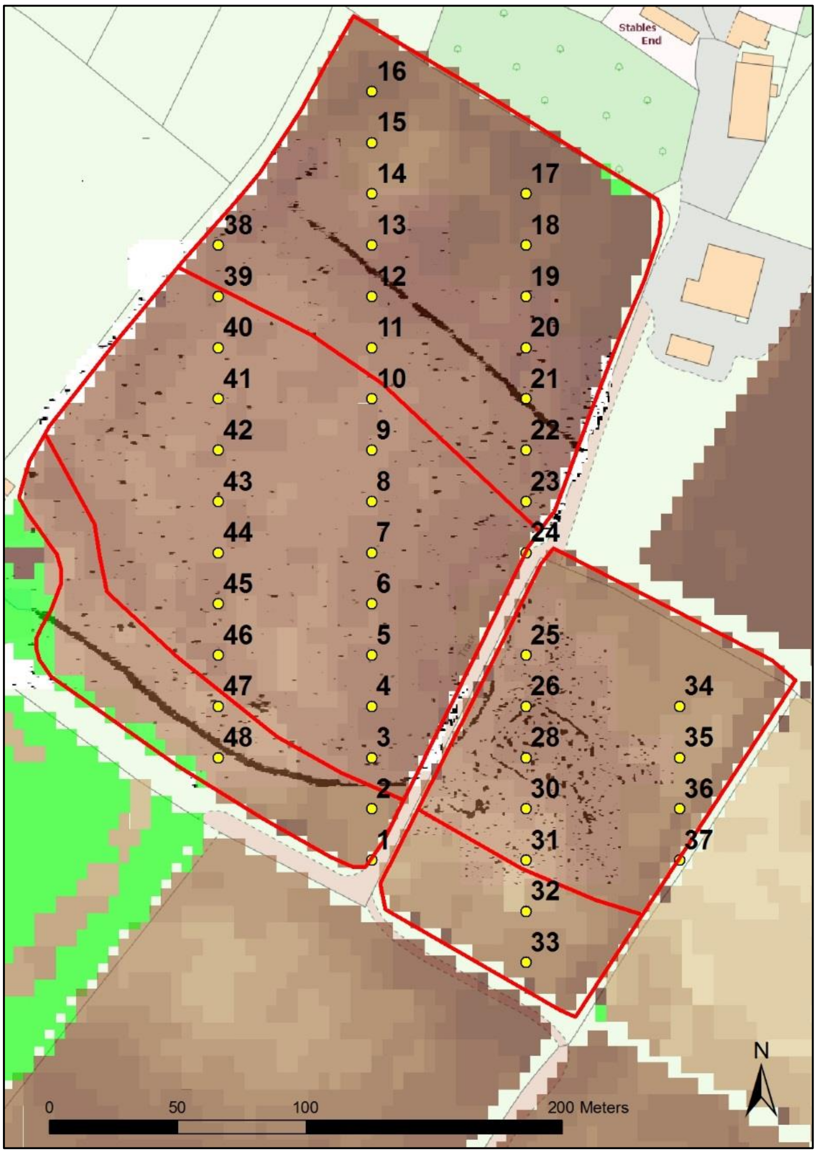

Figure 42: SOB satellite image, core locations (excluding 27 and 29), IPF soil zones and positive magnetic anomalies

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Transect 1

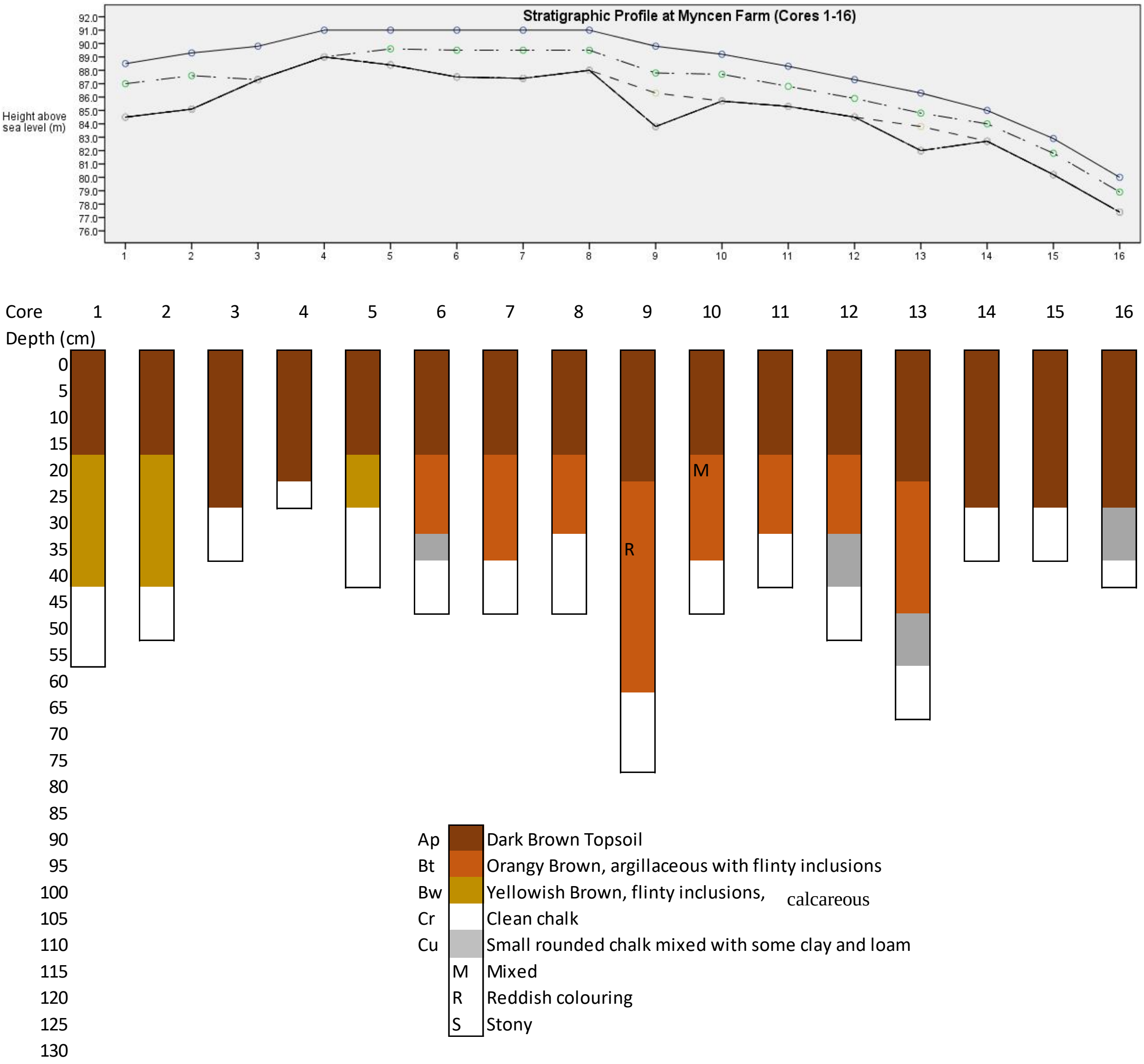

Figure 43: Topographic profile (top) and core drawings (bottom) of transect 1(cores 1-16) (© author)

The topographic profile (with depths below topsoil multiplied by 10 to enhance visibility) and corresponding cores in Transect 1, show the variation in depth to Upper Chalk, with topsoils thinnest on the brow of the slope, and thicker at the foot of the slope. CwF deposits extend over much of the central area, with two cores (9 and 13) showing deeper (*c.* 0.5-0.6m) deposits than the average (0.3-0.4). Transect 2 shows a similar profile, with further variation in the depths of the CwF deposits on top of the chalk, some only 0.10-0.15m while others were 0.6m thick. Significant variation in soil depth concentrated within three main cores (17, 21 and 27). Core 21 can be located directly within the large ditched enclosure, thus enabling a comparative set of measurements for the excavated section on the southern side of the enclosure (Figure 41). The core was 1.78m deep until solid chalk, with a couple of different deposits filling the ditch. This core also found evidence of large chalky inclusions at the bottom of the core, as well as a notable band at approximately 0.70-0.75m.

Transect 2

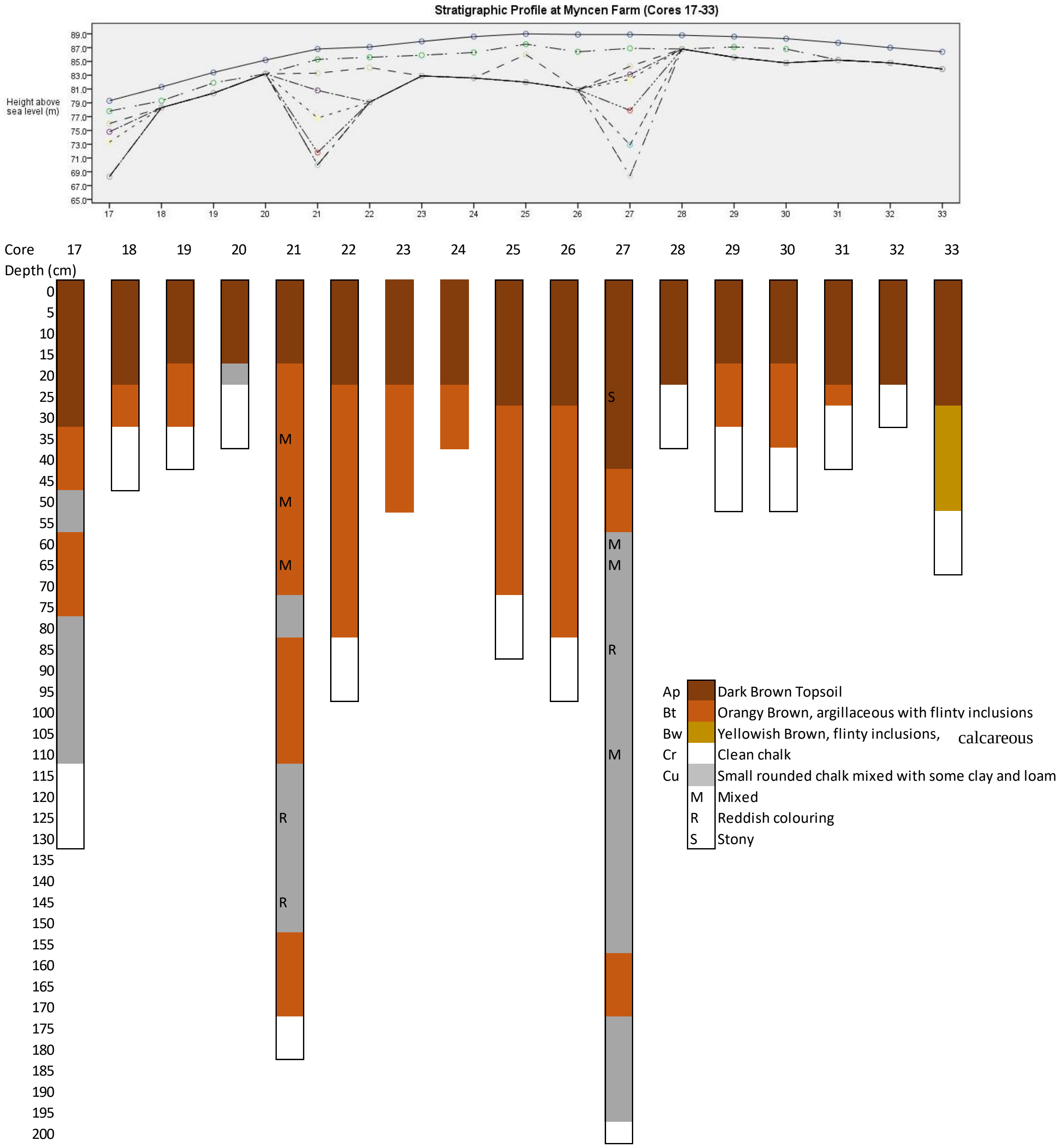

Figure 44: Topographic profile (top) and core drawings (bottom) of transect 1(cores 17-33) (© author)

Core 17 differs from the thin chalky soils of 18 and 19, it is 1.2m deep and has a number of significant horizons within it. It is characterised mainly by residual orangey-brown CwF at 0.35-0.45m but becomes mixed with small chalk particles until 0.6m. From 0.6-0.75m there was a friable layer of clay with no flinty inclusions that also had noticeable charcoal flecks. Below this was more clay with small flinty inclusions before reaching chalk at the bottom. This differs drastically from the thinner chalky soils expected in this location and is similar to other disturbed soils found in cores 27 ad 21. Due to a lack of geophysics in this area it is unknown whether this is part of another archaeological feature such as a ditch or a pit, or whether it is modern disturbance.

Core 27 is located within the small enclosure, between 26 and 28. It was located directly on a pit feature inside the enclosure and gives evidence on the general depth and stratigraphy of this pit. The pit is 1.74m deep, with three main fills apparent. The primary fill contained mixed orangey brown CwF with charcoal flecks. Above that a similarly mixed matrix of clay with chalk and a significant band of reddish brown soil with very small pieces of poorly preserved ceramic or burnt daub and two small fragments of pottery found (Bronze Age or late Iron Age in date). Above this at around 0.65m were grey aggregates mixed with larger flint inclusions and mixed with orangey brown soils (Figure 45). The final layer above this was a layer of fairly clean mixed chalk and dark brown topsoil capped by a compacted 10cm layer of reddish brown soils mixed with small pieces of badly preserved ceramic or burnt daub.

Figure 45 Image of core 27 at 65cm depth

The archaeological impacts on the stratigraphy of the study area, from both archaeological evidence (geophysics and excavation) as well as the core transects, are spatially limited to the locations of specific archaeological features (ditches and pits). This makes their relevance to PF systems and to agricultural soil perspectives of limited value because a 3m wide ditch cannot be managed effectively with the farm’s current equipment. Although spatially these are not widespread, their sharp contrast to the surrounding soils is of importance to retention of water, nutrients and OM in particular locations and at particular depths. This can be shown to effect crop growth even during the late autumn/winter (Figure 46).

Figure 46: The effect of an archaeological pit on root and leaf growth of oilseed rape plants by February (© author)

6.5 Archaeological Data in a PF Context

6.5.1 Remote Sensing and Aerial Photography

As discussed in Section 6.3, various pieces of data from remote sensing techniques have contributed to the archaeological interpretation of Myncen Farm and the case study area in particular. Figure 47 shows one of the aerial photographs identifying the large enclosure that cuts across the field Mushroom Ground. As a single piece of data, this enables a large amount of archaeological interpretation, but does it have relevance for PF at Myncen Farm?

Figure 47: John Boyden's 1973 oblique view of the enclosure. (© Crown Copyright. Boyden Collection) (Wickstead and Barber, 2010)

Ultimately it does highlight the enclosure ditch and its moisture retentive soils, however since these are too small to be managed differently, limits any PF application of that information. The enclosure ditches could indicate the possibility of different soil management either in the time after the enclosure fell out of use, or while it was in use, and this could affect the soil. Therefore this could be useful in a pF context in the establishment and testing of soil zones. The difficulty in using data such as aerial photographs, especially oblique ones, is that it would be very difficult for a PF specialist to input easily into their GIS software, because it needs to be rectified and georeferenced.

Figure 48 shows the result of this aerial mapping, and mapping from 1982-2002, when rectified, georeferenced and put into GIS for polygonisation. This dataset, in digital format and accurately georeferenced, is far easier for PF specialists and farmers to integrate within their analysis of soils. The interpretation of what those enclosure ditches mean for soil would not change, but the ease and adaptability of integrating this type of data into PF systems is far greater than individual oblique aerial photographs.

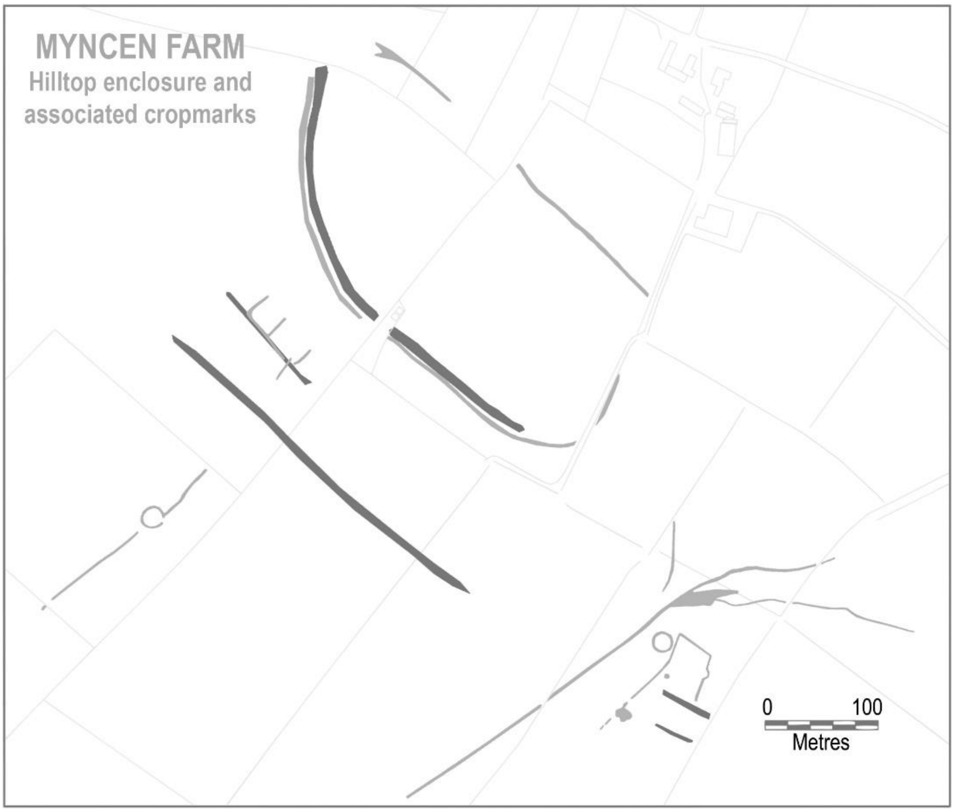

Figure 48: The enclosure and adjacent cropmarks as mapped from the 1982 and 2002 aerial photographs, with north at the top. The darker tones represent features that are, or were, banks, such as the inner bank of the enclosure, and the lynchets. The lighter tones indicate the presence of 'negative' or cut features such as linear ditches, ring ditches, and the ditch of the enclosure itself (© Historic England NMR) (Wickstead and Barber, 2010)

There were no satellite images collected as part of any of the previous archaeological work that would not be freely available to anyone (including PF specialists and farmers). The imagery collected at Myncen Farm has consisted of Google Earth imagery (Figure 27) and Figure 49 shows other available images of the case study area. As PF specialists, farmers and archaeologists all use this service however, it does not represent any new data for either archaeological investigation or PF assessment of soils and crops, despite it being very beneficial for both.

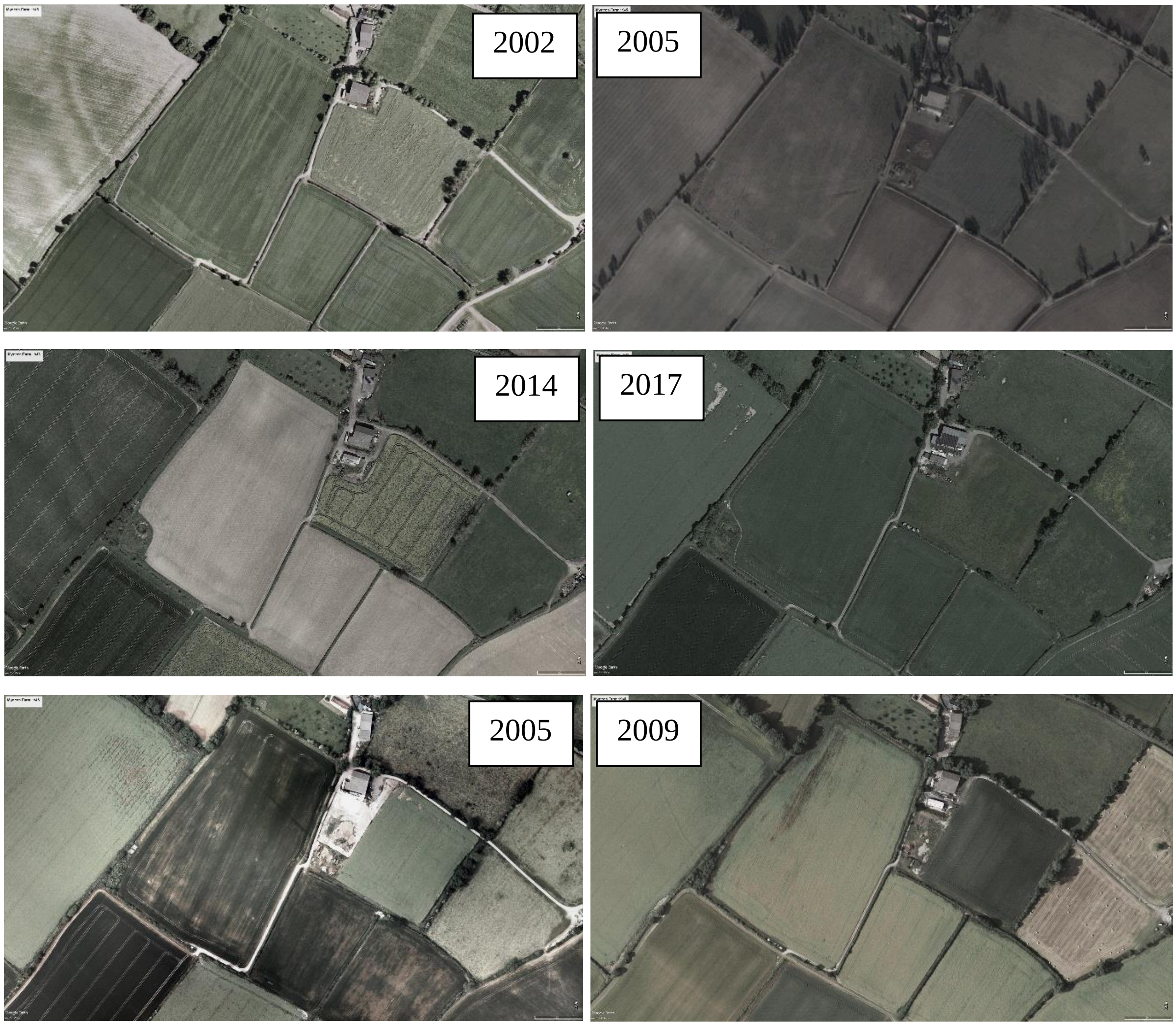

Figure 49: Google Earth satellite imagery of the study area (© Google)

6.5.2 Archaeological Geophysics

The objective of a geophysical survey is to identify possible archaeological anomalies, that might relate to archaeological pits, ditches or buildings etc. Having discussed the impacts that pits and ditches have on the soils' elemental concentration, physical structure and stratigraphy in this case study area. It is worth considering this from a PF perspective, where the causes and exact locations of underlying soil variations is fundamental to accurate management of that land.

The geophysical survey serves as a basis for mapping any sharp contrasts in sub-surface soils, whether those are archaeological, possibly archaeological, or not archaeological. Some of these were visible in existing imagery from Google Earth (Figure 49) but some were not (the Iron Age enclosure). This geophysical survey could have contributed to the soil zoning process when the farm started using PF services (Figure 50). There is obvious interaction between the location of the archaeological features, the large enclosure ditch, and the superficial geological deposits of CwF. To the N of the field, the archaeological feature, the elemental data and the geological map all correspond to the same boundary. On the S side of the field, however, the elemental data shows a wave-like boundary between the chalk-based soils and the CwF, whereas the archaeological feature cuts a straight line.

Archaeological features should not be predicted to always align to geological boundaries, or *vice versa*, but can provide an additional layer of data to inform more accurate placing of PF soil zone boundaries in conjunction with geological or other data. In Mushroom Ground, the division between the two PF soil zones, C2v and B2, should be placed further to the N. In MLG Top, the two existing soil zones could be amended, possibly creating a third zone, to take account of the clear archaeological features within a limited, 30x40m, rectangle. Other smaller archaeological anomalies in the geophysical data cannot be included easily in the soil zoning approach because of their size. Areas larger than 20x20m are more likely to be included in PF soil zoning processes due to the possibility that they might cause variations that affect PF data (such as soil phosphate analysis). It is important that these amendments happen at the start of the PF process, because once soil zones have been decided, soil sampling is directed within those zones, therefore averaging any effects of further internal variation.

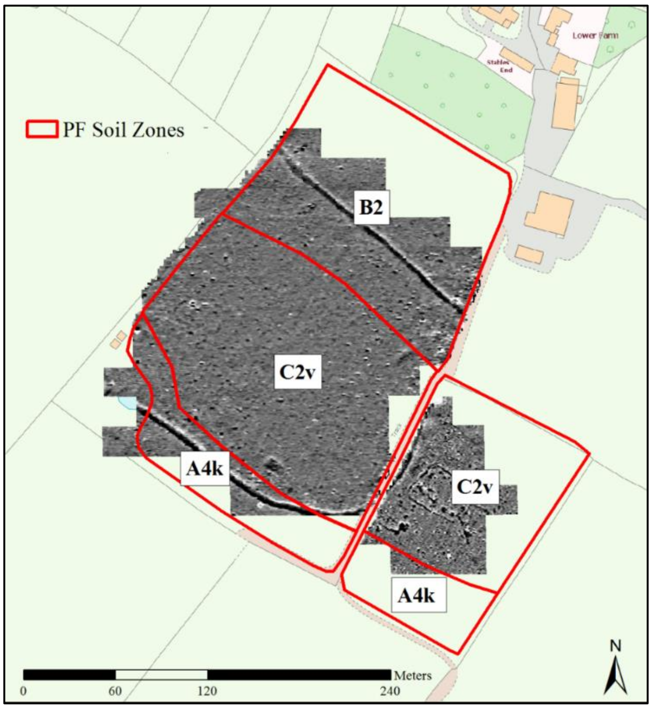

Figure 50: Geophysical survey and PF soil zones

(contains OS data © Crown copyright and database right 2019)

6.5.3 Historic Environment Records

The HER team for Dorset County Council provided the HER data, presented in Figure 51, for the area surrounding Myncen Farm. It contains only point data of the main archaeologically and historically important sites in the area. Unfortunately, it is not up-to-date with regards the archaeological investigations that were described in Section 6.3. Additionally there is no spatial detail regarding the extents of particular sites. Due to these problems, the HER data at this site is only useful indirectly through interpretation of what other sorts of features are in the peripheral landscape, rather than showing accurate information that could aid the investigation of the case study fields directly.

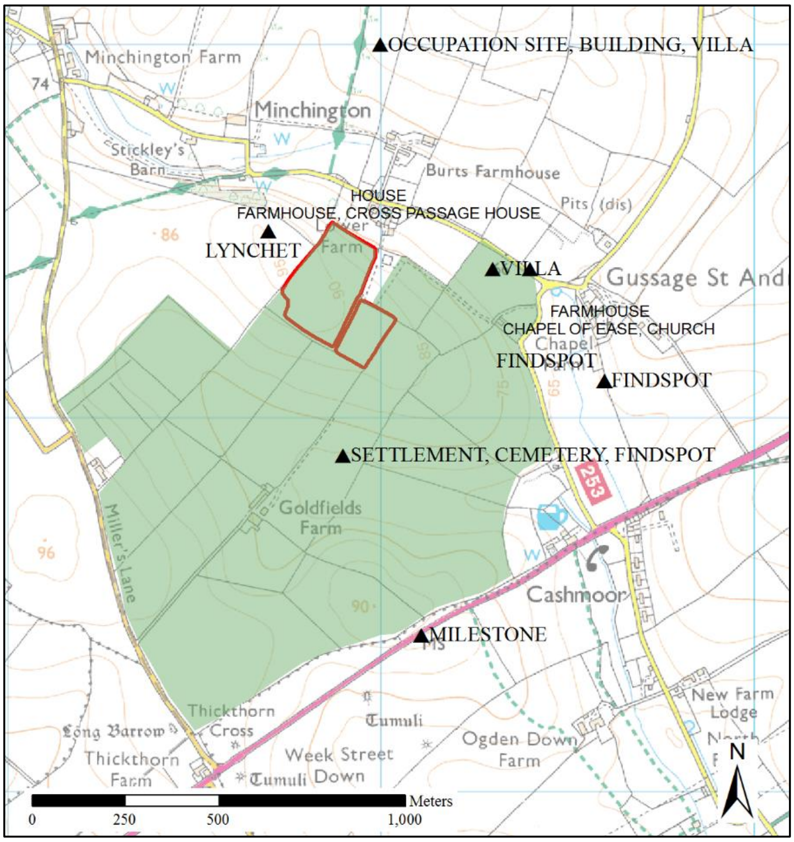

Figure 51: HER records for Myncen Farm with the red polygon outlining the case study area and green shading showing the farm boundary

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There are, for example, sites noted in the wider area, such as an occupation site to the N and lynchet features to the W of the fields. Importantly some of these, the settlement/cemetery and the Roman villa , are within the farm boundary itself and could present useful first step for PF specialists and farmers to understand whether any significant and known archaeological remains lie within the farm boundary as a whole, and in which fields these might relate to.

The relevance of this dataset to PF systems is limited, but may be more applicable to farm scale maps and investigations than field scale which this research focuses on. It is a broad indicator of archaeological activity, rather than a dataset that can enhance the accuracy or interpretation of PF data.

6.6 PF data in Archaeological Investigations

6.6.1 PF Field and Farm Soil Analysis

Figure 52 shows the plant-available phosphate measurements for the whole of Myncen Farm, including Mushroom Ground and MLG Top, with each field subdivided into soil zones within which soils were sampled for plant-available P, K, Mg and pH.

The fields within the case study area, and including the next field to the SE, show particularly high phosphate values in comparison to the surrounding areas, and the rest of the farm. Traditionally, both from archaeological evidence and farm nutrient maps, high phosphate indexes are often related to areas that have a high OM content and where large volumes of organic materials have been applied. This tends to focus around older farmsteads, due to organic materials being difficult to carry further and crop requirements. The historic use of organic manures and other materials could certainly have contributed to higher phosphate values in these fields, yet it would usually be applied relatively evenly if meant as a fertiliser. Therefore the within-field variation presumably was already there, and indicates either geological or archaeological causes for these high phosphate values. In addition, the phosphate values in the field directly to the E of the old farmstead was not as high as the case study field, bringing into question the historic farmstead theory.

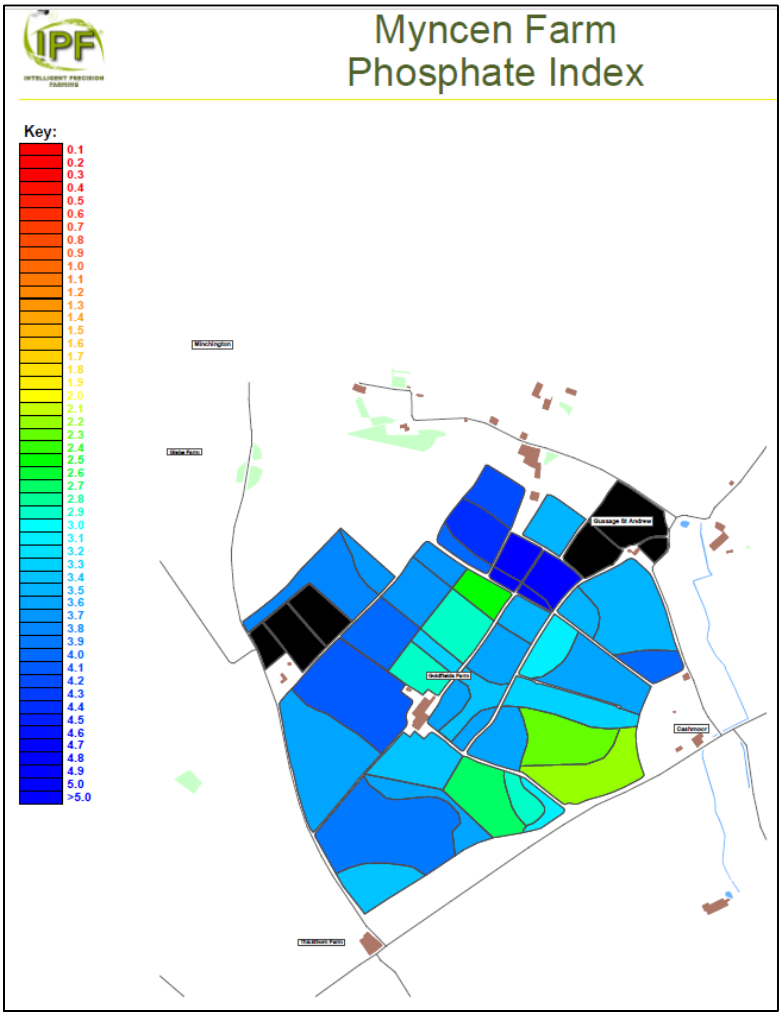


Figure 52: Plant-available phosphate map produced by sampling each soil zone across the farm. Key relates to Olsens P index (AHDB, 2017) (courtesy of IPF UK)

Table 9 shows a comparison between the pXRF measurement of total P compared to the agricultural analysis of plant available P (Olsens extract). This highlights the within-field variation of each field separated by PF soil zone to enable comparison between existing data. Interestingly, although it can be assumed that a greater total P equals a relatively greater proportion of available P, this table shows that this cannot be the case in certa*in situ*ations. Within the CwF soils (C2v soil zone), the total P is on average, lower than the other two soil zones (chalk-based soils), yet the available phosphate is higher than the other two zones. One interpretation for this is due to the measurement of different forms of P, the pXRF measuring elemental P that may be bound up in calcium phosphate compounds and not in the plant available pool. Therefore the enhancement of available phosphorus would be negated by the larger volume of tightly bound elemental P.

Field	IPF Soil Zone	Average Total P (ppm)	Decimal Phosphate Index	Approximate Olsens P (mg/L)
Mushroom Ground	B2	1233	4.2	50.8
Mushroom Ground	C2v	1174	4.6	60.4
Mushroom Ground	A4k	1294	4.4	55.6
MLG Top	C2v	1173	4.8	71.8
MLG Top	A4k	1255	4.7	65.2

Table 9: Comparison of different measurements of P per PF soil zone (© author)

The second interpretation is that the archaeological enhancements of P may only be within certain pools of P. Explaining why concentrations of available P are higher in areas where there are known archaeological features and this is being demonstrated by the bulked agricultural analysis. The question of which method of P analysis is most suitable to archaeological deposits and P residues has been tackled by Holliday and Gartner (2007), but show it varies depending on complicating factors such as parent material, types of residue, intensity of occupation, post-depositional processes.

The result could of course be a mixture of both of these reasons, and it is not possible to conclude any more from this data since the sampling for each dataset was very different: comparing different numbers of points within each average, and different sampling methodologies.

This data could be relevant for archaeological investigations. Although phosphate surveys are less common in the archaeological world than they were 20 or 30 years ago, this is mainly due to cost and time required, in comparison to the results gained from the survey. Yet if data for a whole farm, and possibly across multiple years, was available even at low resolution such as at Myncen Farm – it could be a quick way to identify areas of intensive activity, whether that be archaeological or in relation to other factors. However, there may be a couple of issues in doing this. Firstly the geological variation will undoubtedly affect phosphate variation measured at a farm scale. This could be countered to a certain extent by dividing up the average values per soil type and using them as guideline to identify enhancements across the farm. A second issue, that can only be resolved by talking to the farmer, is whether manure and other fertiliser applications are concentrated in certain locations and thus affect the distribution of P across the farm.

Other nutrients mapped as part of the agricultural soil analysis (available potassium (potash) and magnesium) are shown in Figure 53. Neither of these show significant variation and therefore were not compared to the pXRF analysis. Despite this, it is worth noting how variable elements are across the whole farm, even within a fairly consistent management system.

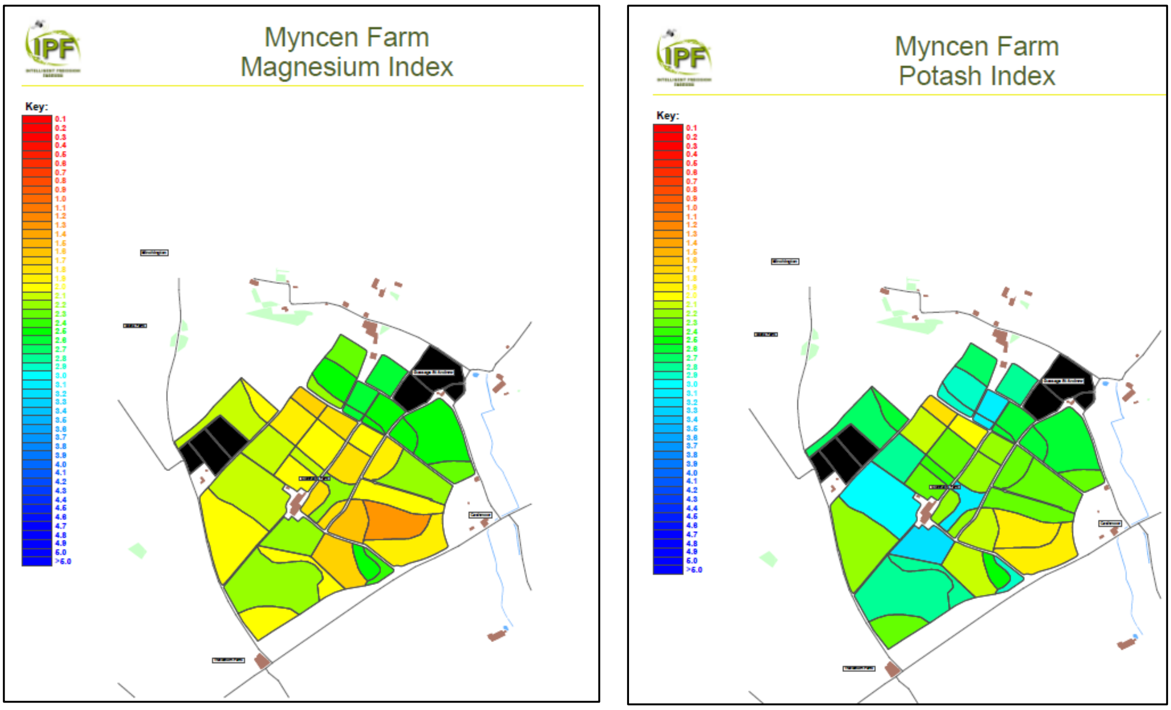


Figure 53: Farm nutrient maps for available Potassium and available Magnesium indexes. (Courtesy of IPF UK)

6.6.2 PF Satellite Imagery

PF is a considerable source of satellite imagery, of varying types. Table 5 outlines the total numbers of satellite images collected across the whole farm for use to scout out poor areas of crop and record crop growth throughout each year. Figure 54 demonstrates the progression of images taken of the study area throughout the year of 2015. These are all NDVI images and are excluding images where cloud cover has obscured view of the field. Immediately it is apparent that some fields are inherently different to other fields, this is due to different crops. The study area is in the same cropping block (farmers tend to put similar crops in blocks to make them easier to manage) and so could be compared. If assessing larger areas, the difference in crop type or even different planting times of the same crop (and therefore different growth stages of crop) can make interpretation of satellite images far more difficult because of changes in canopy colour and structure.

From the images of 2015, it is noticeable that they do not follow each other in increasing NDVI values throughout the growing season. A gradual increase in NDVI would typically be expected from a developing green crop until the crop begins to senesce and change colour. This is not apparent in these images because each image shows the variation within the NDVI range rather than an absolute value. This variation in NDVI is key to identifying variation for PF methods and thus is the same for all satellite images from this commercial provider.

In archaeological investigations, whether by aerial photography, or geophysical survey, data tends to be high resolution but taken at only one or two points in time. It is highly spatial but very often lacks temporal repetition across multiple environmental conditions. PF satellite data takes a different approach, by regularly capturing data at multiple points throughout a growing season, despite at a low resolution. Figure 54 represents how multiple images per year allows comparison of areas over time. The low resolution however can hamper interpretation for archaeological remains, since the satellite data from 2015 shows no correlation to known archaeological features. The crop was oilseed rape, however, which is not known for producing accurate crop marks due to its large spreading canopy, and vigorous growth.

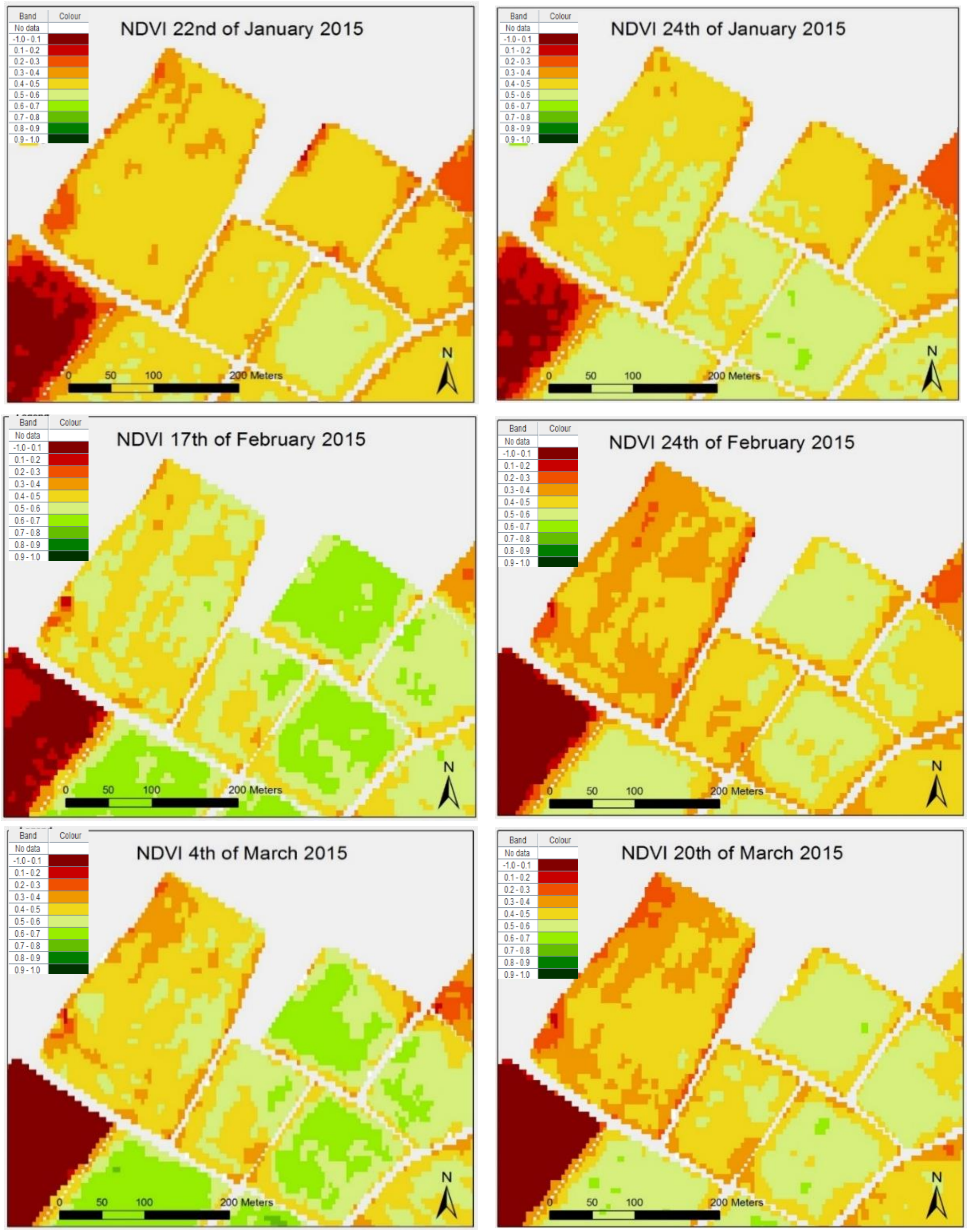


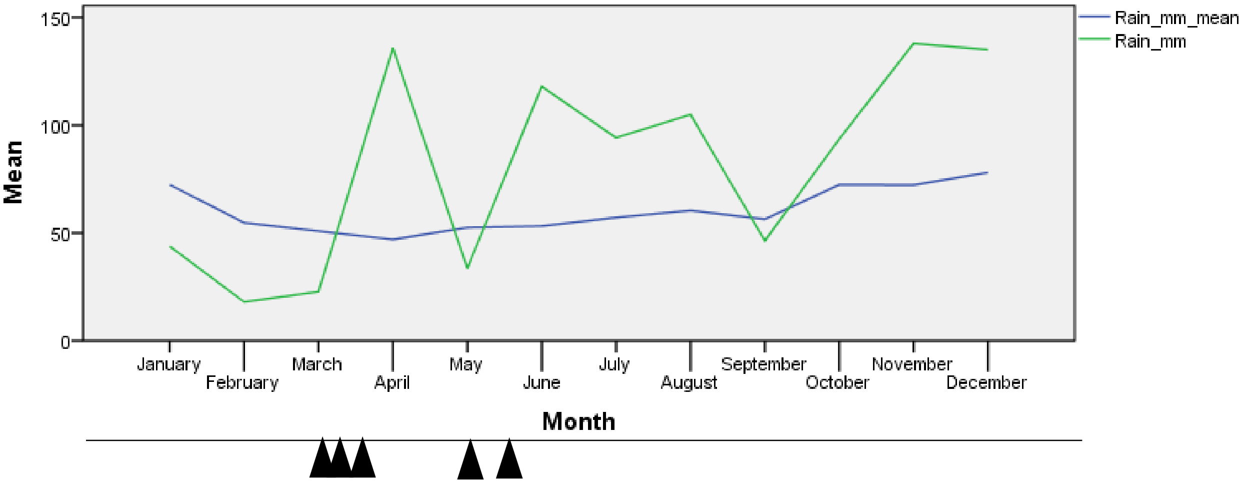
Figure 54: Six NDVI images of the case study site (Courtesy of IPF UK)

Across multiple years, and with many images per year, one way of aggregating this data and simplifying interpretation was to add all of the clean (no artefacts, missing data or cloud cover) images for one year together into a weighted sum image (where each pixel was added onto the other exact pixels from each image, cumulatively).

These average NDVI images, along with the average weather backgrounds to indicate whether it was a dry or wet season and arrows showing when images were taken, show a number of benefits. They include information on 1:1 basis from all satellite images included in that year, providing a better indication of consistent variation than a single image that may be skewed by a particular problem in one particular month by a weed infestation, or pest damage from birds. Figure 56, for example, was affected by an area of high NDVI values within the large enclosure in Mushroom Ground. This, although appearing significant in the satellite imagery, was found out to be a patch of weeds that had grown that year. This highlights the importance of ground-truthing if looking at these datasets with no knowledge or information about the site in question.

Since there were images from 2012 to 2015, there was enough data to go through one entire cropping cycle from winter oilseed rape (Figure 55), winter wheat (Figure 56), spring barley (Figure 57) and back to winter oilseed rape (Figure 58). This allows comparison of two of the same crop, on the same area but with different weather patterns. 2012 was a comparatively wet year, 2015 a comparatively dry year. There are some similar patterns in the data marked by black arrows, showing anomalies within the field, one in Mushroom Ground that correlates with a geophysical anomaly and potential entrance way into the enclosure, the other an area that is outside of the geophysical survey area. These do not appear as positive increases in NDVI each time, and in the 2012 image the area has an negative effect in relation to the rest of MLG Top, whereas in 2015 it has a positive effect in comparison. This is most likely explained by the relationship between the soils and rainfall data. In a dry year such as 2015, that area of soil might have held more moisture in the soil profile in comparison to the surrounding areas, whereas in 2012 (a wet year) it may have become too wet and suffered from too much moisture effecting crop growth or other soil conditions and nutrient supply.

2012



*Black triangles represent the timings when satellite images were taken in that year.

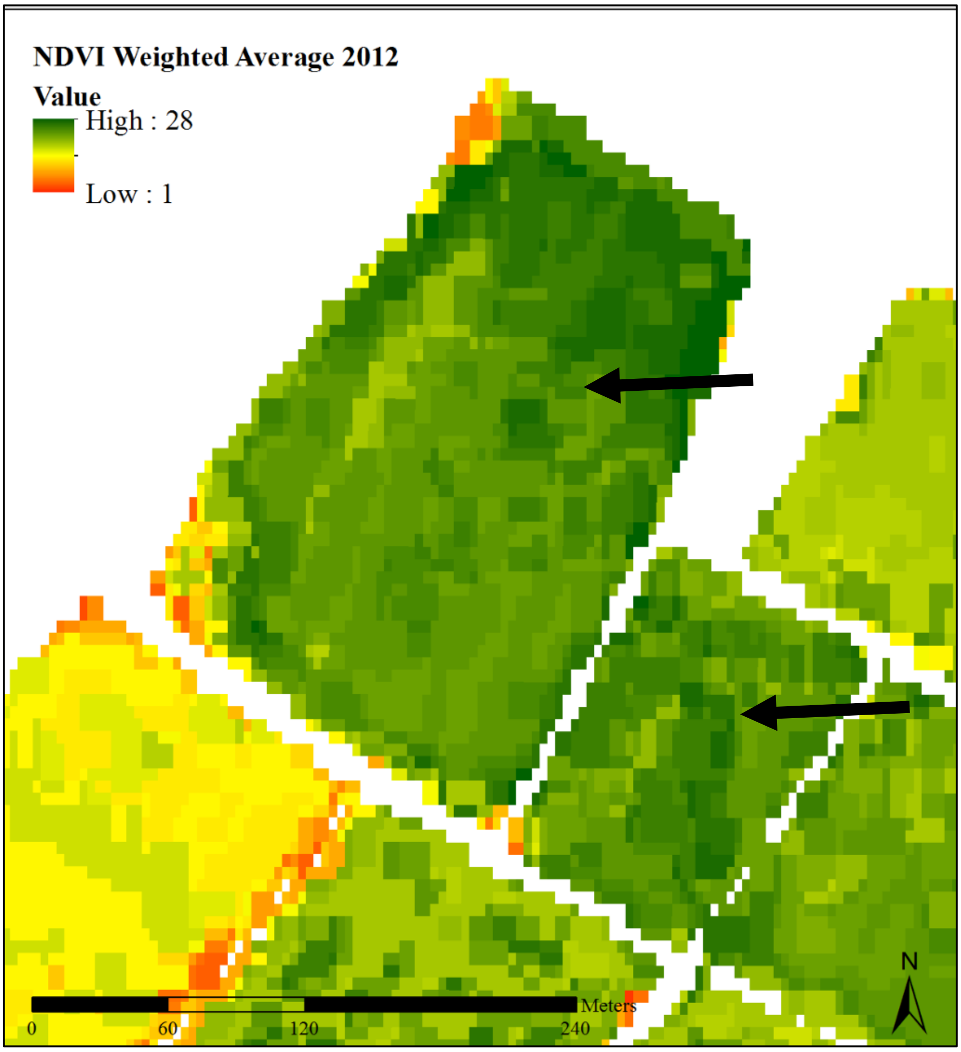


Figure 55: Weighted sum average of NDVI images for 2012 in a winter oilseed rape crop with weather averages above and the timing (courtesy of IPF UK) (© MET Office historic data)

2013

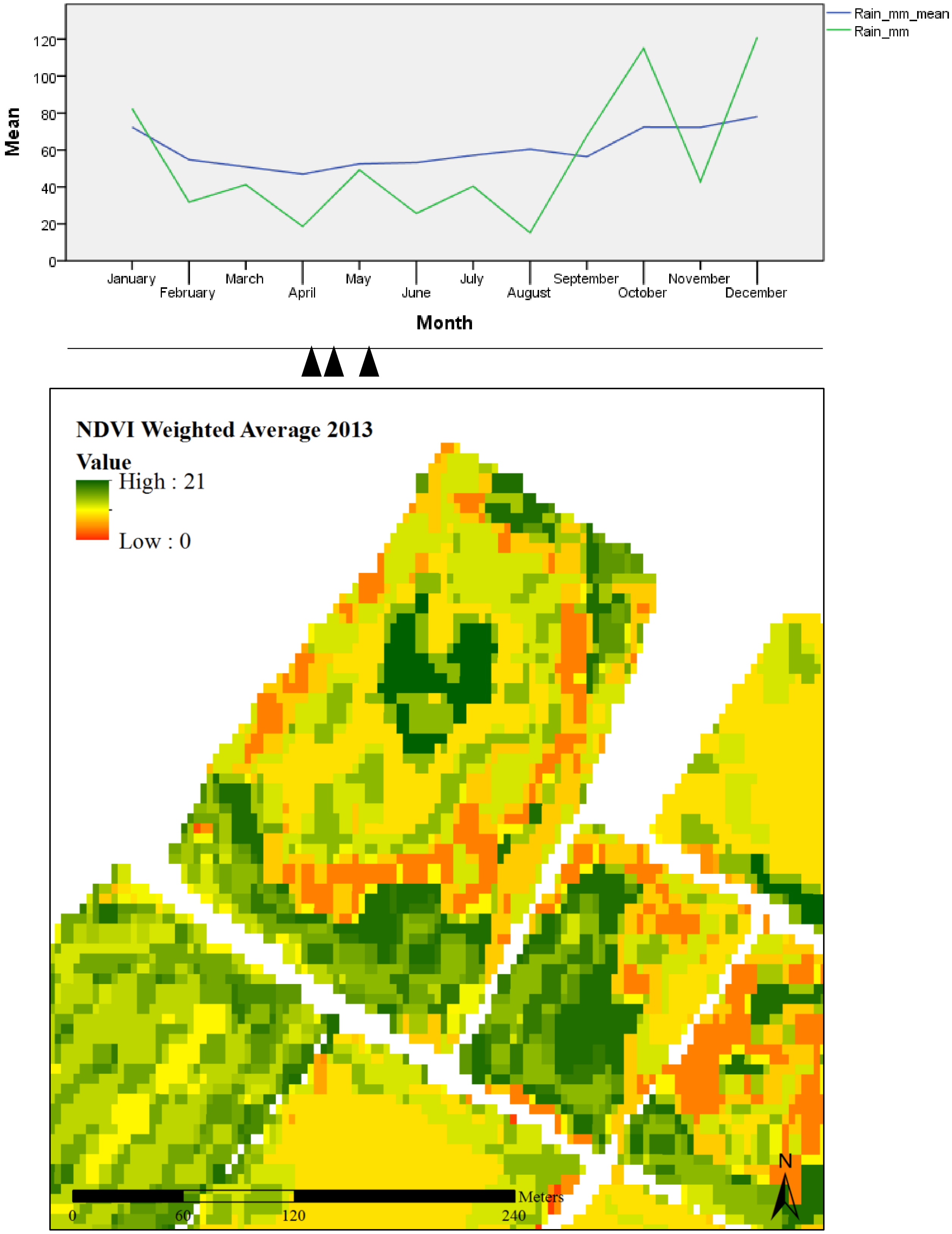


Figure 56: Weighted sum average of NDVI images for 2013 in a winter wheat crop with weather averages above and the timing (courtesy of IPF UK) (© MET Office historic data)

2014

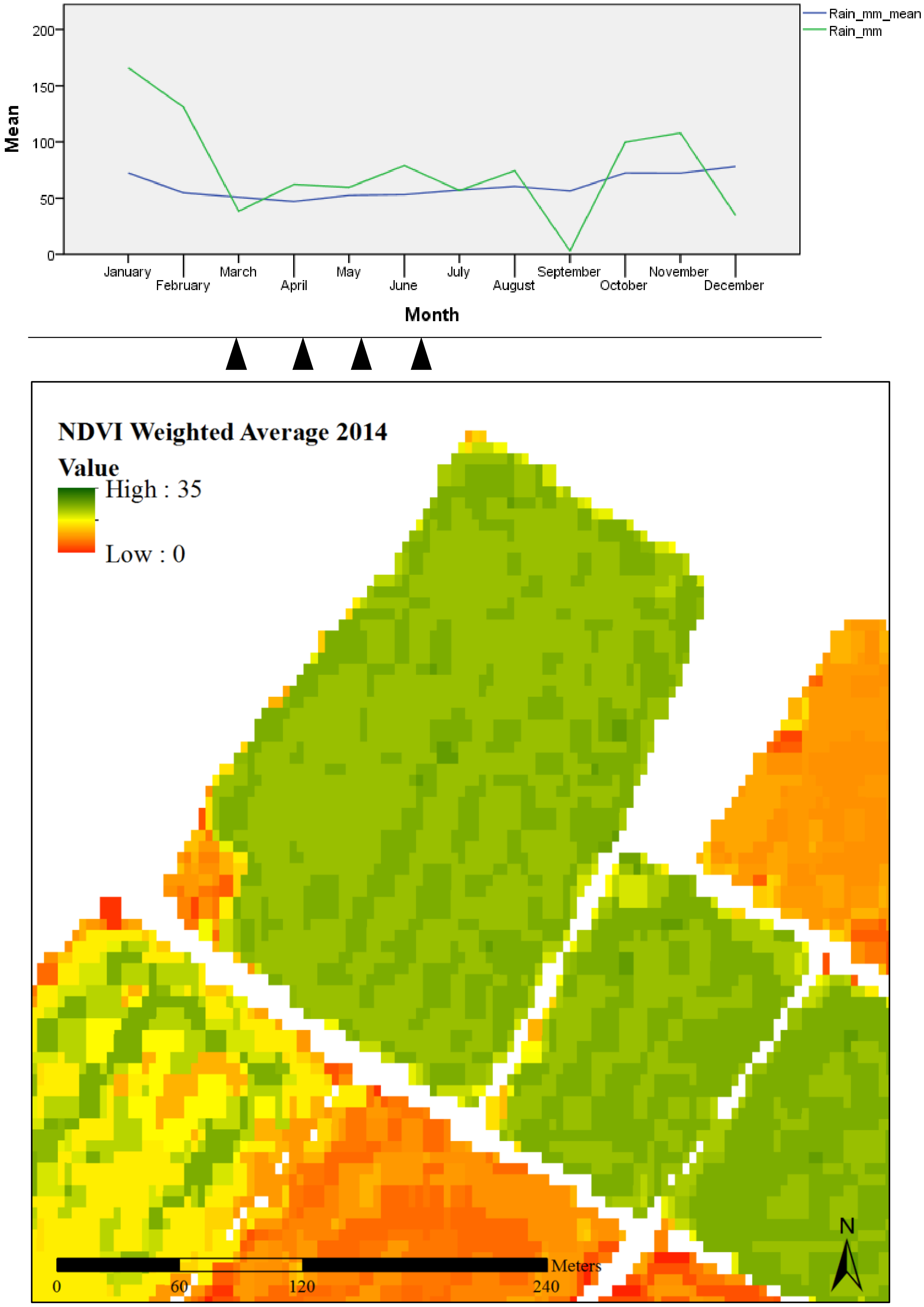


Figure 57: Weighted sum average of NDVI images for 2014 in a spring barley crop with weather averages above and the timing (courtesy of IPF UK) (© MET Office historic data)

2015

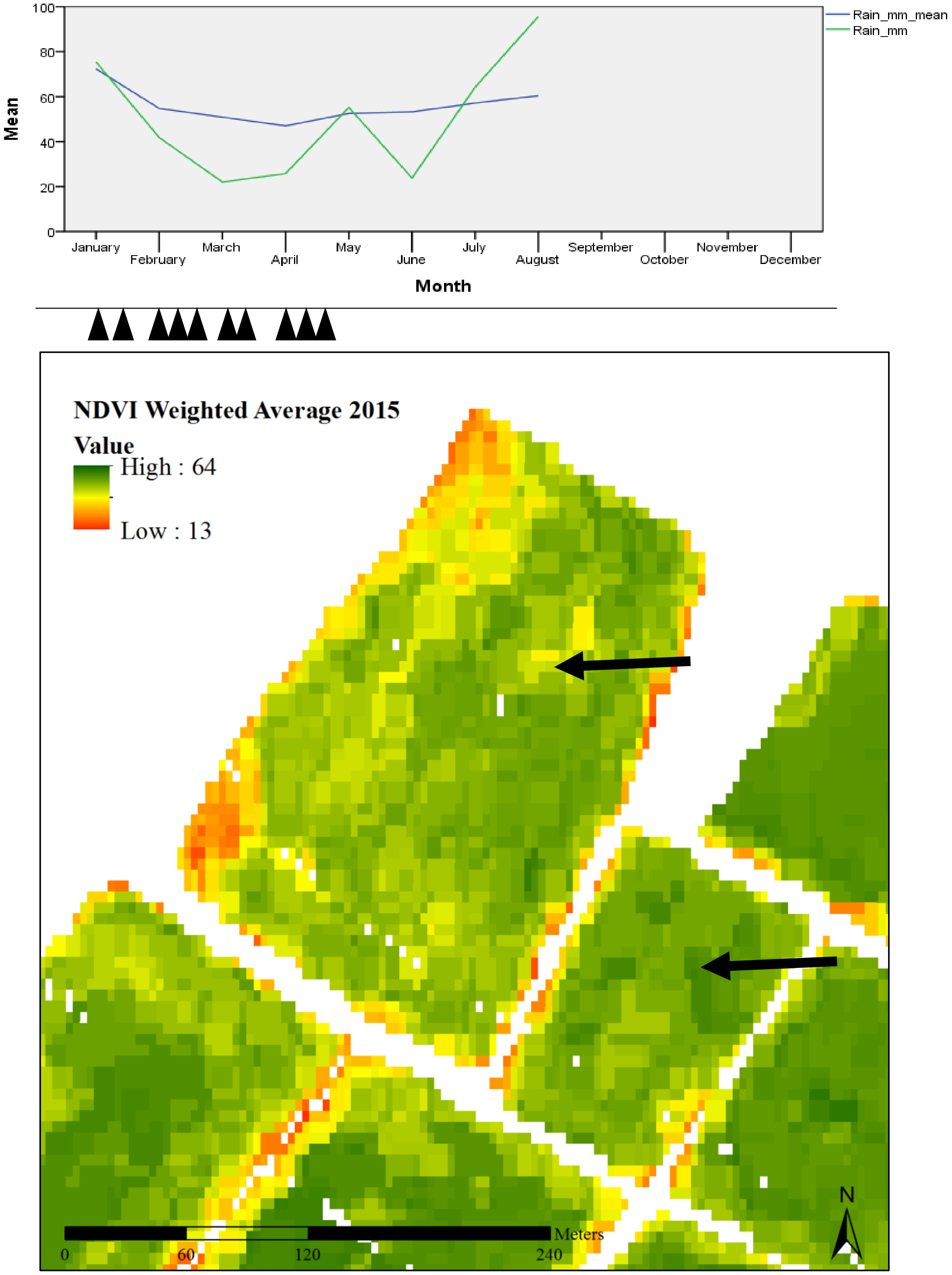


Figure 58: Weighted sum average of NDVI images for 2015 in a winter oilseed rape crop with weather averages above and the timing (courtesy of IPF UK) (© MET Office historic data)

Some crop types are known for their responses to archaeological aerial survey. Evans and Catt for example shows that spring barley is a very useful crop for showing discrete soil anomalies (Evans and Catt, 1987). Yet here spring barley shows the most even distribution in NDVI over the year in comparison to other crops, despite the rainfall data showing on average rain for the year (a factor which could cause less stress in the crop and therefore less variation). Instead oilseed rape, a crop not normally noted for showing crop marks, has considerable variation, some of which are in relation to archaeological features.

Figure 59 shows an image, from the 27th February 2015 in an oilseed rape crop, with two areas relating to archaeological features. This satellite image, as are the rest of the images from this service provider, have a 5m pixel size. Small areas of 10x10m can be noticed, however these could be less visible when the background variability is higher. Instead areas such as the small Iron Age enclosure, 30x40m, is more noticeable. This was caused by the multiple pits and short ditches retaining moisture and possible nutrients or OM, contributing to higher NDVI values.

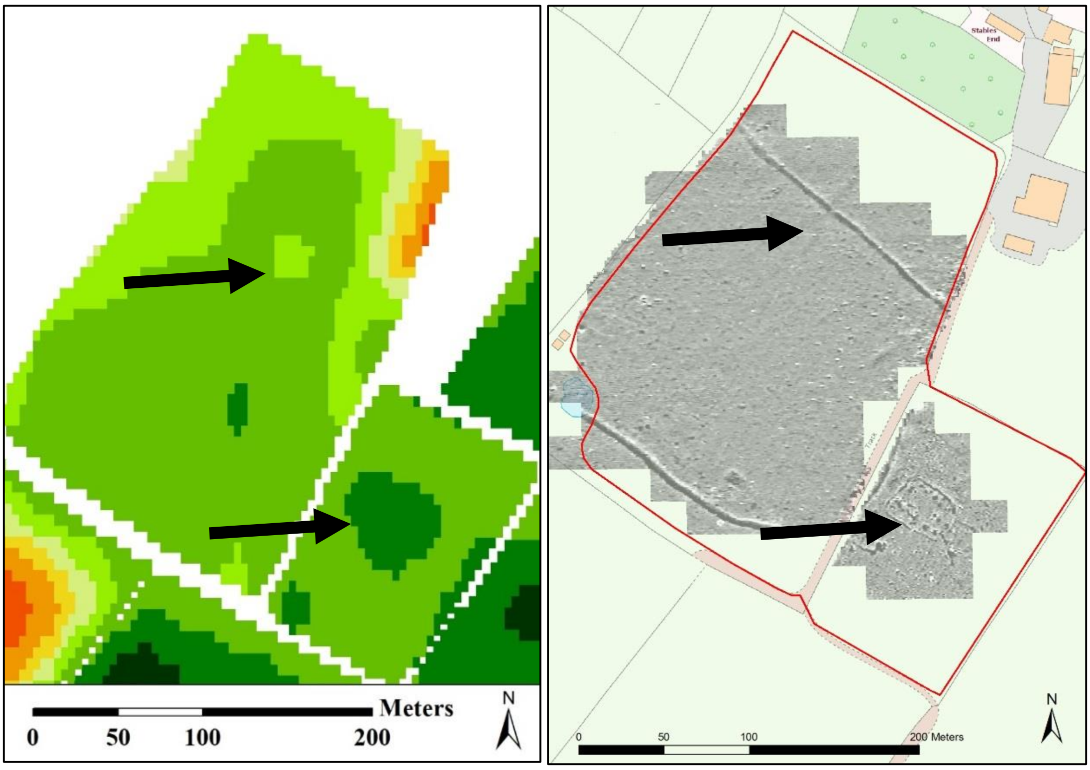


Figure 59: NDVI satellite image from 27 February 2015 in an oilseed rape crop (left), with the geophysical survey results (right)

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6.6.3 Agricultural Drone Imagery

Two separate drone flights were completed over the growing seasons of 2017 to trial out the use of a small commercial drone with both a multispectral camera as well as a standard RGB camera. The flights were completed on the 24th April 2017, the 12th of May 2017 (spring barley crop). The flights recorded both multispectral and RGB bands enabling vegetation indexes to be calculated at two points in the year and assess crop health with more detail than only visible wavelengths.

Earlier in the year the farmer held a motorbike/lawnmower race on Mushroom Ground, leaving compacted areas where the crop did not germinate as well as the rest of the field, as can be seen by the curving lines across the field (Figure 60). Drone imagery provides improvements in spatial resolution (pixel size of 3-5cm) in comparison to satellite imagery (5-10m), allowing individual tramlines to be seen and far greater detail in the variation in any crop.

This image (Figure 60) was taken just after emergence of the barley, and therefore still shows a lot of soil variations, such as the white patches where soils contain increased chalk fragments. In between two of these chalky patches of topsoil, at the N end of Mushroom Ground, there is a clear gap aligning to the entrance into the enclosure. This has not been visible from other PF satellite imagery and is outside the extent of the geophysical survey, although the geophysical survey does suggest a very subtle anomaly leading to this area, as can be seen on the NDVI image with the geophysical anomalies overlaid. The interpretation of this as an entrance to the enclosure has not been stated before.

Other features such as the ditch of the large enclosure, and the smaller Iron Age enclosure, can be seen through a mixture of soil and crop variations. At such an early stage in crop growth, these images demonstrate how cropmarks are not only an artefact of a ripening crop in early summer, but can be seen at much earlier times, as is the case here shortly after germination, and during the 3rd to 4th leaf stage in the oilseed rape crop.

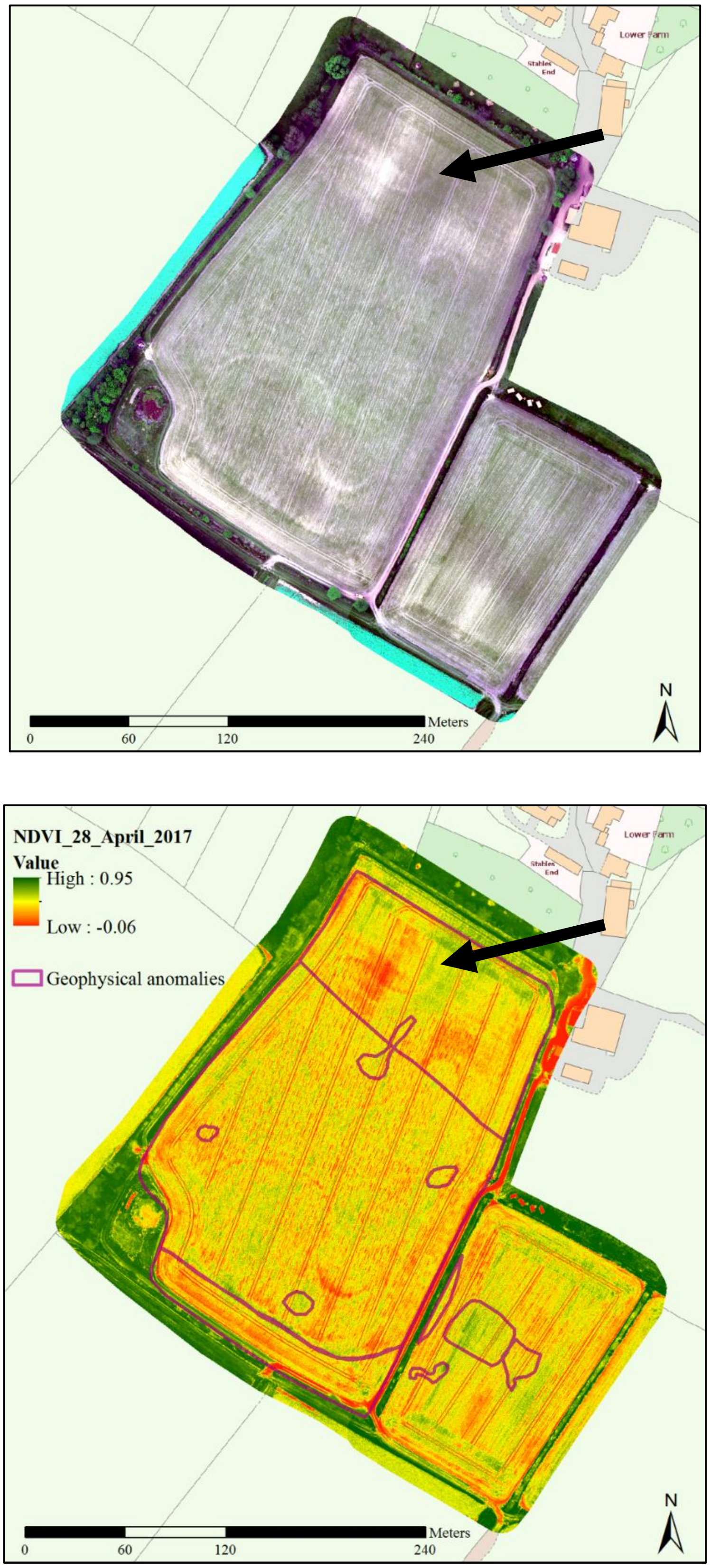

Figure 60: RGB drone image form 27th April 2017 (top) and NDVI drone image with geophysical anomalies (bottom)

The subsequent image, taken approximately two weeks after the first image (13th of May 2017), shows how the crop has grown, nearly covering the soil surface with green cover (Figure 61). The race tracks are still visible, as are some of the other anomalies pointed out above. The small Iron Age enclosure is more clearly visible on the NDVI image, in comparison to the RGB image, showing how utilising different wavelengths, such as NIR, can help improve the contrast between healthy crop and poor crop with soil interferences.

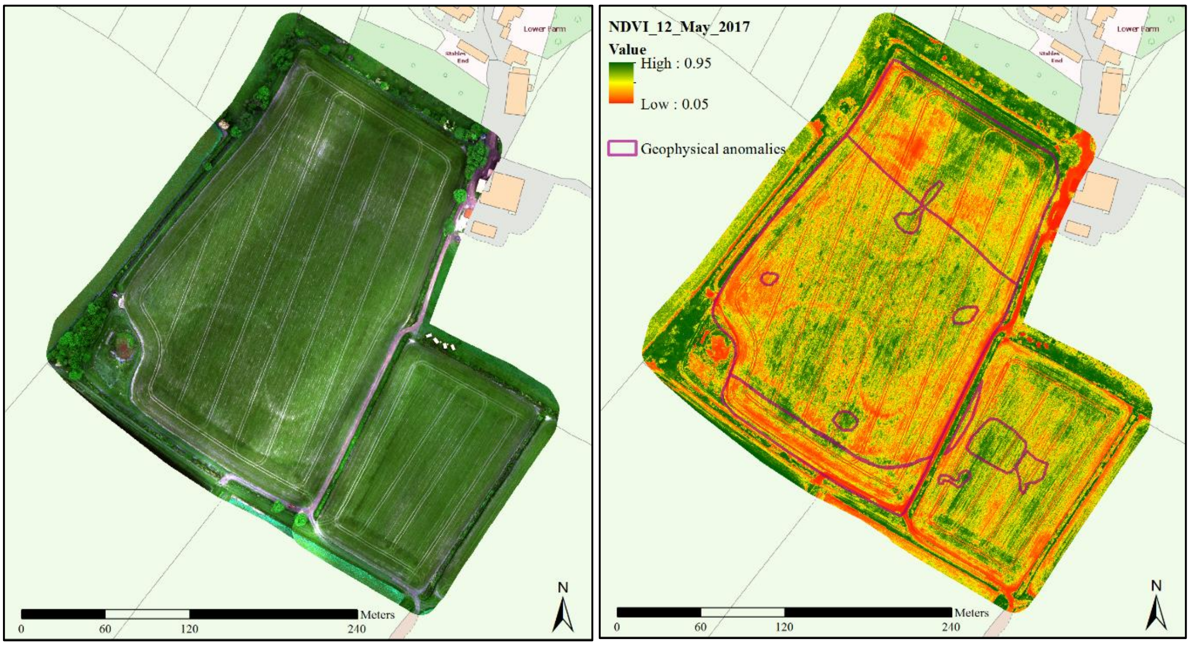

Figure 61: RGB drone image 12th May 2017 (left) and NDVI image with geophysical anomalies (right)

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Between the two dates, the cropmarks have changed considerably, showing two key advantages of PF imagery for archaeological investigations. Firstly that cropmarks can develop from the very beginning of crop growth, being influenced by local conditions, and from then on carry that variation throughout the year. This means that because agricultural and PF imagery tends to be focused on crop growth, it will monitor growth at multiple stages throughout a year, allowing observation of cropmarks at multiple times of the year. Secondly, some cropmarks appear at different points in the year depending on the particular soil and crop conditions, therefore multiple images allows a greater chance of detecting a variety of different types of cropmarks, not only the most visible and clear.

Figure 61 does draw attention to the limitations of drone imagery in comparison to satellite imagery, where varying light intensities during the drone survey produce lighter stripes across the orthorectified image. This can be corrected for by some commercial drones (not the DJI

Phantom 3) and is less apparent in the calculated vegetation indexes (due to the use of NIR bands) but can affect the data. Satellite imagery does not have this problem, however equally is limited by cloud cover and other artefacts that can be found in satellite data.

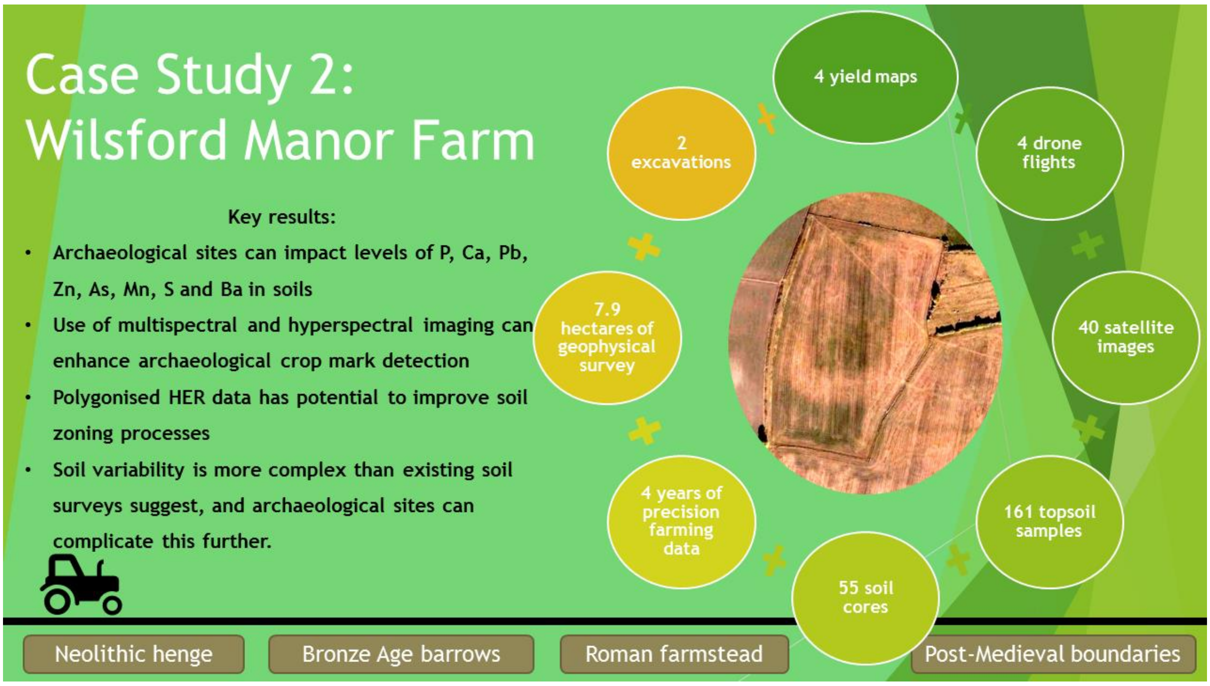
6.7 Summary

The two fields studied at Myncen Farm have provided a range of archaeological and PF data for evaluation. Archaeological data such as geophysical and HER data could have potential for use in soil zoning process within PF approaches. Their low resolution, and limited extent, can limit their usefulness for PF approaches that focus on the whole of a field rather than parts of it. Satellite imagery, drone imagery and farm nutrient maps all have shown that they can provide valuable archaeological information at a number of different levels. PF data can help evaluate parts of fields not covered by existing archaeological surveys through multi-image analysis, as well as build up aerial observations of existing archaeological anomalies, and promote large scale scoping of a whole farm through hot spots in farm phosphate analyses.

All of this has been brought together with the results of soil coring and pXRF analysis that highlighted the importance of the layers of soil between the topsoil and the parent material for archaeological impact on soils. In these limited but spatially defined locations soil elemental concentrations of Ba, P, Cu, K, Mn and Zn were altered. Topsoil variations were, however, more elusive with only P confidently detected and correlated with an Iron Age enclosure. The varying parent material and mixed soil profile complicating any subtle archaeological enhancements in the topsoil. The evidence collected has shown that the larger enclosure has a significant entrance way, but few physical or chemical signatures that would help determine its past use.

Chapter 7

7 Wilsford Manor Farm



Case Study 2:
Wilsford Manor Farm

Key results:

- Archaeological sites can impact levels of P, Ca, Pb, Zn, As, Mn, S and Ba in soils
- Use of multispectral and hyperspectral imaging can enhance archaeological crop mark detection
- Polygonised HER data has potential to improve soil zoning processes
- Soil variability is more complex than existing soil surveys suggest, and archaeological sites can complicate this further.

Figure 62: Summary of data and results from Wilsford Manor Farm (© author)

7.1 Site Introduction

Wilsford Manor Farm is a medium-sized farm situated near the village of Wilsford, in the Vale of Pewsey, Wiltshire, UK. It is a 224ha elongated block of arable land which is no longer directly connected to a farm yard, instead it is contract farmed by a local farmer on behalf of the landowner. The Vale of Pewsey sits in between the chalk landscapes of Salisbury Plain to the S, and the Marlborough Downs to the N; dividing the prehistoric sites of Stonehenge and Avebury, which together form a UNESCO World Heritage site.

7.1.1 Location

The block of land at Wilsford Manor Farm stretches from the fields surrounding the village of Wilsford itself (immediately S of the River Avon), up the slope towards Wilsford Hill and the edge of the military training area of Salisbury Plain. The study area (Figure 63) itself consists of a single field, named ‘Charles Sands’ (NGR - SU 0933 5722) which is 7.9ha.

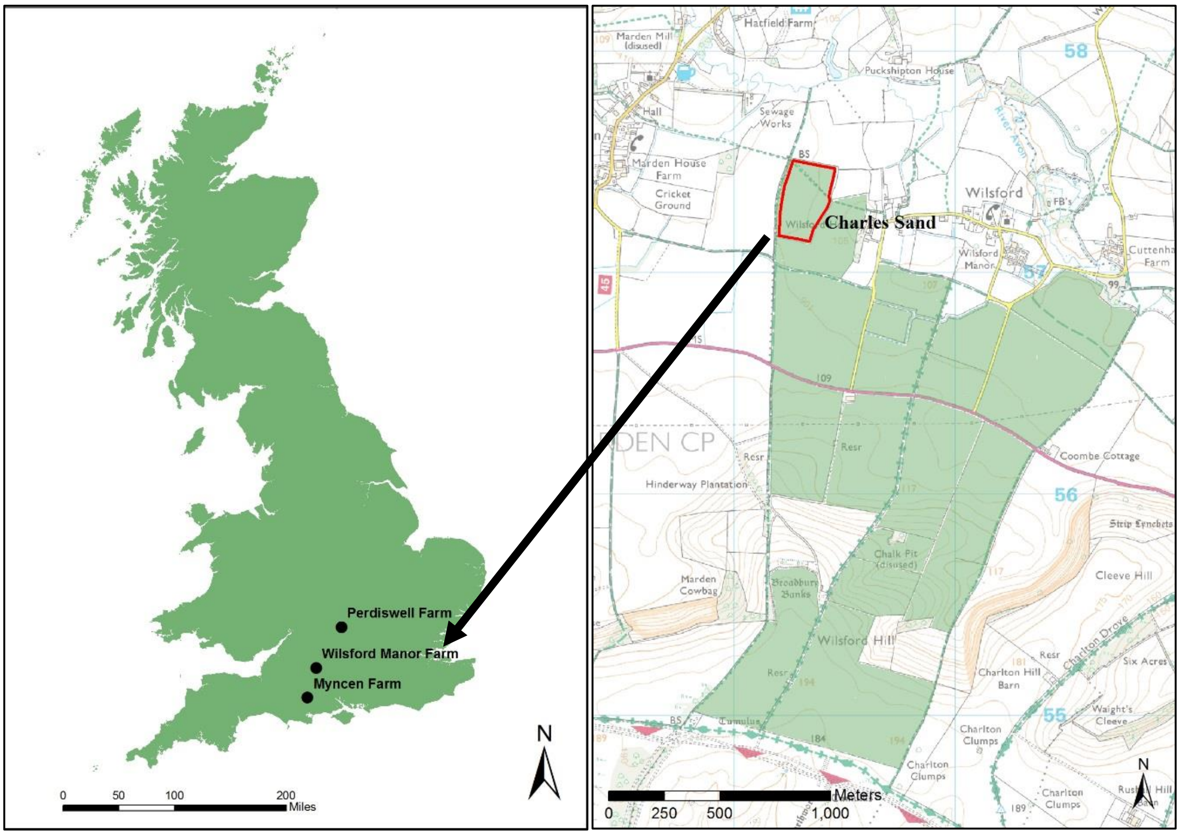


Figure 63: The location of Wilsford Manor Farm (left), and the outline of the farm and case study field 'Charles Sands' in red (right)

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7.1.2 Geology

The landscape surrounding the case study site has formed out of the erosion of the Upper, Middle and Lower chalk subgroups, down to the Upper Greensand below. The case study site itself, lies on the S side of this valley, on the transition between the West Melbury Chalk Formation (Lower chalk) and the Upper Greensand (Figure 64). Superficial alluvium deposits and some areas of peat lie along the lower areas of the landscape surrounding the river Avon.

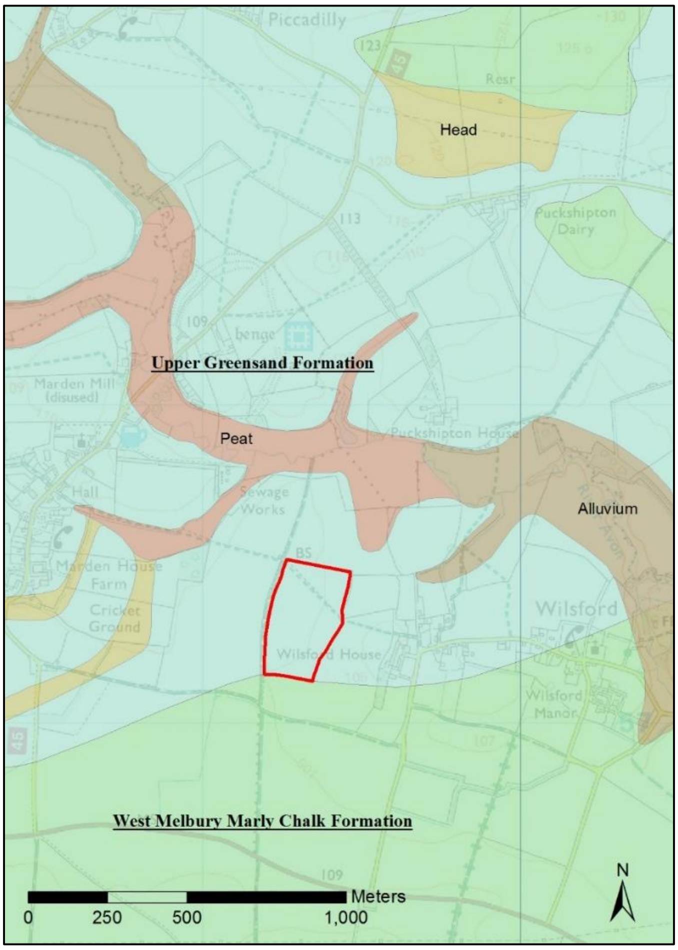

Figure 64: Solid and superficial geology of the area, the study field 'Charles Sands' is outlined in red.

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7.1.3 Topography

The variation in height across the case study area can be seen in Figure 65, A and B. Within the Vale, there is some subtle variation near the meandering of the River Avon. Lower lying areas surround higher outcrops of land, although the height difference is still small (a matter of metres). Charles Sands field lies at a height of 108-101m AOD, with the highest areas to the W, and the land gradually sloping away to the E and S (Figure 65 C). The hillshade created for the field shows a few undulations (Figure 65 D) and ephemeral E-W linear features in the northern half of the field but little else notable.

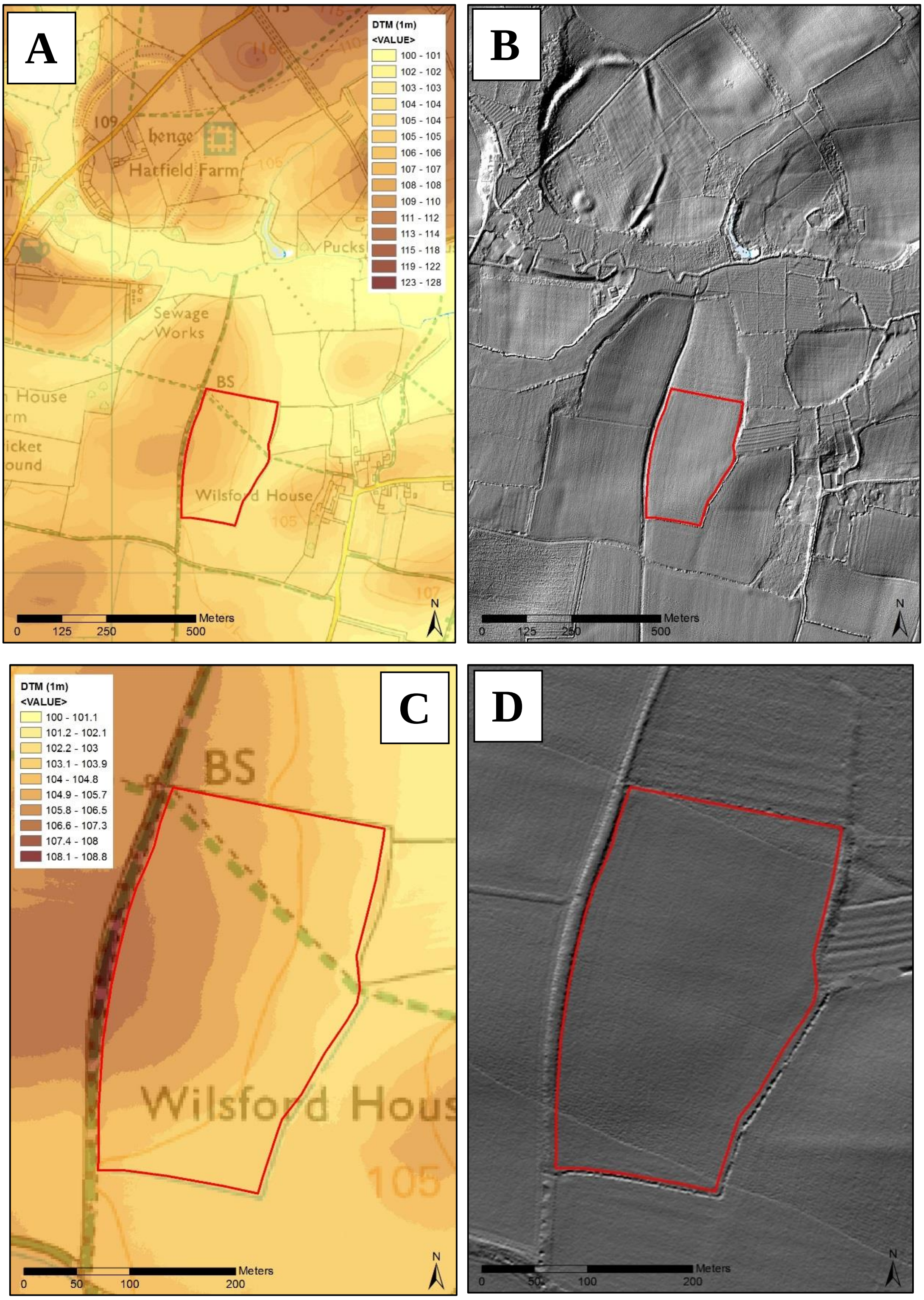

Figure 65: Topographical data for the study area, A = DTM of the wider area, B = Hillshade of the wider area, C = DTM of Charles Sands, D = Hillshade of Charles Sands

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7.1.4 Soils

There are the two key soil associations that cross the site, 511f Combe 1 and 571h Ardington (National Soil Resources Institute, 2018c). The descriptions given, suggest that the Combe soils are well-drained calcareous, fine, silty soils, with flinty inclusions. While the Ardington soils are deep, and well drained, fine and coarse loamy glauconitic soils. Typical profiles are indicated on Figure 66.

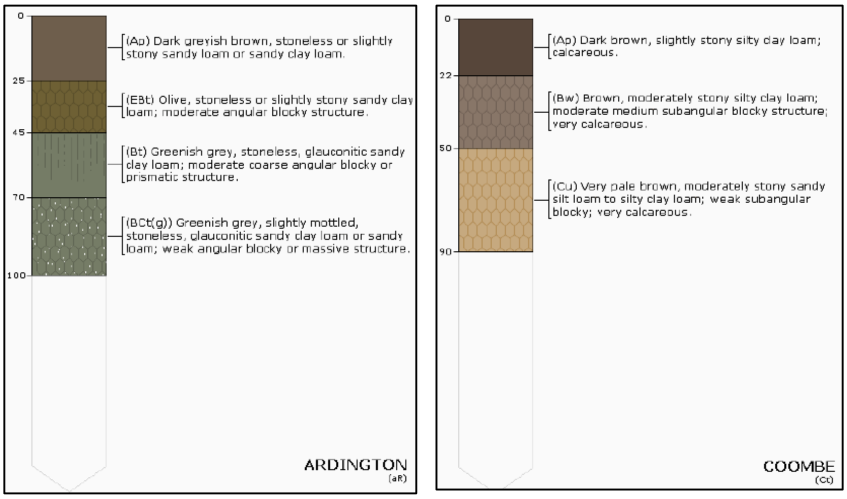


Figure 66: Typical soil association profiles for Ardington (left) and Coombe (right) (National Soil Resources Institute, 2018c)

More specifically, within those associations there are more detailed descriptions of each soil series. The three soil series are noted for this are field; Coate, Rougement and Stretham (Figure 67) (Cranfield University, 2019).

Within the Coate series, the topsoils are mottled dark-grey silty clay loams, with a similar textured grey subsurface horizon and overlie a finer textured mottled, olive-grey coarse blocky subsoil. Below 90cm there is usually coarser, greener glauconitic sandy loam.

Rougement series (within the Sutton soil association), not noted on the NSRI soil report but is noted in the Soil Survey for England and Wales map sheet SU 05/06, is defined as a coarse sandy loam over calcareous sands, often with eluvial and illuvial horizons in between. The series' distribution suggests that they are developed in remnants of gravelly drift, probably of the same age and origin as those underlying the Stretham soils, but in the case of Rougement soils, covered by a later loamy drift derived from nearby greensand outcrops.

Stretham series consists of a dark greyish-brown calcareous clay or clay loam, over a lighter olive-brown stony clay, with potential for mottling depending on local drainage.

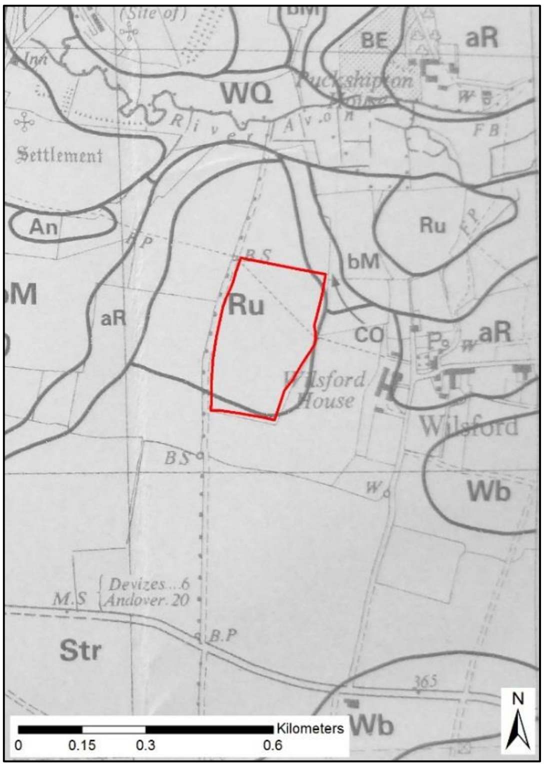


Figure 67: Charles Sands outlined in red (© Soil Survey England and Wales map sheet SU 05/06)

7.2 Agricultural and PF Background

7.2.1 The Farm

The 224ha farm is managed by a contract farmer, for the landowner. This is in contrast to Myncen Farm where the farmer and landowner are the same person. Here at Wilsford Manor Farm the whole set of operations is contracted out (from sowing to harvest and all operations in between).

7.2.2 Cropping and Fertiliser

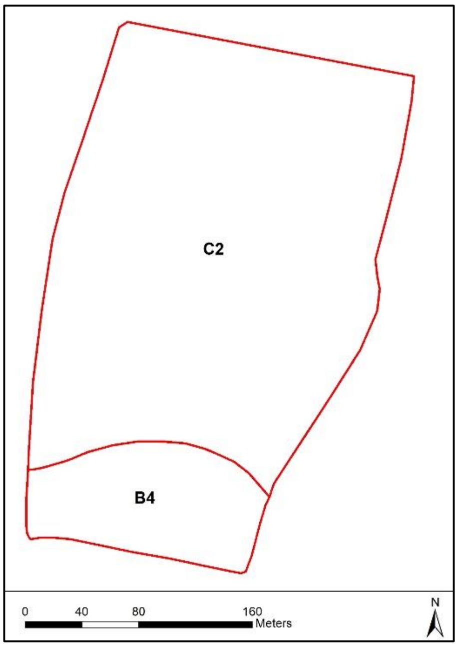
The arable block has a typical rotation of oilseed rape, winter wheat, followed by spring barley. The fact that this farm is away from the main farmyard of the contract farmer, and that the business does not include livestock, means that this land has not had organic manures or bio-solids spread on it in the recent cropping history. This does not mean that it has not had in the past. The fertiliser records collected (dating back to 2016 in the IPF Toolbox) show routine use of manufactured fertilisers and some variable rate applications of specific fertilisers to specific zones when necessary with a variable rate fertiliser spreader.

7.2.3 Cultivations

The typical cultivation system used at Wilsford Manor Farm is primarily a min-till system. The farm does some direct drilling (no disturbance of the soil between harvest and planting) depending on crop type and weather conditions. Ploughing is still used occasionally when conditions restrict min-till methods and where necessary to correct compaction or bury weed seeds.

7.2.4 PF

The contract farmer started using the PF service from IPF in 2011. The initial set up of the PF service involved a full zoning (completed by a soil scientist) to create the soil zones and provide additional details such as estimations of stone content, soil depth, calcium carbonate content, as well as a representative soil sample for each zone. This was collated with existing remote sensing data in the same way as at Myncen Farm, to form the final soil zones (Figure 68). Satellite imagery has been collected through the Toolbox from 2011-2015, but was stopped to save costs on this block of land. The Toolbox holds soil analysis data for P, K, Mg and pH from 2009, 2012 and 2015. Historic yield maps were available for 2006, 2007, 2008 and 2015. Total numbers of satellite images of the case study field are shown in Table 10.



IPF Soil Zone Codes
C2 = Non-calcareous topsoils, medium loam texture.

B4 = Deeper calcareous soils overlying chalk or chalky drift, clay loam texture

Figure 68: shows the IPF soil zones for Charles Sands, along with code descriptions (courtesy of IPF UK)

Total number of satellite images	**40**
NDVI	33
NDVI Early	15
SOB	2
CHL	5
Average number of images per year	**7**
Total number of images without cloud	**37**

Table 10: Total number of satellite images collected at Wilsford Manor Farm, separated into each type of image.

7.3 Archaeological Background

7.3.1 Pre-20th Century

The Vale of Pewsey, having been noted from the 16th and 17th centuries as a fertile valley most suitable for agriculture, has been subject to archaeological research and observations since the early 19th century (Carpenter and Winton 2011,10-12). Marden henge is the most significant site within the area, it is now a scheduled monument under the Ancient Monument and Archaeological Areas Act 1979. It was previously known as the ‘Hatfield Earthworks’ and represents one of the largest Neolithic henges in Britain. Marden henge was studied by Colt Hoare, and together with his work at Stonehenge and Avebury, he suggested that all three were religious sites and connected by a routeway (Colt Hoare 1819,117 in Carpenter and Winton 2011).

7.3.2 20th Century Work

Aerial work by O.G.S. Crawford and Alexander Keiller provided some of the first details on the similarities between the henges at Marden, Avebury and Stonehenge, capturing the first ever aerial images of the surviving monuments (Carpenter and Winton, 2011). The noticeable difference between the three being that Marden sat upon the Upper Greensand, unlike the other two, which sit upon higher chalk downland. Later work in the 1960s and 70s revealed Iron Age features, Roman buildings and an Anglo-Saxon cemetery in the vicinity of Marden henge which added to the complexity of this archaeological landscape.

7.3.3 21st Century Work

After the Avebury World Heritage Site NMP and the Salisbury Plain Training Area NMP in the late 1990s, a gap was left in between the two areas, which was noticed when renewed work at Marden began by Field and Leary (2012). The Marden and Environs NMP was undertaken in 2009 to fill in these gaps, creating a continuous area of mapped historic environment between the three important prehistoric sites, as well as recording of other periods. This Marden and Environs NMP covered 75 square kilometres and added another 304 previously unknown records to the Historic Environment Record (Carpenter and Winton, 2011).

7.3.4 The Field: Charles Sands

Within the case study field itself, the Wilsford henge, as it is now known, has been recorded numerous times over the last 50 years by aerial photography (Figure 69 and 70), and published as the Wilsford henge by Harding and Lee (1987: 301–2). It is a broad and irregular penannular dich with a gap facing to the NE. There is no clear evidence of an external bank visible, however, the whole field has been ploughed in the past flattening any surviving earthworks. Also of interest are the ring of pits surrounding parts of the circumference of the ditch.

Figure 69: Aerial Photograph of the Wilsford Henge in July 1990 (© Historic England NMR – 4622/18)

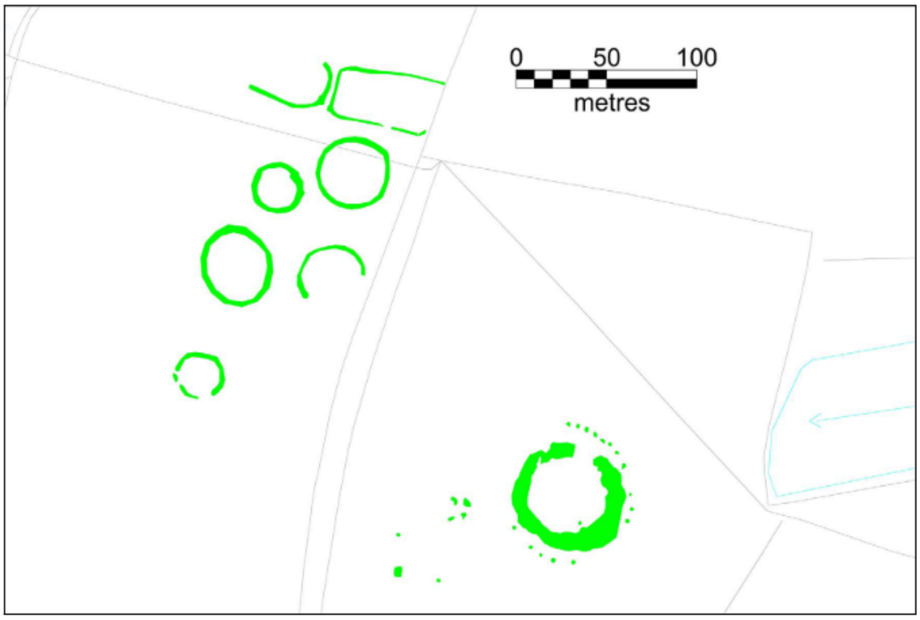


Figure 70: Cropmarks recorded from the Marden and Environs NMP (Carpenter and Winton, 2011)

Further geophysical surveys completed in 2013 (Figure 71) suggested that in addition to the pits recorded on the outside of the henge ditch, there were also pits on the inside of the ditch (Linford *et al.*, 2013). These formed a sub-circular shape and were only recorded on the southern portion of the henge. The magnetic gradiometer results identified a number of linear features not recorded from the aerial survey, which cut through the henge ditch, and form a number of rectilinear enclosures to the W and SW of the henge. These were interpreted as a Roman settlement of some kind next to the henge and Wilsford barrow cemetery. Previous field boundaries and cultivation marks from different time periods were also visible when exposed in particular types of soil.

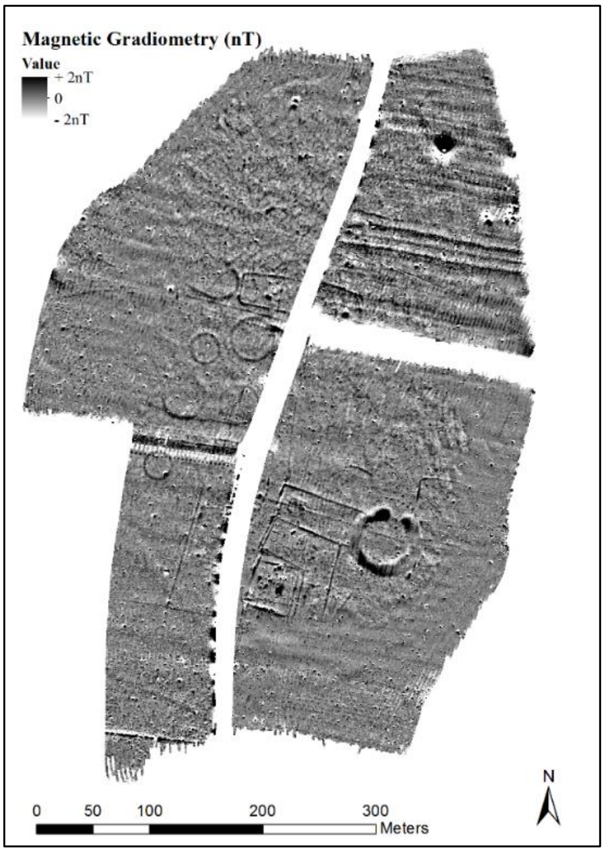


Figure 71: Magnetic gradiometer data from the 2013 geophysical survey (Data courtesy of Historic England)

In 2015, two excavations took place as part of the University of Reading's Archaeological field school. The first trench was excavated across half of the entrance to the Wilsford henge revealing a 3m deep henge ditch cut into the greensand (Figure 72). The excavation of this ditch and the creation of what is presumed to have been a substantial external bank, now completely eroded away, will have introduced a substantial amount of greensand sediment to the topsoil surrounding the henge. In the lower part of the ditch fill there was a middle Bronze Age burial, and in the upper part a substantial midden of late Bronze age to early Iron Age date, with quantities of pottery and bone etc. The ditch cutting across the henge was also excavated and confirmed as of Romano-British date (Leary, 2015).

The second trench excavated part of the cropmarks to the W of the henge. This was confirmed to be a Romano-British settlement with associated ditched enclosures. Traces of a building were found (D. Roberts, pers. comm.). Borehole survey across the track which is in a raised causeway forming the W edge of the field, showed that there were Romano-British artefacts on a land surface below the causeway which is accordingly a post-Roman feature as the continuance of ditch crop marks across the causeway indicates (M. Bell, pers. comm.).

In 2016 two test pits targeted features outside the Wilsford henge identified from the aerial photography and geophysics. The test pits found two large pits/postholes, both over a metre deep. One contained a ramp and a postpipe indicating it was a large posthole, the other a charcoal-rich fill. Both were of contrasting geological context, one which was on calcareous drift having a chalky-fill, the other having a non-calcareous fill of greensand derivation, demonstrating the complex soil profiles across a relatively small area (Leary, 2016).

Figure 72: Aerial photograph of the excavation at Wilsford Henge in 2015 (left) and photograph of the excavation of the ditch terminus (right) (© University of Reading)

7.4 Fieldwork Results

7.4.1 Soil Geochemistry

The collection, preparation, and pXRF analysis of 392 soil samples from Charles Sands field provided a large enough dataset to investigate the spatial and vertical variation of elements within the soils. There were 166 samples that related to the topsoil (0-20cm) at a 20x20m grid spacing (Figure 73A), with the number of samples down the soil profile determined by 55 cores (Figure 73B).

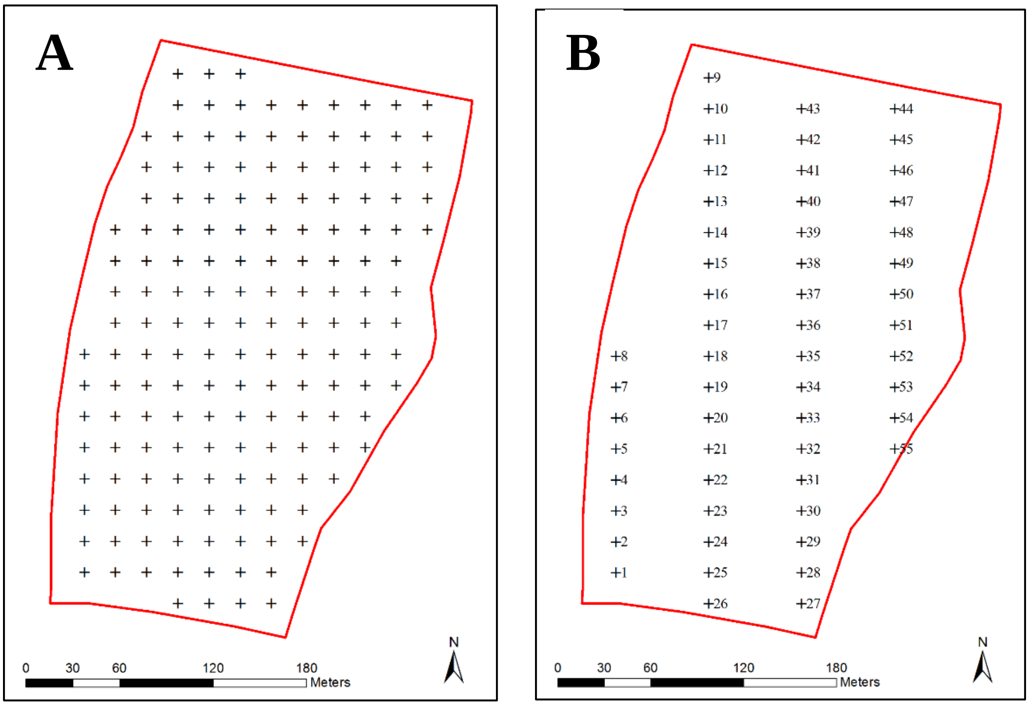


Figure 73: The sampling grid for topsoil samples (A) and core locations (B) (© author)

From this combined dataset of 392 soil samples, 20 elements were detected by the pXRF with reasonable detection reliability and were entered into the PCA analysis. The component matrix gives four components covering 75% of the total variance of the dataset. The 1st component, covering 40% of the variance of the dataset shows Si, Ti, V, Rb, Nb, Zr, Zn, K forming a group that positively (> 0.7) correlate with each other (group A in Figure 74). This is in contrast to elements Ca and Sr which negatively correlate with the above elements (> -0.7) but correlate strongly together (r^2=0.96) (Figure 74 group B). This distinguishes between the samples that have high calcium and strontium content *i.e.* the soils and subsoil that are derived from, or contain high levels of, the lower chalk substrate, and the soils that are mainly correlated with other elements *i.e.* the greensand-based soils and clay-rich soils.

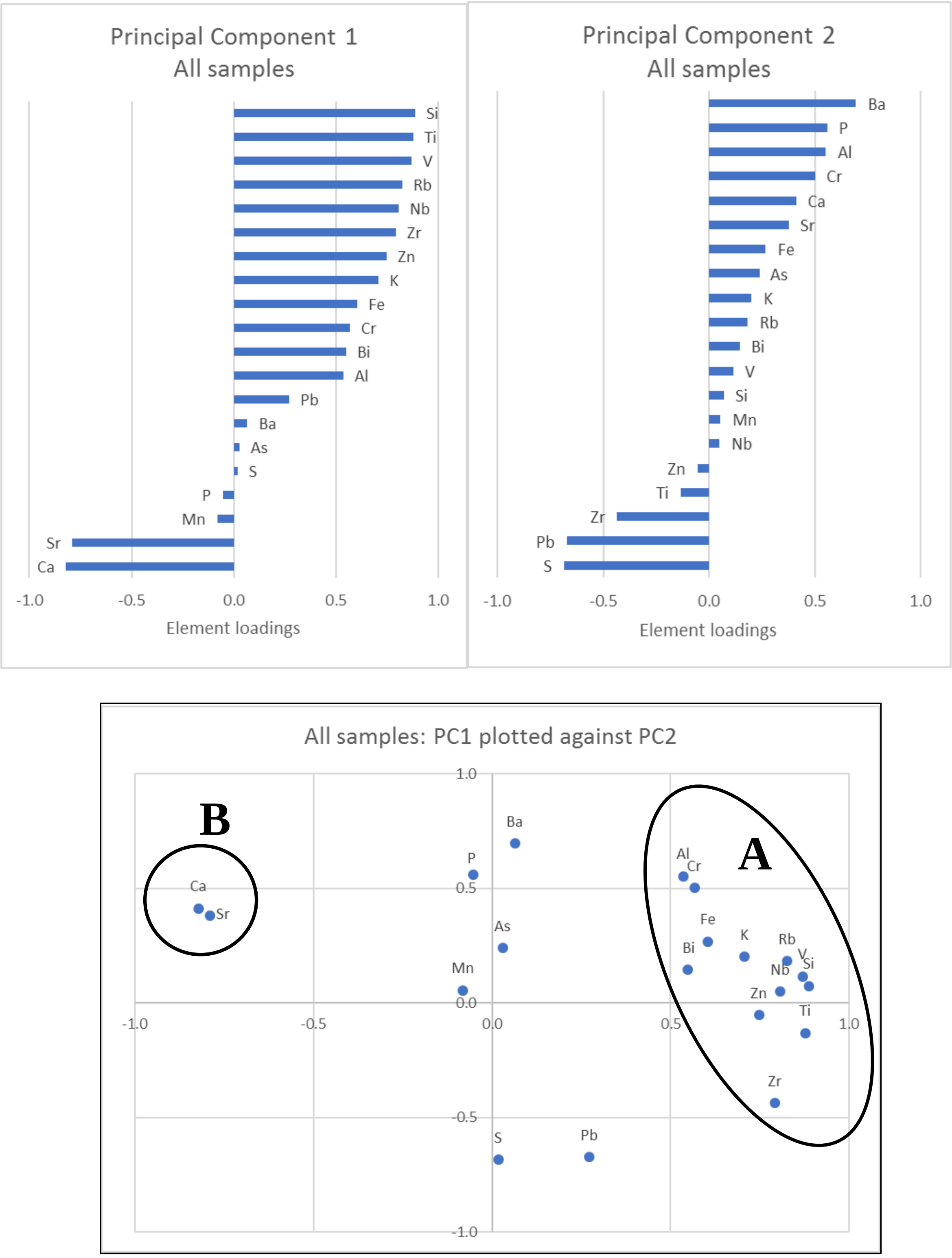


Figure 74: Elemental loadings for PC1 (above left) and PC2 (above right), and graph of PC1 plotted against PC2 showing elemental groups A and B (© author)

Elements that did not fit into either of those two groups were As, Ba P, Pb, S, and Mn. From PC2 this group can be further divided into S, Pb with negative loadings, Ba and P with positive loadings, and Mn and As sitting in the middle. Some reason for this may in part be due to the limit of detection, especially for arsenic which only has 209 detections out of 392 samples, with 183 samples below the threshold of detection of the pXRF.

These initial results, being based on all 392 samples, will include samples with a high concentration of parent material, allowing an objective assessment of the different elemental associations each particular soil type has. It also shows that P, Ba, As, Mn, S and Pb do not relating strongly to either major elemental grouping. This could mean that their connection is fairly random to the soils they are in, but could also hint a relationship to anthropogenic impacts that would not necessarily relate to soil types.

To explore this further, a separate PCA was done on each horizontal layer of soils (irrespective of their soil type) to identify any major variations with depth (Figure 75). The topsoil (layer 1) produced a different set of elemental loadings in comparison to the whole sample dataset. As could be expected, the topsoil is more homogenous due to the thorough mixing of upper layers, as well as the addition of fertilisers and plant material into the Ap horizon over many years, meaning the loadings are less distinct and there is not such a clear delineation between the Ca/Sr soils and the silicate/clay soils. Instead two elements (K and Mn) stand apart from the widely spread, main group.

In the lower layers, 2,3 and 4, there is an increasing division between the positive and negative loadings. This is likely to be caused by samples becoming more polarised between stronger chalk-based elemental signatures, in comparison to the greensand signatures. Spatially, the colourmap of layer 4 (PC1) shows the distribution of these loadings and correlates well with the elemental depth maps (Figure 76) of calcium distribution throughout the top four layers.

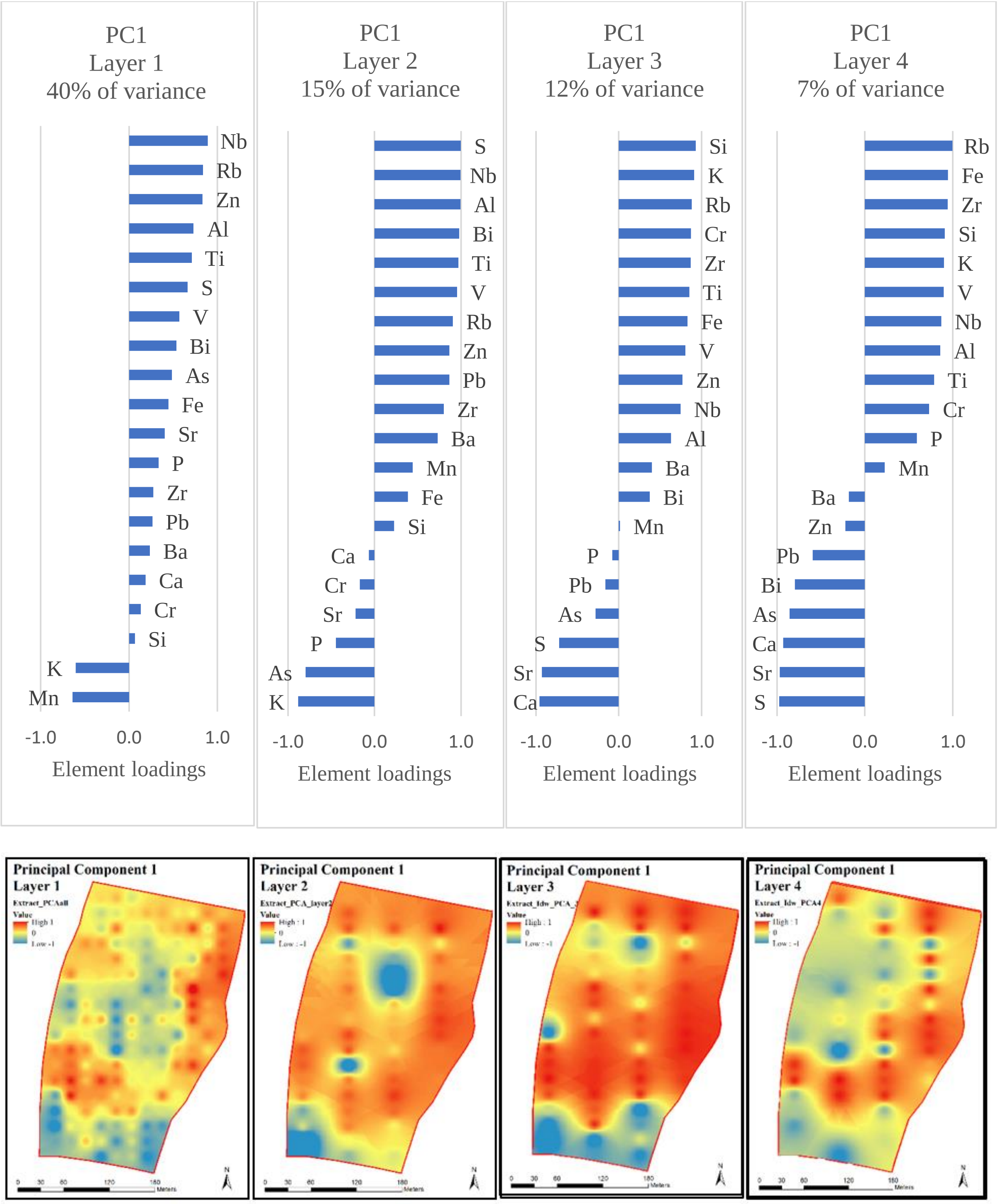


Figure 75: Elemental loading values (above) and corresponding colour map for each soil layer (1-4) (below) (© author)

The subsoil variation, and topsoil variation, is clearly much more complicated than suggested by the large scale geological mapping (Figure 64), or even the more accurate Soil Survey for England and Wales map (Figure 67). Instead of widespread greensand over most of the site, there is a significant area of fragmented chalk deposits (soliflucted calcareous drift) on top of the greensand in the near surface stratigraphy (0-2m), as was further evident from the excavations at the Wilsford henge and Romano-British farmstead.

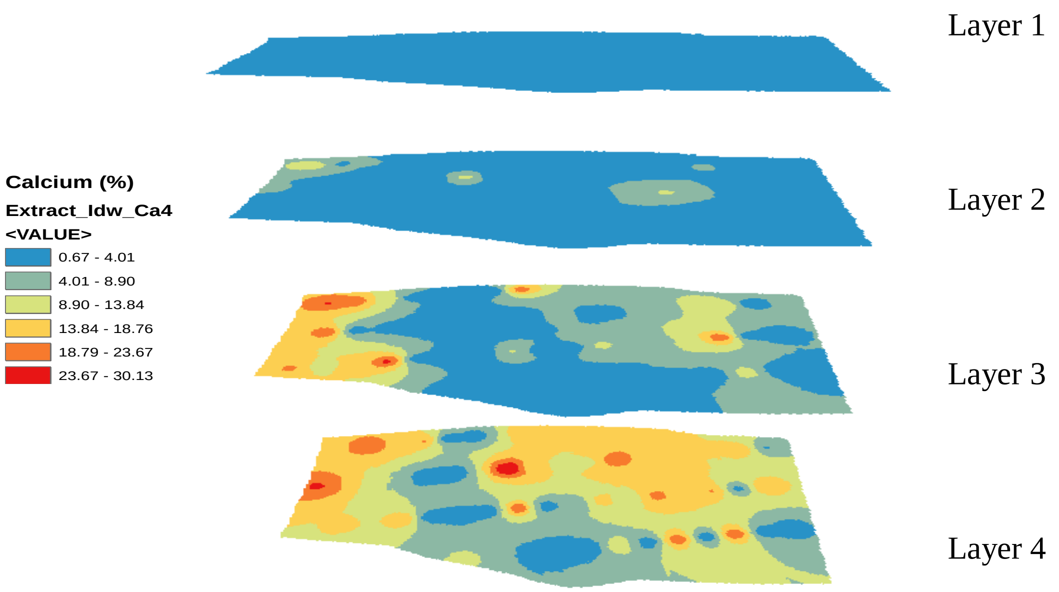


Figure 76: Ca variation across the site at various depths (© author)

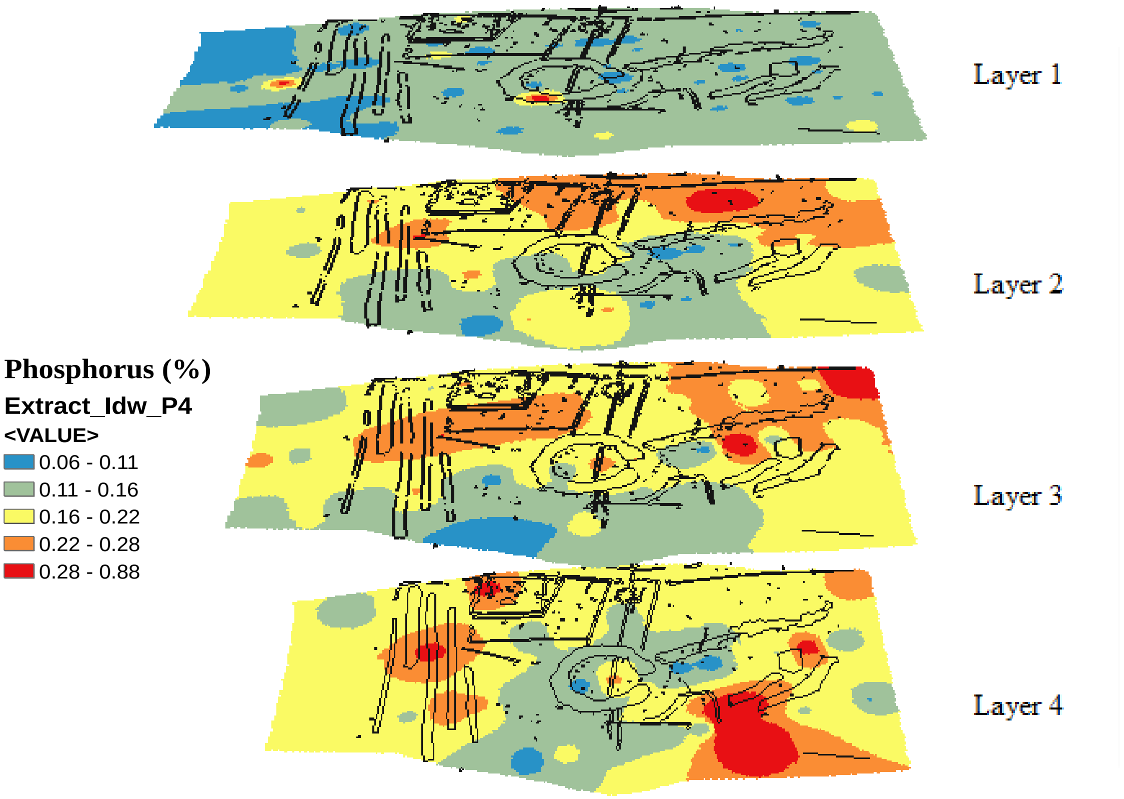
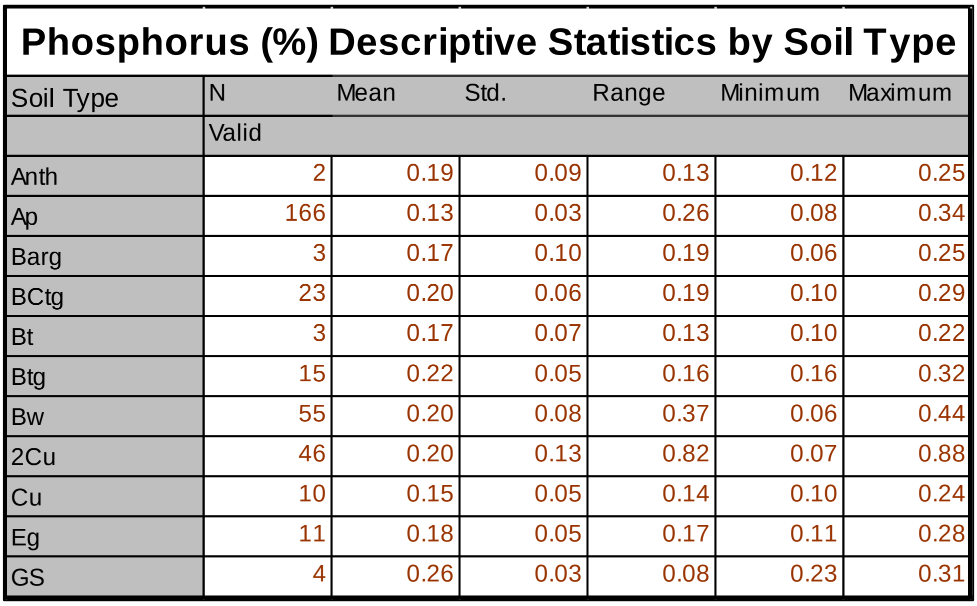


Figure 77: P variation across the site and at various depths with geophysical anomalies (courtesy of Historic England) (© author)

Turning to other specific elemental distributions, the spatial P maps corresponding to each soil layer are shown in (Figure 77). In the topsoil, there is little variation in P, with levels averaging higher in the N of the field in comparison to the S (divided by an old field boundary showing variation in historic land management). In layer 2 the variation becomes more significant, with very high P levels in the W of the field. This pattern continues in layer 3, but in layer 4 the pattern shifts with a couple of very high P values in the E of the field. These results show that P variations occur across different soil types (whether those are chalk or greensand-based) and confirm the PCA analysis.

P levels in this field have a mean of 0.19% with a SD of 0.08% across all samples. Breaking this figure down, there are some subtle variations which can be separated out by soil type (Table 11). Greensand (GS) samples have a mean P value of 0.26 (SD 0.03%), while fragmented chalk (Cu) samples have a mean P value of 0.15 (SD 0.05%). This only counts for a small number of the total samples but does represent the most consistent chalk and greensand samples collected across the site and therefore are reliable background samples.



Phosphorus (%) Descriptive Statistics by Soil Type

Soil Type	N	Mean	Std.	Range	Minimum	Maximum
	Valid					
Anth	2	0.19	0.09	0.13	0.12	0.25
Ap	166	0.13	0.03	0.26	0.08	0.34
Barg	3	0.17	0.10	0.19	0.06	0.25
BCtg	23	0.20	0.06	0.19	0.10	0.29
Bt	3	0.17	0.07	0.13	0.10	0.22
Btg	15	0.22	0.05	0.16	0.16	0.32
Bw	55	0.20	0.08	0.37	0.06	0.44
2Cu	46	0.20	0.13	0.82	0.07	0.88
Cu	10	0.15	0.05	0.14	0.10	0.24
Eg	11	0.18	0.05	0.17	0.11	0.28
GS	4	0.26	0.03	0.08	0.23	0.31

Table 11: Descriptive statistics of P across different soil types at Wilsford (© author)

The Ap horizon is relatively low in P (0.13%), with many soil types that form the main subsoil (Barg, Bt, Btg, Bw, Eg, BCtg) zone being around 0.17-0.22%. For samples with high levels of glauconitic sands (GS) there are high levels of P (0.26%), and soils formed on soliflucted chalky drift have lower P values (0.15%). This granularity in the data allows some comparisons to be made in relation to the spatial distribution of P shown in Figure 78. The high levels of P in the W of the field, within layers 2 and 3, do not match a greensand-based soil. Instead those soils sit on top of chalky drift (Figure 78 shows a core for that area). Therefore, either soils in this area have had more greensand transported into the layer 2 and 4 horizons (between 30 - 50cm deep), or this could relate to anthropogenic inputs of P. Other elemental values were checked to see whether increases in other elements were seen in these samples indicating a geomorphological interpretation. No significant variations appear in Ca, Fe, Si or Al results in this area that would link to the pattern of P. Unfortunately a lack of geophysical anomalies limits the interpretation of this spatial pattern, however, an area devoid of geophysical anomalies does not rule out the possibility that this P enhancement is of anthropogenic origin and related to land use of that particular area (animal penning, middening etc).

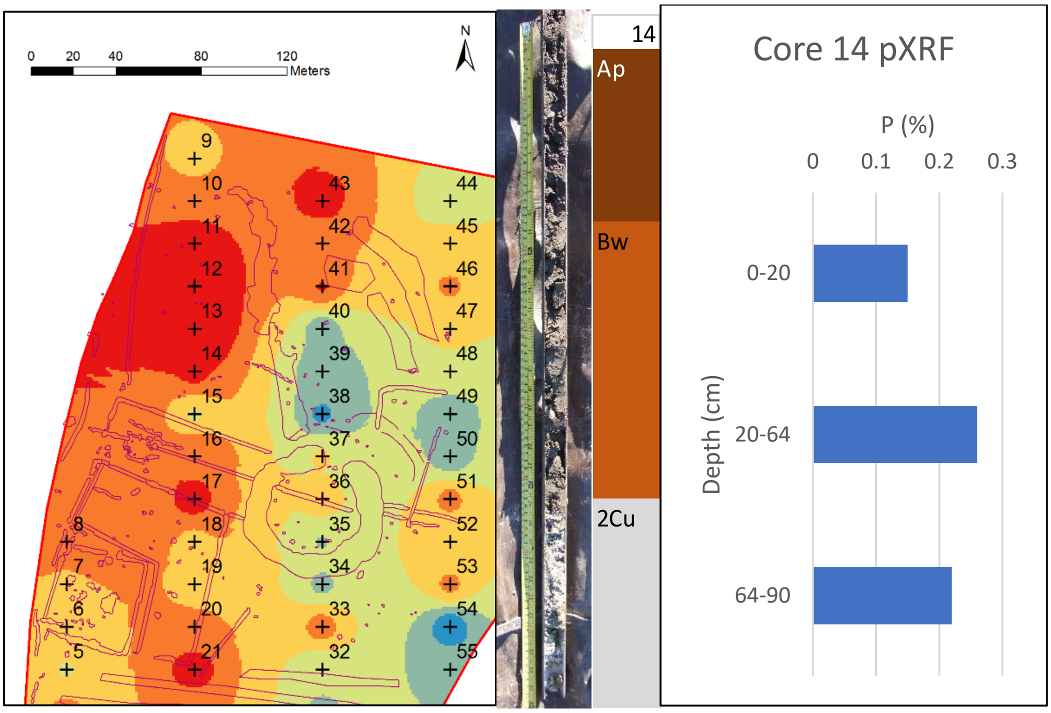


Figure 78: P variation in layer 2 with core locations (left), the core photograph and profile description (centre) and the pXRF values of P for that profile (courtesy of Historic England)(© author)

Other elemental variations across the site include a contrast between the S part of the field and the N part (divided by a historic field boundary). It appears that the topsoil in the S area is higher in a variety of metals such as Zn, Ba, Bi, Cr, Al, V, Nb, Rb and Ti. This enhancement appears in layer 1 and layer 2, broadly upper and lower topsoil, but disappears further down the profile and does not correlate with any parent material effects (Figure 79). This indicates that the management and manuring (with this mix of mainly metals it is likely that manuring or some kind of inorganic fertiliser application is the cause) was different during the past in comparison to the N part of the field.

Other elements of interest that were not related to major soil groups, such as S, Ba and Mn, did not show any particular spatial patterns other than division between S/N parts of the field as described above, and are not explained any further. Arsenic, zinc and lead, however, do show intriguing spatial variation.

Arsenic levels across the field are low (0-13ppm) and certainly within the average expected values within soils (Kabata-Pendias, 2011: p.353). Despite this, the spatial distribution of As for the topsoil requires some evaluation, since it appears that there is an enhanced halo (*c.* 12ppm in comparison to background topsoil levels of 7ppm) surrounding the henge area (slightly wider than the henge itself) (Figure 80). The scenario is similar for Zn where average values in the topsoil are from 20-40ppm, but surrounding the henge analysis results in 50-60ppm. Figures 79 and 80 show that the variations in As and Zn only appear in the topsoil, but not in lower layers. Both of these elements do not correlate particularly well with either the greensand (where As has average of 6ppm and Zn an average of 31ppm) or the chalky deposits (average As is 5ppm and average Zn is 28ppm), showing that it is unlikely to be parent material causing this variation.

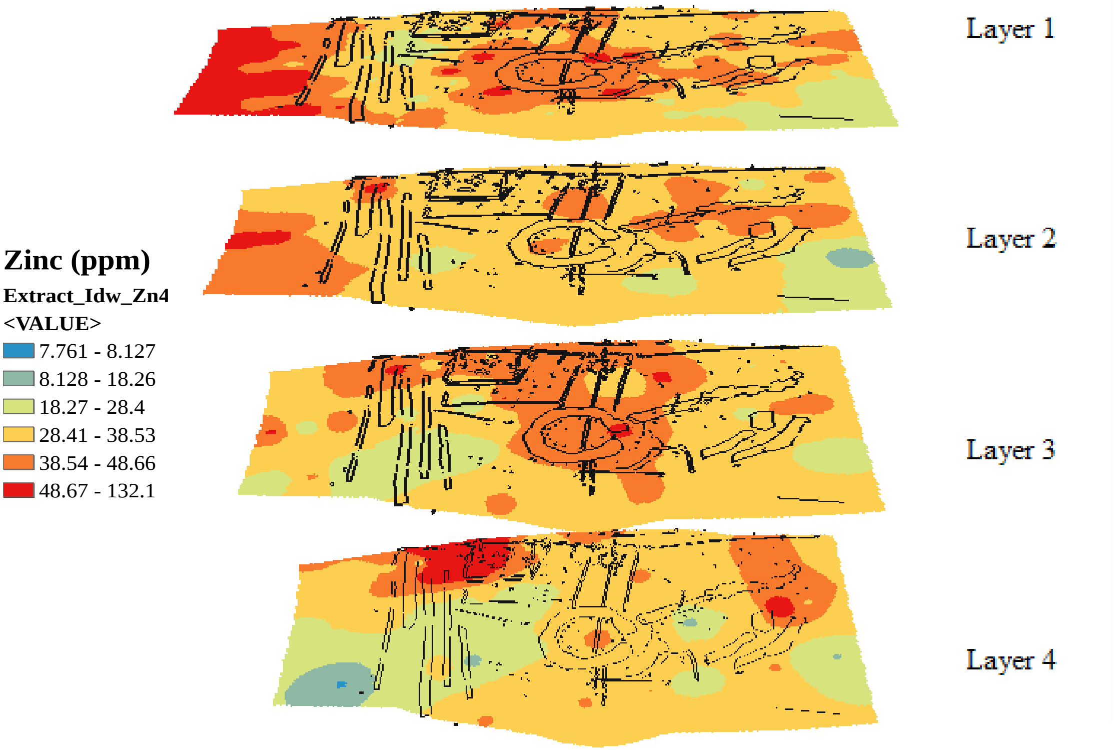


Figure 79: Zn variation across the site, at various depths and with geophysical anomalies (courtesy of Historic England)(© author)

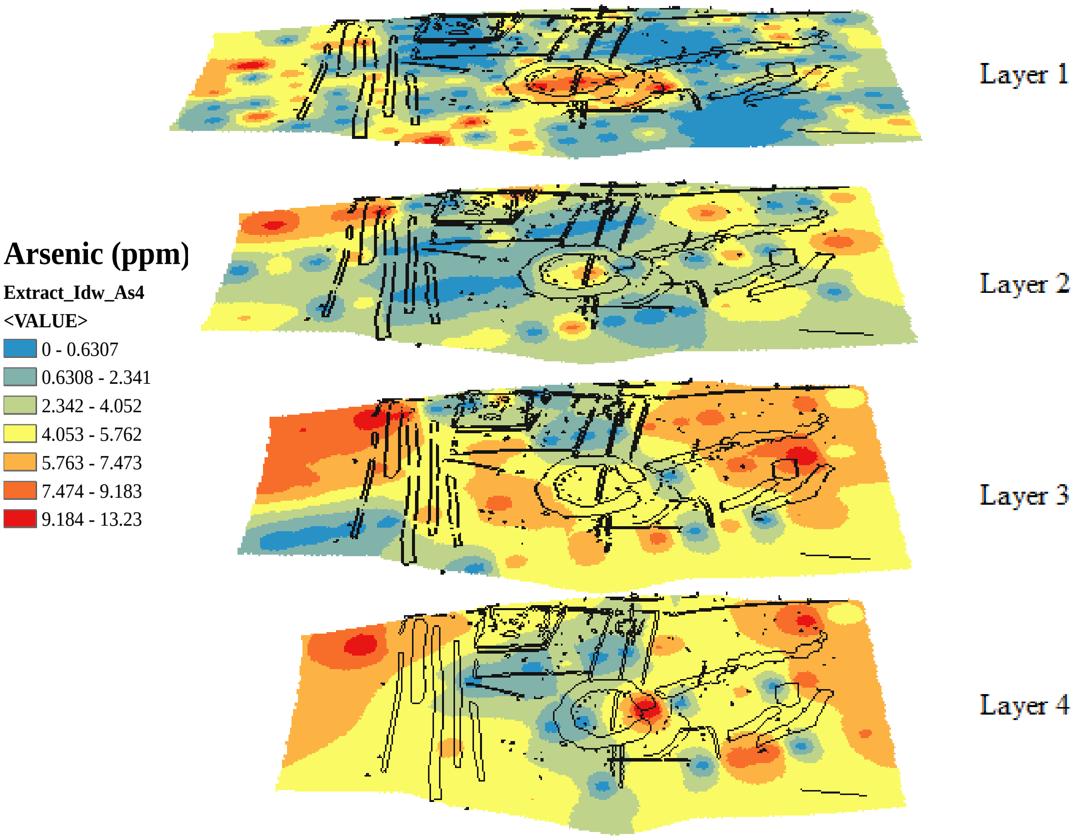


Figure 80: As variation across the site, at various depths and with geophysical anomalies (courtesy of Historic England)(© author)

The origin of these variations in As and Zn is uncertain. If increased concentrations are not coming from parent materials, then three further explanations are possible. One is that other soils from specific horizons, do have higher values that might have been mixed into the topsoil surrounding the henge. From soil statistics segregated by soil type, however, none have a higher average than 8ppm for As and , making this unlikely. Secondly, due to the generally low levels (especially relating to As) the detection of the pXRF has to be taken into account. Although there are consistently higher detections in the area of the henge, many data points surrounding (coloured blue in Figure 80) are below LOD. Therefore it is possible this is an artefact of detection. In which case for a more robust interpretation, samples and perhaps even more detailed sampling, should be analysed by a more robust method such as ICP-MS or XRF to confirm if this is a genuine variation. The third, and from the data presented here quite likely, scenario is that this pattern of variation is actually caused by human actions relating to the henge (whether that is the use, destruction or subsequent land use of the henge area in late Bronze Age/early Iron Age) that have contributed to the As and Zn content of the soil.

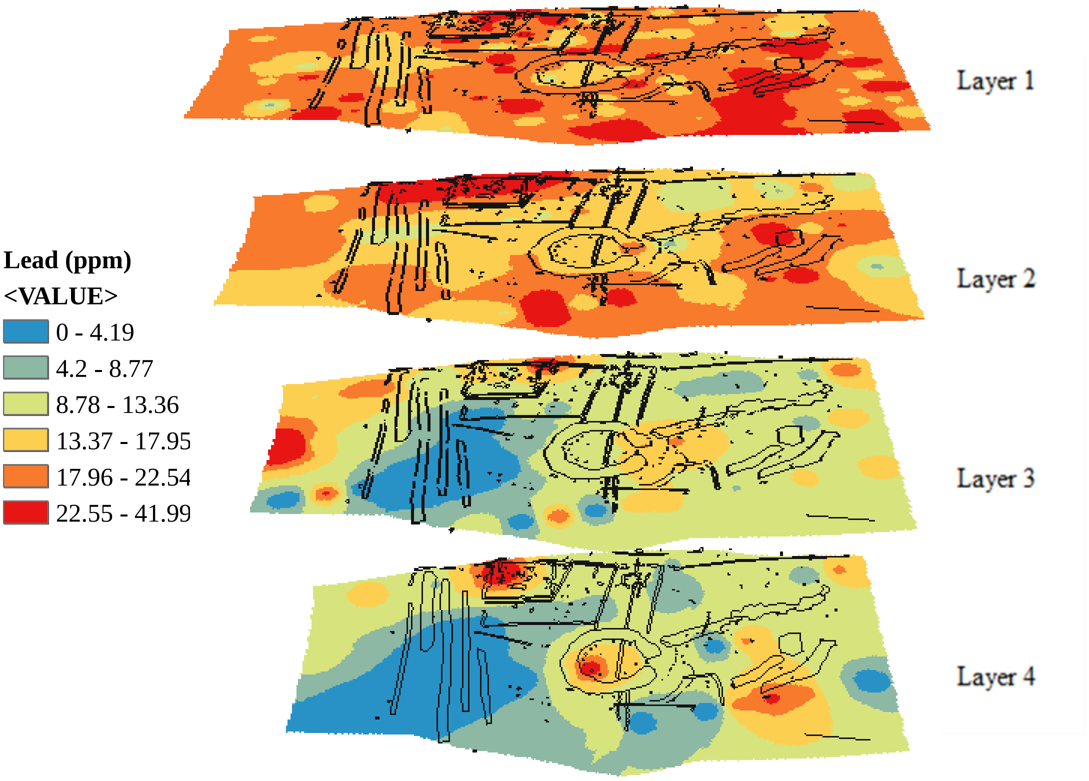


Figure 81: Pb variation across the site, at various depths and with geophysical anomalies (courtesy of Historic England)(© author)

The Pb content of the upper and lower topsoil is higher than the lower layers (by *c*.20-40ppm), with a fairly even distribution across the field. These ranges are again within normal soil levels (Kabata-Pendias, 2011: p.339). Pb showed no strong correlation with either major soil group and is shown by Figure 81 to vary in different places to the underlying parent material. There is a subtle but noticeable enhancement surrounding the Roman farmstead and enclosures at the W edge of the field, especially in layer 2, which could be related to activity in the Roman period. However, the enhancement is not significant in comparison to other enhancements in the rest of the field which do not correlate to archaeological anomalies from the geophysical survey. This makes it difficult to conclude whether the enhancement is caused by anthropogenic action or not.

The University of Reading excavations in 2015, enabled an opportunity to take samples from some of the *in-situ* archaeological features investigated. Two Roman ditches excavated (feature 442 and 443 on Figure 82 and 83), were sampled semi-systematically, targeting particular stratigraphic horizons. These two ditches relate to the network of ditches that cover this area of the field and surround what is interpreted as a likely Roman agricultural barn with chalk pads for large timber structures and a number of other smaller post holes and pits.

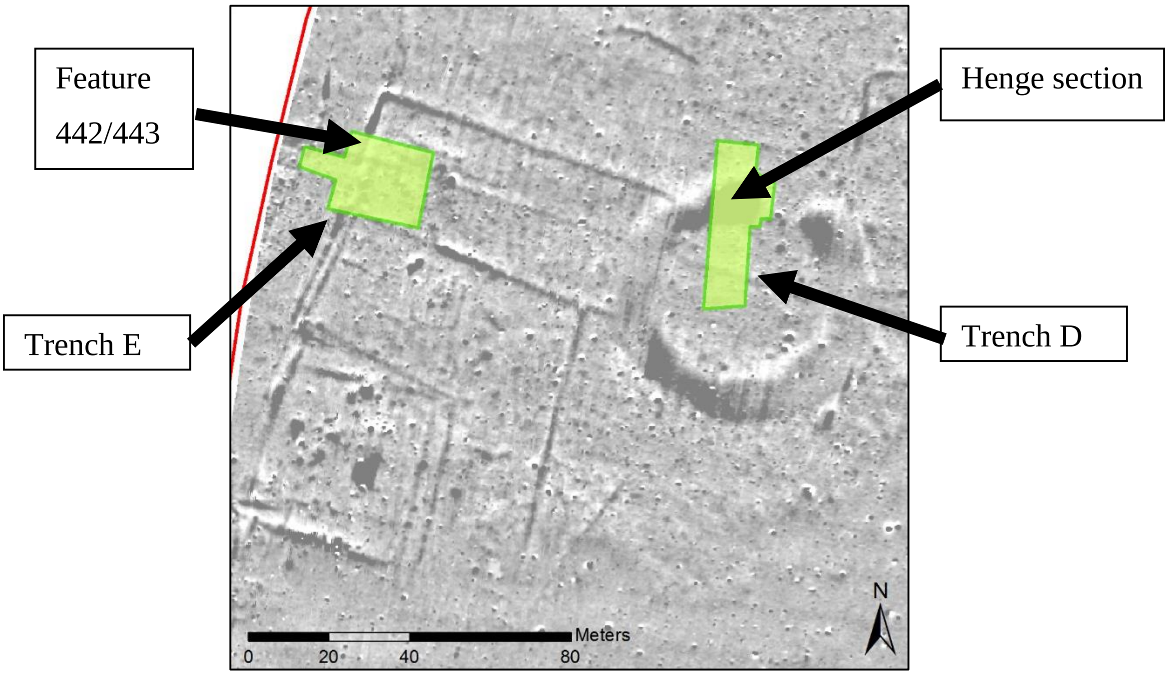


Figure 82: Location of Trenches E and D, and ditch features 442 and 443 in relation to the geophysics (data courtesy Historic England)

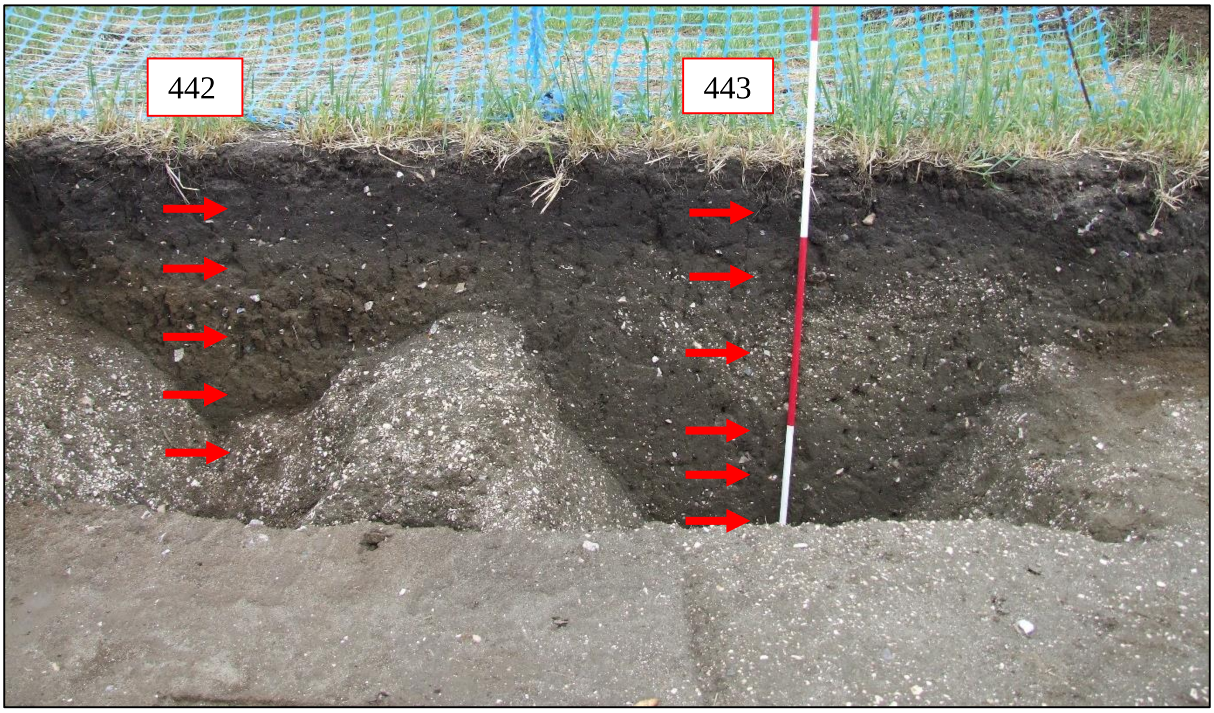


Figure 83: Excavated sections of feature 442 and 443 in Trench E, with arrows indicating pXRF sampling (© author)

The pXRF analysis for feature 442 (Figure 84), which was shallower than 443 and is filled with a more homogenous deposit, shows an enhancement of P (0.21%) and K (11,300ppm) in layer 4 (*c*. 60cm deep). The other elements shown do not vary in any significant way and generally conform to the typically expected elemental profile that matches other similar areas of the field, with increasing Ca values closer to the underlying calcareous drift, and decreasing levels of Pb from the topsoil down.

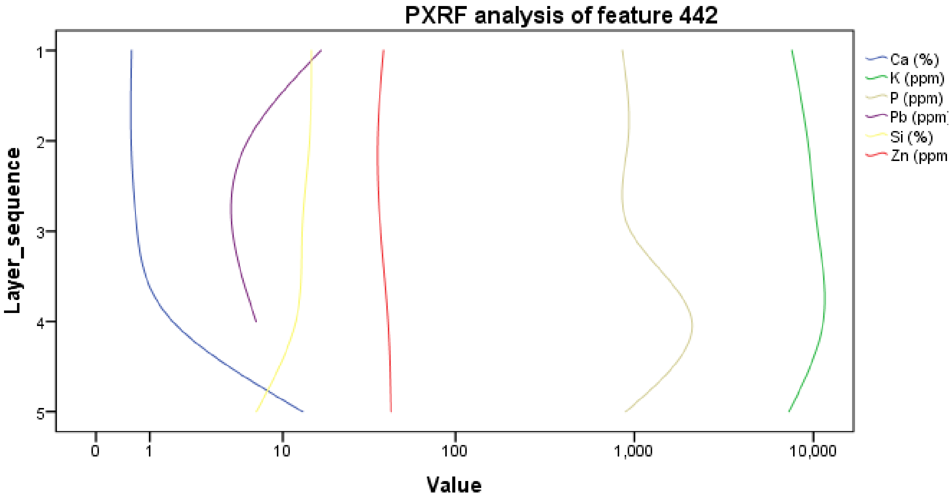


Figure 84: pXRF analysis of Ca, K, P, Pb, Si and Zn for feature 442

Feature 443 was a more varied deposit within the cut of the ditch, including a primary, secondary and even perhaps a tertiary fill, as can be seen from Figure 83. The primary fill had visibly fewer small chalk fragments and was more similar to the fill of 442, however a secondary deposit above this contains more chalk fragments and this is confirmed in the Ca profile from the pXRF data (Figure 85). Along with this there is a more variable Pb profile with a value of 32ppm in layer 6 (*c.*1m deep). Other elements, including P and K, did not show any variation.

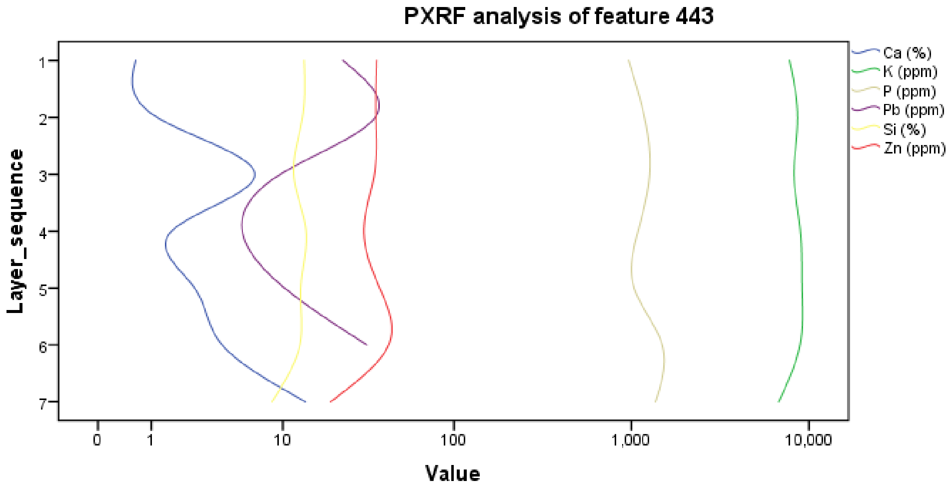


Figure 85: pXRF analysis of Ca, K, P, Pb, Si and Zn for feature 443

In the exposed section of henge (Figure 86), samples were taken every 10cm down the centre of the ditch to sample a number of different fill deposits that were contained in this 3m deep and 13m wide ditch terminus. At the time of sampling, the ditch had not been fully excavated and so samples for pXRF analysis were taken for the upper 2m of the ditch. This data is shown in Figure 87 which demonstrates at approximately 1-1.3m deep there are significant enhancements of Ca, Pb, Zn, and P (over 10 times average levels). Si and K show relatively little variation across the whole profile. The relatively deep band of dark soils within the centre of the ditch fill are clearly the cause of these geochemical enhancements, and represent a re-deposited midden relating to the late Bronze Age or early Iron Age (Leary, 2015). The deposits contained a substantial amount of pottery, animal bone, a shale bracelet, antlers and antler tools, flints, a pot loom weight.

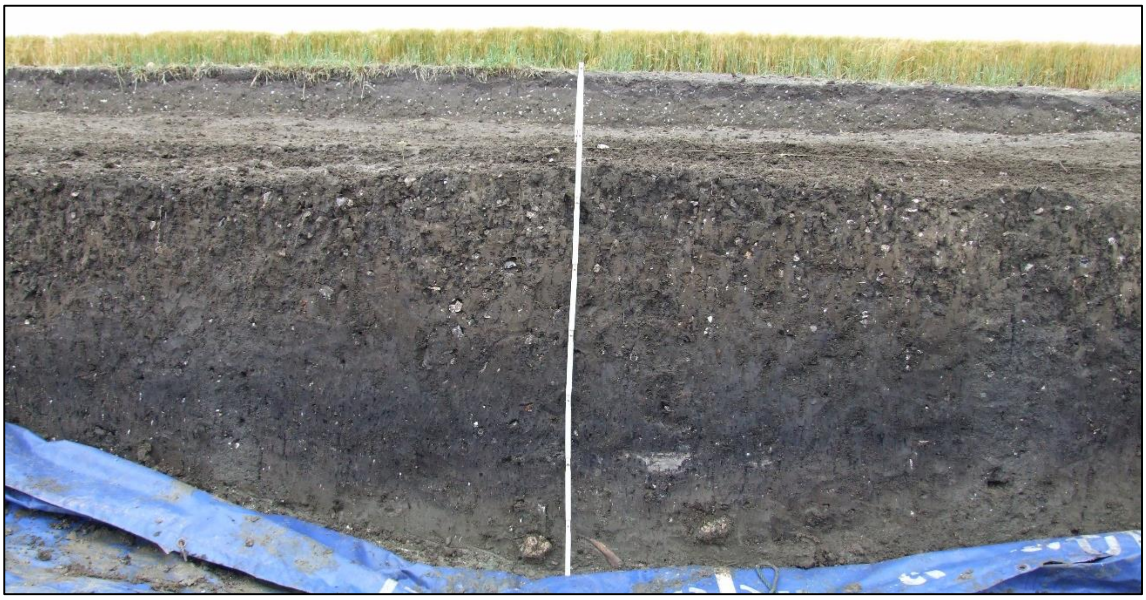


Figure 86: Upper 2m of the terminus of the henge ditch in Trench D before sampling (© author)

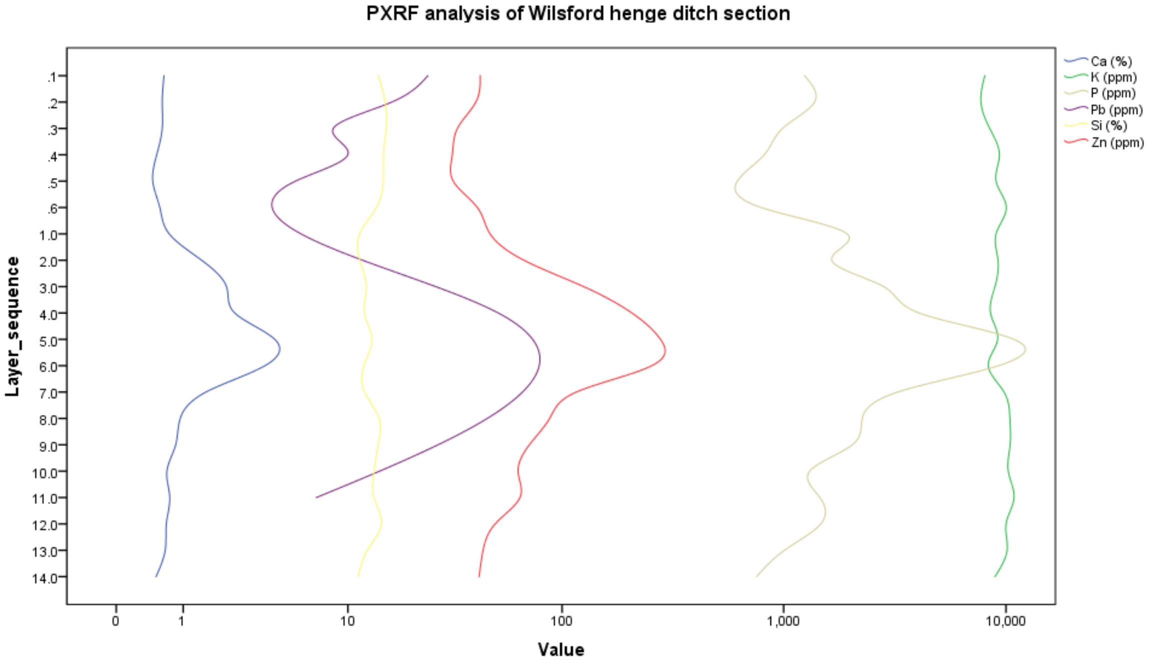


Figure 87: pXRF analysis of Ca, K, P, Pb, Si and Zn for the henge ditch, each layer represents 10cm depth, layer 1 and 2 were not sampled exactly over the henge ditch due to topsoil stripping having taken place at time of sampling but were only 5m away (© author)

7.4.2 Soil Stratigraphy

Soil depth, and the changing stratigraphy down the profile, are important variables to know in an agricultural context. Especially in landscapes where the shallow soils predominate, for example on chalk geologies, soil depth to the underlying chalk is absolutely crucial for both nutrient content, as well as the moisture retention. With 55 cores across Charles Sands field in four transects, with cores every 20m in a N/S orientation (Figure 73B), it provides the opportunity to investigate in more detail how the stratigraphy of the soil profile changes across this field, and with knowledge of where archaeological features, and without knowledge of possibly unknown archaeological features on the site, to understand the impact of those features on the soil stratigraphy.

Figure 89 shows all 55 cores drawn in Microsoft Excel from field notes, measurements taken while in the field, and from later evaluation of photographic records and pXRF data. In general across the site there is a clear Ap layer, that is 15-25cm deep and represents the modern plough soil. Below this the majority of the soils (Bw) have developed on top of the chalky drift (2Cu and Cu) and have a quite variable thickness (between 20-50cm). The soils developed on top of the greensand (BCtg) are very different, however, from the Bw soils above the chalk. There are also sandy clays (Btg) present in places that have no chalk fragments mixed within them, and some sandy clay loams (Eg) that have no or very few stones, and are generally much lighter in colour (2.5YR 3/3 - (5/4) rather than 7.5YR/10YR). Soils vary in thickness but reach around 1m deep in cores 6, 31 and 52, whereas in other places soils can only reach 25-30cm before chalk (Figure 88). The cores show the varying depths of chalky drift that have been left on top of the greensand, while most cores did not reach clean greensand, the few that have, show those drifts can be only 20-50cm deep. The greensand itself varies in itself, with core 20 showing clean greensand appearing only 60cm below the surface.

Figure 88: Photograph showing the variation in soliflucted chalky drift underlying the Ap and B horizons (© author)

Some cores also show the impact of archaeological activity on the overall stratigraphy of the field, despite the complicated variability that already exists across the field before human impact. For example cores 34 to 40 intersect the area of the Neolithic henge, but also show an increase in stratigraphic layers with organic-rich deposits sometimes occurring (core 34) and deeper layers in amongst the natural variation (core 15). Determining whether a core has been impacted by archaeological activity or not can sometimes be difficult due to such wide variation across the whole field. So I will evaluate specific cores within their local context and taking into account other evidence that shows their spatial background to help identify where cores may be affected by archaeological activity or not.

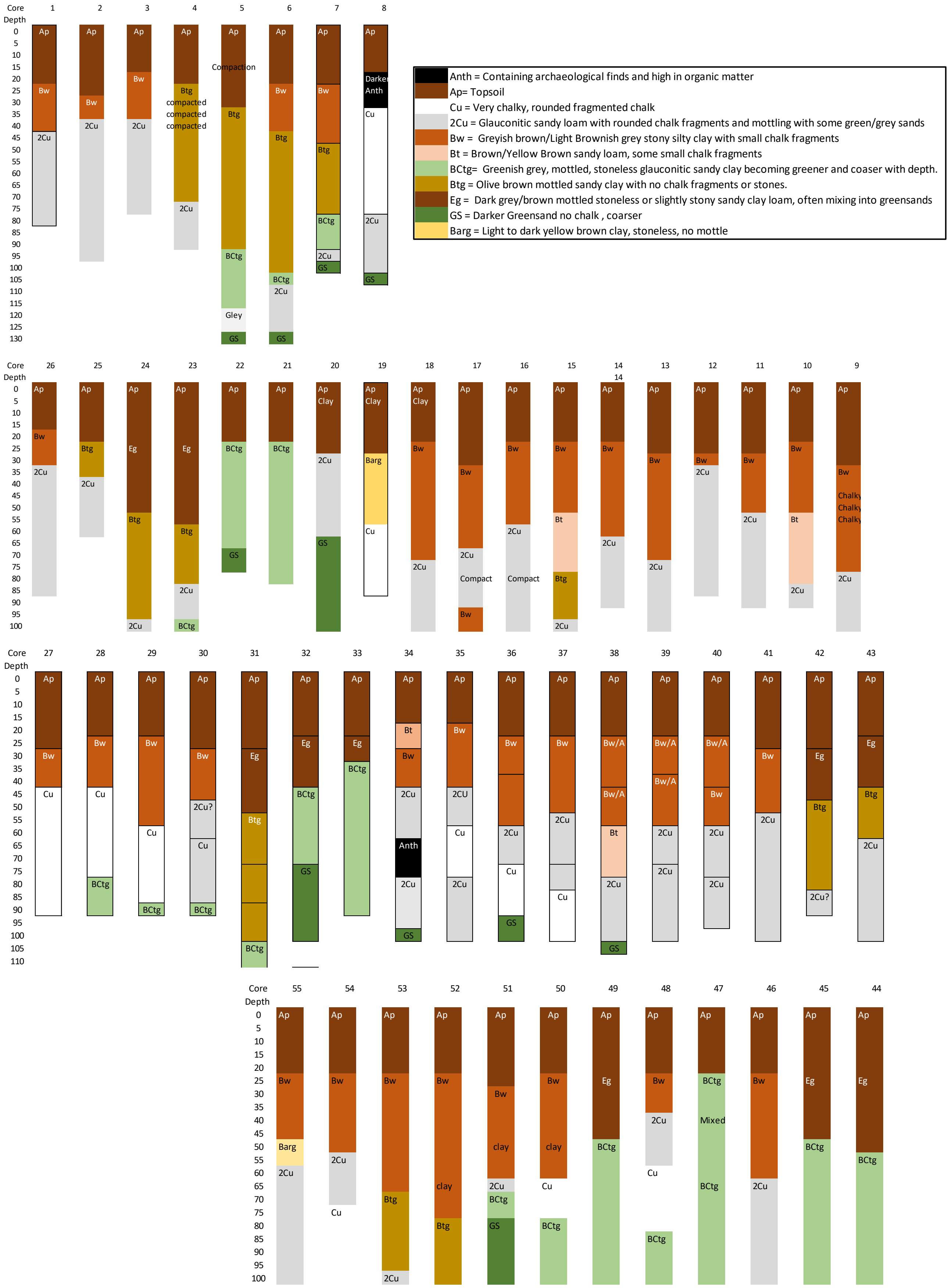


Figure 89: Core drawings of all 55 cores, divided into individual transects not topographically corrected (© author)

Core 15, for example, is not located near any geophysical anomalies, or previously known anomalies from aerial photographs, so could be considered to be a relatively representative location the soils in this part of the field. An NDRE drone image from 2017 shows, however, that core 15 may be over a linear archaeological feature, most likely a ditch (Figure 90). The difference between these two images shows how two similar archaeological features, i.e. ditches, can respond differently to different remote sensing techniques. The patterns shown in the NDRE image are not the same as the ditches in the geophysical data, consequently the deposits filling those ditches are likely to not be the same from a geophysical and geochemical point of view.

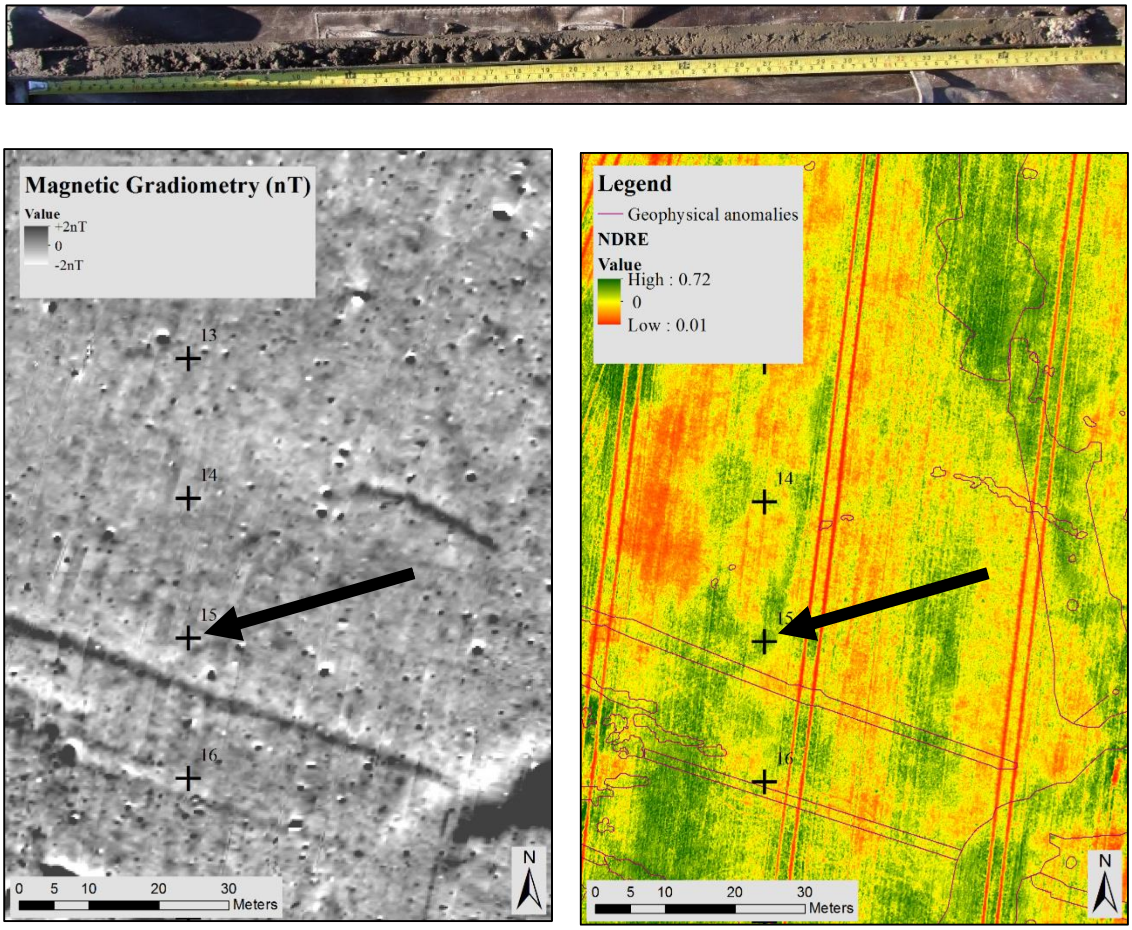


Figure 90: Photograph of core 15 (top),with the location of this core on the geophysics (left) and in an NDRE drone image from 2017 (right) (magnetic data courtesy of Historic England)

The photograph of core 15 (Figure 90), and the drawing in Figure 89 shows that it is 40cm deeper than the cores either side of it in relation to where chalky drift appears, and that it changes to a slightly heavier texture towards the lower end, with a change in colour to more of a dark olive brown, rather than a lighter yellow brown. The deposit is free from stones and chalk fragments, noticeably different from the same layer deposits at cores 14 and 16.

Core 38 is another example of a location where, on both the geophysical survey and across the multiple pieces of imagery that have been collected since 2014, no anomalies relate to it. From the core photograph (Figure 91) and the PXRF data (Figure 92), there is an obvious mixing of stratigraphy at 25-55cm below the surface. There is also a visible piece of ceramic building material within this layer. The pXRF data shows that there are enhancements of P and Pb at layer 3 (39-55cm) and a decrease in Ca levels. These levels of variability are well within the average ranges for the whole field, but is not expected in this cores local context.

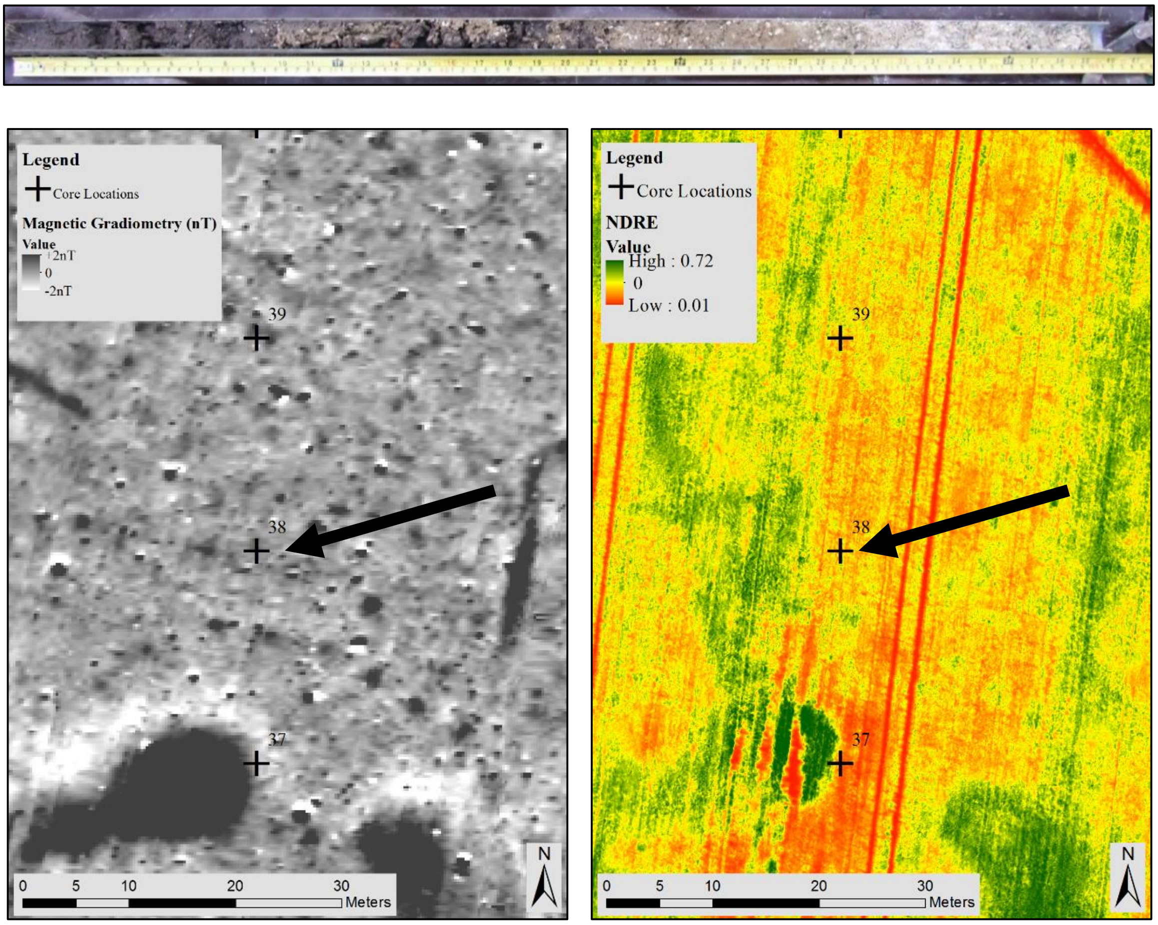


Figure 91: Photograph of core 38 (top),with the location of this core on the geophysics (left) and in an NDRE drone image from 2017 (right) (magnetic data courtesy of Historic England)

Some of the mixing in these layers could of course not be due to archaeological impacts from the Roman or Prehistoric periods, but later in the Medieval, post-Medieval, or modern use of this field. Indeed the physical mixing could have been due to post-depositional processes such as deep sub-soiling cultivations, or bioturbation. However, in light of the pXRF data as well as the core and artefact data, this disturbance is interpreted as archaeological. How this relates to the drone imagery and geophysics is however unclear. Its invisibility in these datasets maybe due to its subtle elemental changes, and similarity in magnetic contrast and moisture content to surrounding soils.

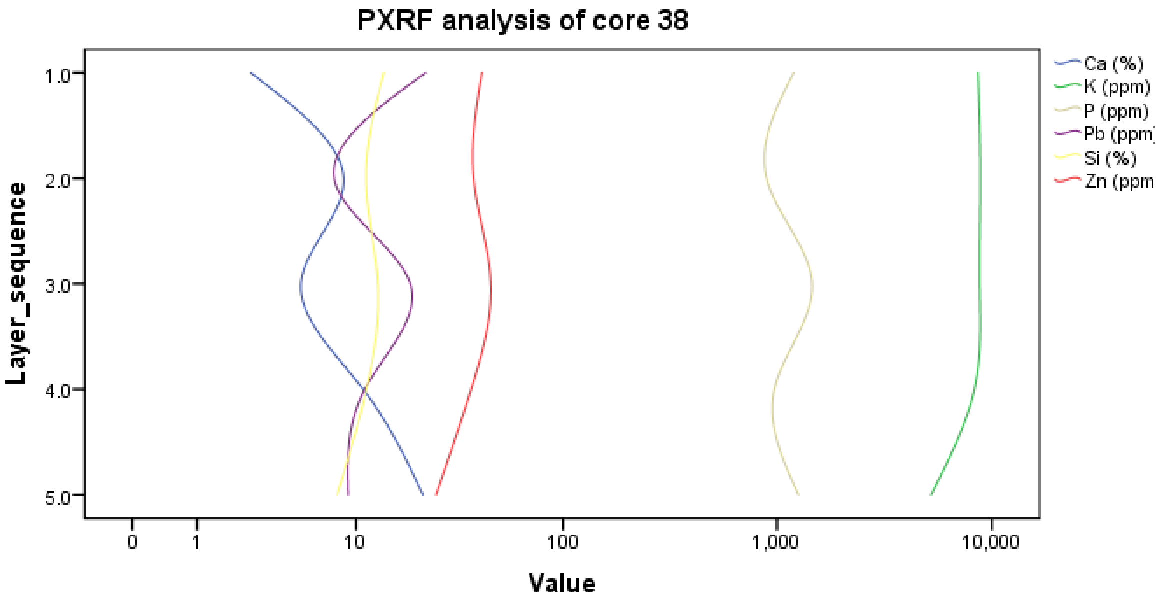


Figure 92: pXRF analysis of Ca, K, P, Pb, Si and Zn for feature 443 (© author)

7.5 Archaeological Data in a PF Context

7.5.1 Remote Sensing and Aerial Photography

At Wilsford, in addition to the aerial photograph already shown (Figure 69), additional photographs from the summer of 1990 have contributed to the recording of the Wilsford henge (Figure 93 and 94), alongside many others over the past 50 years (Carpenter and Winton, 2011). The oblique view of all of these photographs, however, limits their exact position and shape to be digitised and easily integrated into PF systems, such as the IPF toolbox. Therefore while they represent detailed and high resolution images of the field, and its crop and soil variations (as well as archaeological remains), they cannot be utilised within the soil zoning process, or for interpreting variations in NDVI satellite imagery for example.

The Marden and Environs NMP (Figure 70) work, in combination with the geophysical survey that added far more detail and will be discussed below, tackles this limitation and has produced accurate maps of recorded archaeological crop or soil marks over the project area, including Charles Sands field. Once into a polygonised format, this can be exported as a shapefile into other GIS programs or web applications, and therefore integrated into PF systems for use.

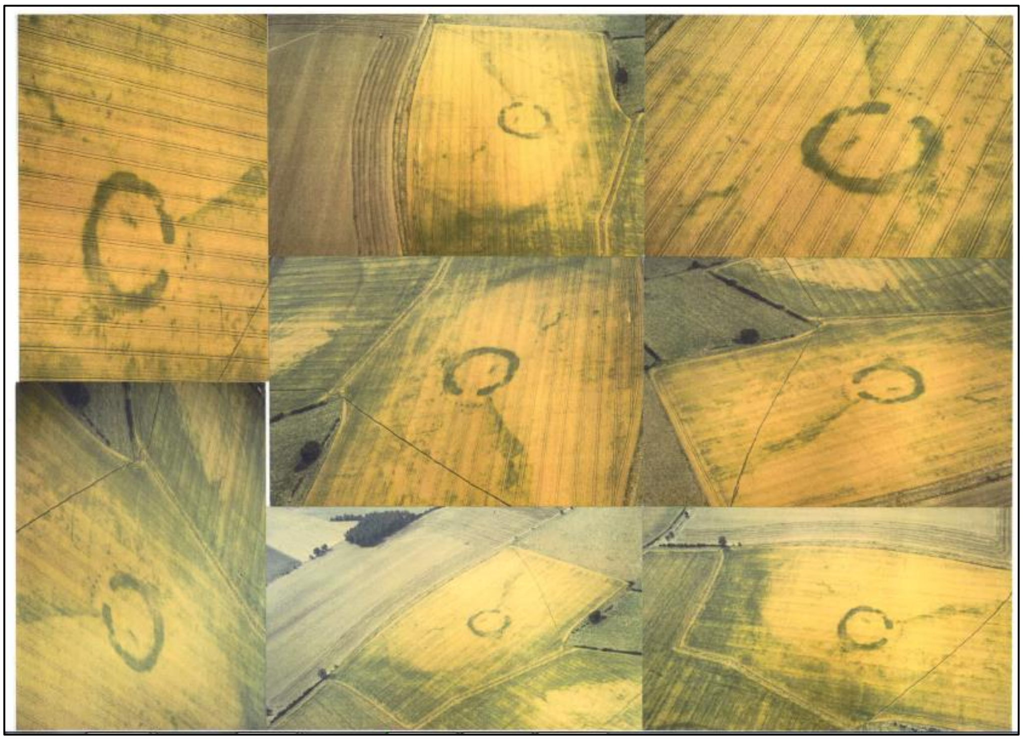


Figure 93: Selection of aerial photographs from 17 July 1990 in colour (© Historic England NMR)

Figure 94: Aerial photograph from 17 July 1990 (© Historic England NMR 4653/39)

Previous archaeological investigations have not used any commercial satellite imagery that has been published, therefore the only other satellite imagery used in archaeological investigations for Wilsford comes from Google Earth and Bing Images. These two images show some variation but come from times of the year where no crop was growing, or soil was cultivated, meaning images show little variation (Figure 95).

Figure 95: Two satellite images, Google Earth 2003 (left) and Bing Image no date (right) (© Google)

7.5.2 Archaeological Geophysics

In addition to the earlier discussion describing the geophysical survey by Historic England of both Charles Sands field, and the surrounding fields to the N and W, it is important to consider how this dataset might itself, on its own, be of use within a PF context. The geophysical data reported on and interpreted in Linford *et al* 2013 is of high quality and high resolution (0.5m sensor interval x 0.125m sampling interval). Its value, however, may not only be for archaeological prospection and management, but also for detailed delineation of agriculturally relevant soil features.

The dataset shows some clear background variation in the underlying soil magnetic properties. Figure 96 shows how in the N zone, where there is clear visibility of archaeological features, and which is an area of chalky drift sitting on top of the greensand below, there is a more mottled background. In the central zone the background is far more consistent and the anomalies that are visible are very different to the ones in the N zone. The strong magnetic contrast between the buried ditch deposits and the underlying chalk is lost when these ditches run into the central zone where the soil profile consists of the deeper sandy clay soil, affecting the magnetic contrast. Yet there are linear magnetic enhancements within this central zone in an E/W direction, which are not seen in the chalky zone, even though they are assumed to run across the whole field. The situation changes again in the S zone, which from a soil profile perspective returns to a shallower topsoil over varying depths of chalky deposits.

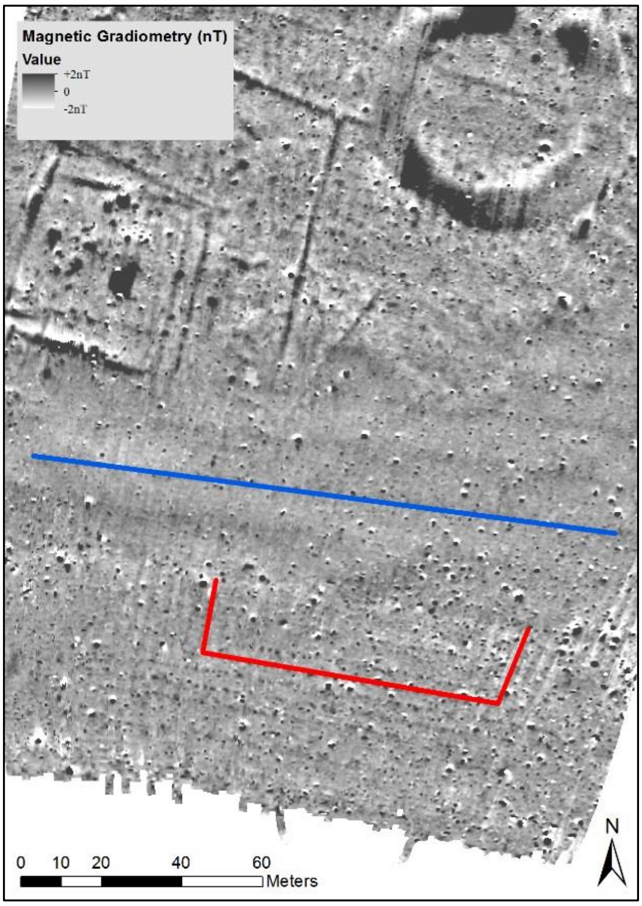


Figure 96: Magnetic gradiometer survey, blue line showing linear magnetic enhancements, and red line showing past agricultural mark (Data courtesy of Historic England)

These subtle background changes across the field are showing the contrasting magnetic characteristics of the soil profile (from topsoil, through the subsoil layers and into the geologies beneath) and how it varies spatially. In this field, these magnetic properties clearly define the boundaries between major soil types and match accurately with the soil coring data, and geochemical data.

The subtle linear anomalies that are represented in the central and the southern zone are from agricultural management of this land at some point in its history. The central zone, with E/W lines of positive magnetic readings (shown by the blue line on Figure 96) or conversely wider bands of subtle less positive readings, are most likely related to previous mole drainage or ridge and furrow cultivations of that field. The red line on Figure 96 indicates a very separate agricultural effect. These lines align to the current shape of the field (i.e. after the removal of the field boundary visible in the First edition OS maps) and so must be within the last century. They are also far too close together to be related to drainage of any type. These are most likely related to cultivation lines, whether by ploughing creating mini ridge and furrow effects in the soil stratigraphy, or by ploughing or tine-based cultivations that may perhaps leave a stronger magnetic effect in the soil from small particles of ferrous metal being worn away gradually. These are interesting effects, and if the latter is true, this could have implications for future geophysical surveys with high resolution magnetic gradiometry.

7.5.3 Historic Environment Records

HER data represents another archaeological dataset that relates to the broader knowledge and understanding of the historic features within a particular landscape. This kind of archaeological evidence has great potential for informing people about the known archaeological features and sites in an area, from the national scale, down to the local landscape and farm scales.

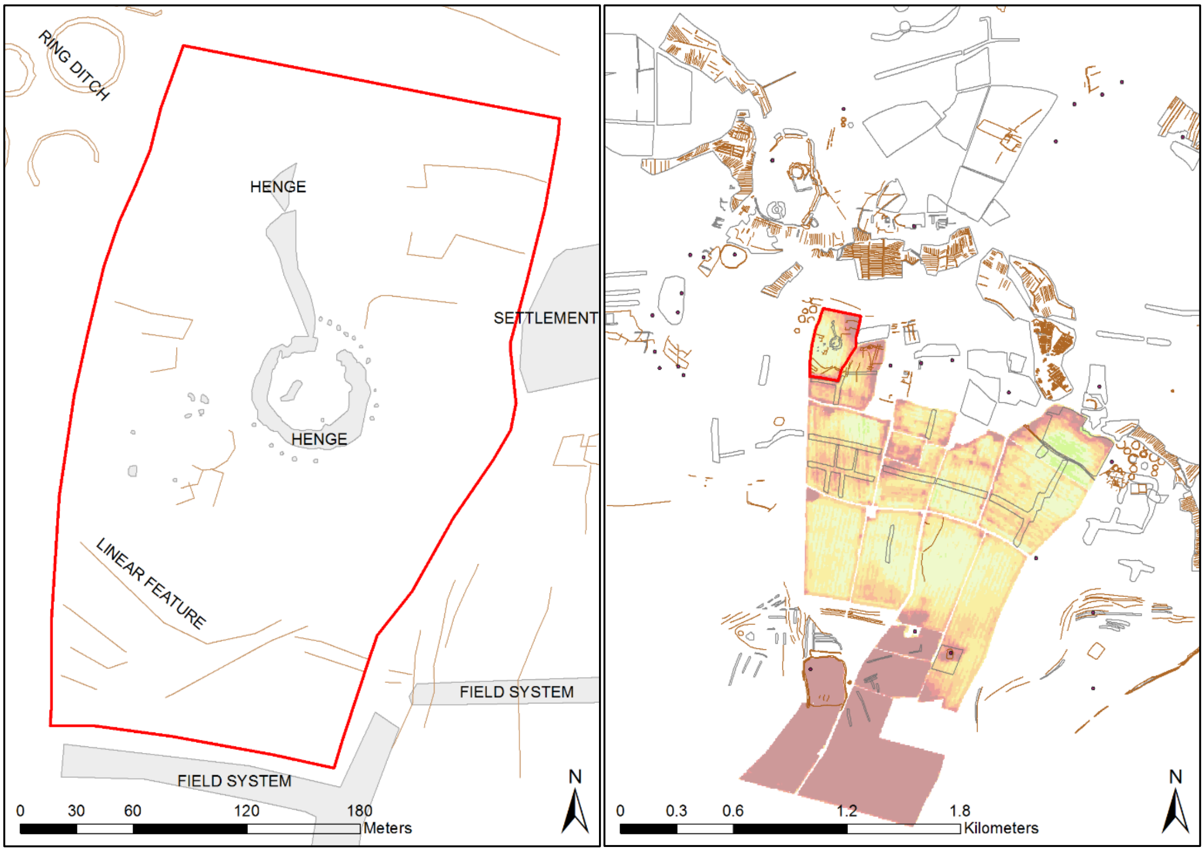


Figure 97: Two images showing the level of detail of the Historic Environment Record at both the field scale (left), and at the farm and landscape scale (right) (courtesy Wiltshire HER)

At the field scale, the HER data shows some of the main archaeological features from the site such as the henge ditch and surrounding pits, and a number of linear features (Figure 97). The HER data does not yet include further results for example from the University of Reading's excavations, or Historic England's geophysical survey. It takes time for the HER teams to update their resources and it is necessary that people completing any fieldwork on sites inform the HER departments as well as completing final reports on their work. This can limit some of the available information, especially at this site, since there are many more archaeological features than those that are shown in the HER data. Yet if approaching this field from a PF perspective, this map gives you an indication of their location and their classification (age/ type of site), which can help consider the likelihood of surrounding crop or soil marks, as well as the type of impacts these may have on the soils and crops.

The scale of, and in this case the level of detail in, the HER data is quite significant for application within agriculture, and especially in PF. If HER datasets can be useful at the field level, then being able to access the data for a 5km square surrounding the whole farm (Figure 97) would be substantially more useful. It allows the connection of archaeological sites, and the inference perhaps of other archaeological sites that could lie on neighbouring pieces of land that were once connected. It also allows a better understanding of the frequency of archaeological features within the landscape that may not necessarily be of great historic or archaeological importance such as Marden henge, but can never the less have impacts on the soils and crops that are grown in the landscape today.

7.5.4 Archaeological Evidence and the Soil Zoning Process

The current IPF soil zones for Charles Sands have been shown in Figure 98, where the dividing line drawn between the C2 and B4 zones is a curving line. It is odd that the dividing line should be curving as there is no clear evidence from any of the datasets collected that suggest this. In fact the First Edition OS map shows a straight trackway that divided the S portion of the field with the fields to the N of it (Figure 98). This is correlated with the geophysical data and in the geochemical data. Suggesting that the soils have been altered by their previous management aligning to that field boundary (which is also plausibly follows natural changes in topography and soil type), rather than the curving boundary suggested by the PF soil zone. This partly may relate to the inherent perceptions that 'natural', 'geological' or 'pedological' forms are not linear in the real world and thus that when drawing soil zones, they should also not appear straight. Which in this case, is not justified. If this boundary was re-drawn it would be more representative of both the historic land use, and the current nutrient variability in both topsoil and subsoil, if it were a similarly curved concave boundary rather than a convex one. This would take account of the mixing of the soil within the headlands of modern field shape that perhaps explains some of the moisture variations in aerial photographs (Figure 94) and SOB satellite imagery (Figure 98).

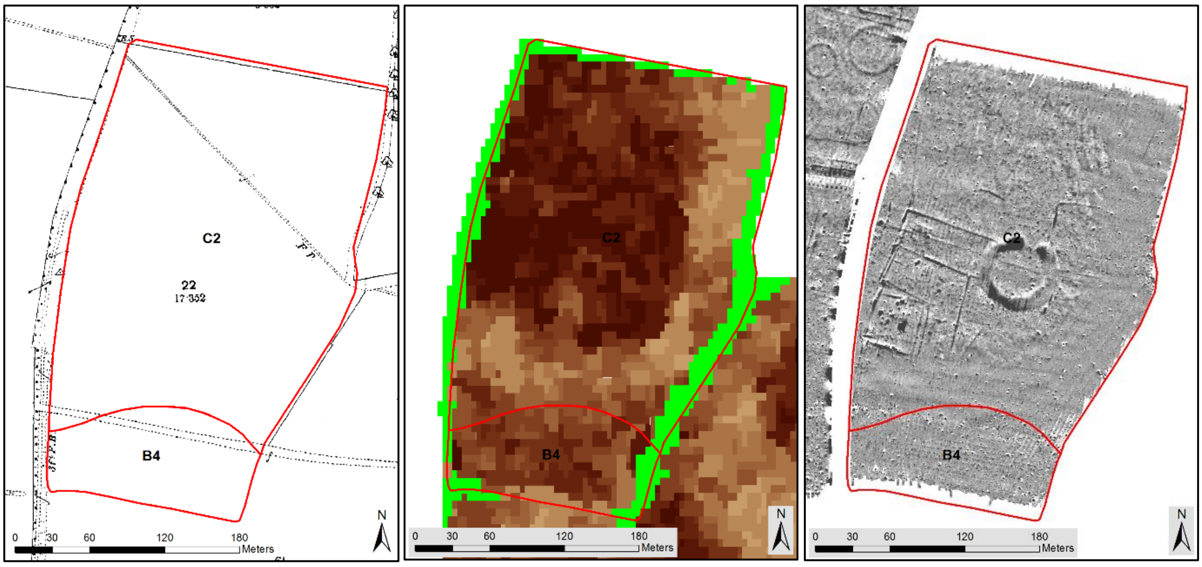


Figure 98: IPF soil zones and; First Edition OS map (left), SOB satellite image (centre) (courtesy of IPF UK), magnetic gradiometry (right)(courtesy of Historic England)

(contains OS data © Crown copyright and database right 2019)

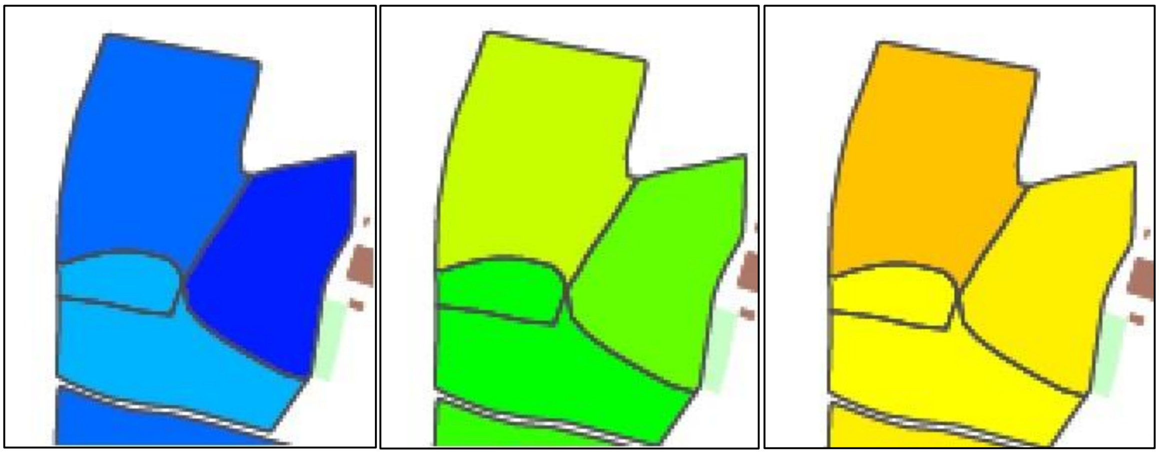
The level of detail in the archaeological evidence for the PF C2 zone is quite considerable. With existing knowledge of the geophysical anomalies and aerial transcription of crop marks, and with new evidence relating to soil elemental variation and stratigraphic variation, there are further sub-divisions that could better take account of soil variations. The suggested zones (Figure 99), based on archaeological features excavated, geophysical anomalies, the background soil boundaries from pXRF and PCA as well as available satellite imagery and drone imagery, would better capture some of these distinct areas and the likelihood of variability within these zones.

Figure 99: showing current PF soil zones (left) and proposed new soil zones (right)(courtesy of IPF UK)

7.6 PF Data in Archaeological Investigations

7.6.1 PF Field and Farm Soil Analysis

The results from the soil sampling based on representative bulked sample (most often the ‘W’ shape method) from each PF soil zone are shown in Figure 100. The levels of phosphate and magnesium oxide are higher (darker/deeper colours = higher values) in the N zone, whereas the opposite is true of potassium oxide. On a field scale, clearly the resolution of this data is not high enough to add any value to archaeological questions relating to the Neolithic henge, or Roman farmstead, for example. This does not render the potential data useless though, especially when considering the larger scale of these datasets at the farm scale, rather than the field scale. Unfortunately the farm scale nutrient maps for Wilsford Manor Farm were unavailable due to a loss of data. The resolution of the PF soil analysis will ultimately depend on how the soil zoning process occurs, *i.e.* whether farmers zone fields and only test those zones (therefore the larger number of zones = larger number of samples), or whether samples are taken on a grid basis regardless of soil zones. Equally if archaeological evidence was used within the soil zoning, it could improve the relevance of the soil analysis for particular archaeological zones.



P K Mg

Figure 100: PF soil analysis in each soil zone (darker colours = higher index values) (courtesy of IPF UK)

7.6.2 PF Satellite Imagery

At Wilsford Manor Farm there were 40 satellite images collected between 2011 and 2015 (and one in 2017), with an average of seven images per year. There is a mixture of resolutions produced by different satellites or different cameras on the same satellite, and this is dependent on what level data is required by PF companies and what sort of temporal resolution is needed by the farmer. Figure 101 shows the difference between the two types of image provided to this farmer. The usefulness of this data for archaeological interpretation, or even cropmark mapping, is very limited by this resolution. It can help discern broader areas of positive or negative crop growth but shows little internal variability in comparison to where known archaeological features are.

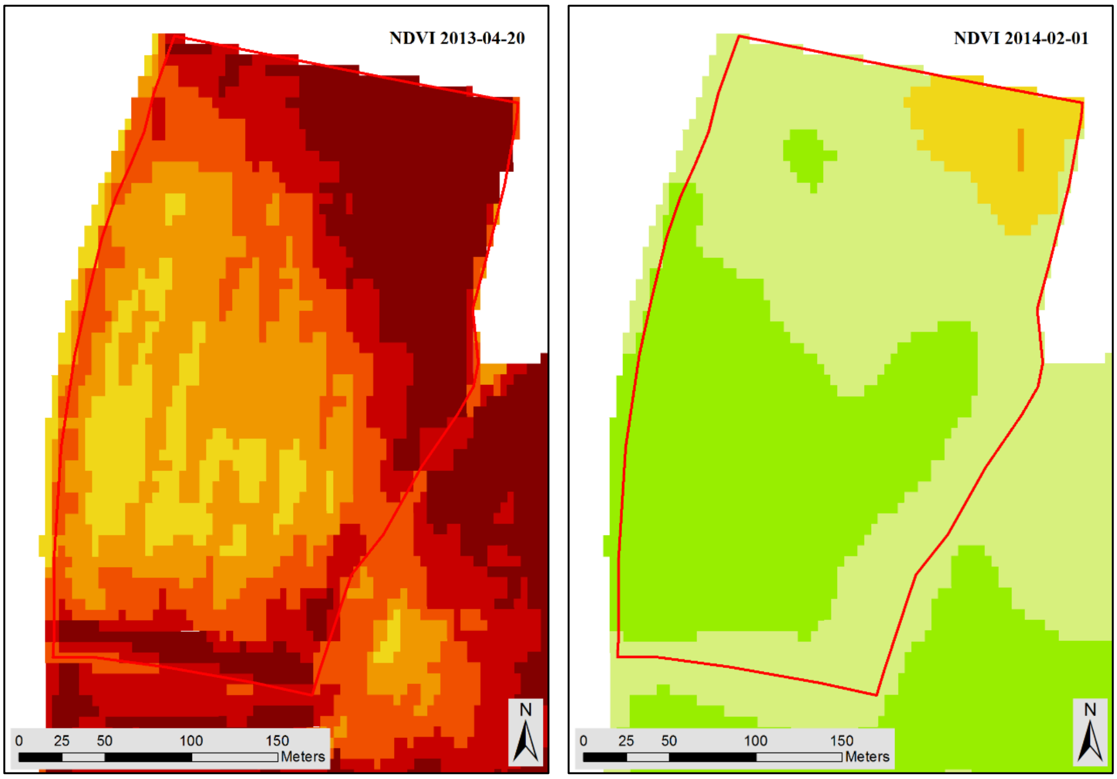


Figure 101: PF satellite image with 5m resolution (left) compared to a different satellite image with 20m resolution (right) (courtesy of IPF UK)

Figure 102 shows a direct comparison between drone collected NDVI data and satellite collected NDVI within a couple days of each other. This demonstrates the significant difference in the quality of the data between different resolutions (shown at field level (A and B) as well as around the henge (C and D)). At the broad level there is agreement between the drone and satellite data showing better areas of crop compared to poorer areas (such as the area of the 2015 excavation). However, the visibility of archaeological features (especially pits or ditches) is poor in the satellite data in comparison to the drone data. The henge is often the most contrasting feature on the site and parts of it can be seen in the satellite NDVI image but not enough to identify it as a henge without any other data.

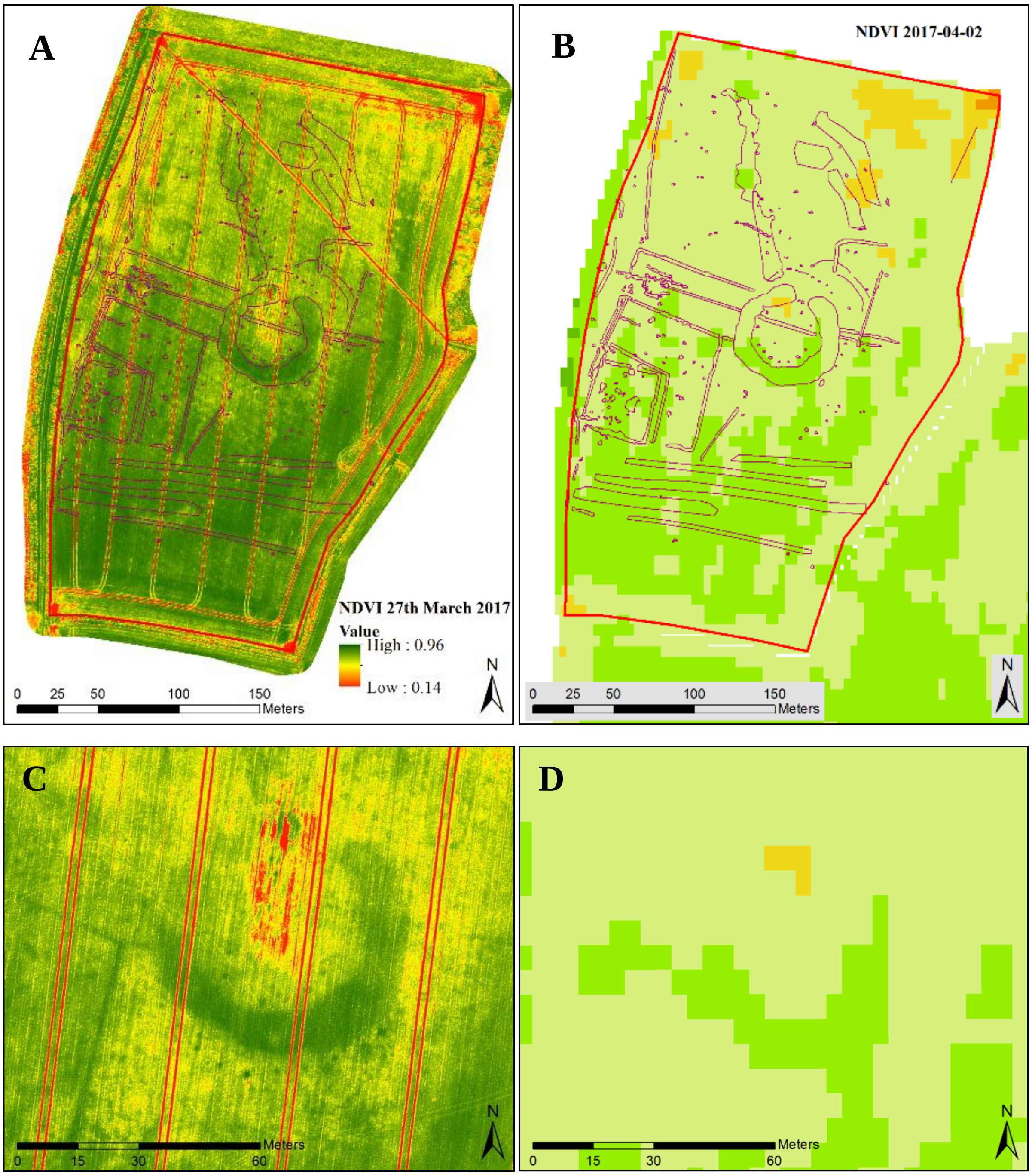


Figure 102: Comparison between a high resolution drone NDVI image (A and C) and a satellite-based NDVI image of the same area (B and D) (courtesy of IPF UK)

The large number of satellite NDVI images was broken down into each year, and averaged using a Weighted Sum calculation in Arc GIS. This results in a single image that highlights the average variation in the field for that year, and allows a simpler way to interpret the large number of images and especially for identifying consistent areas of variation. The results (Figures 103, 104 and 105) for the years 2013, 2014 and 2015 (winter wheat, oilseed rape and spring barley respectively).

2013

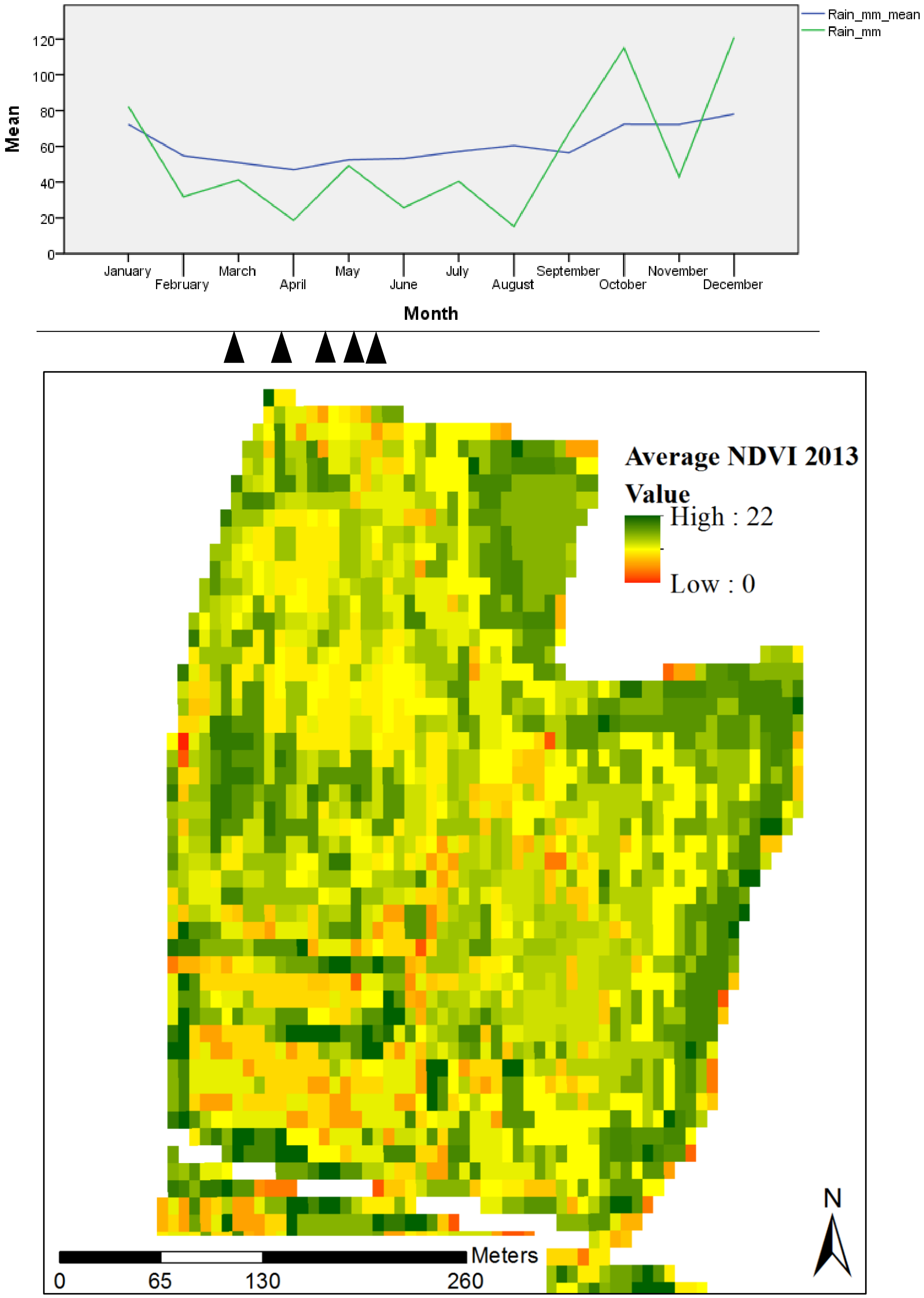


Figure 103: Weighted sum average of NDVI images for 2013 in a winter wheat crop with weather averages above and the timings of images (courtesy of IPF UK) (© MET Office historic data)

2014

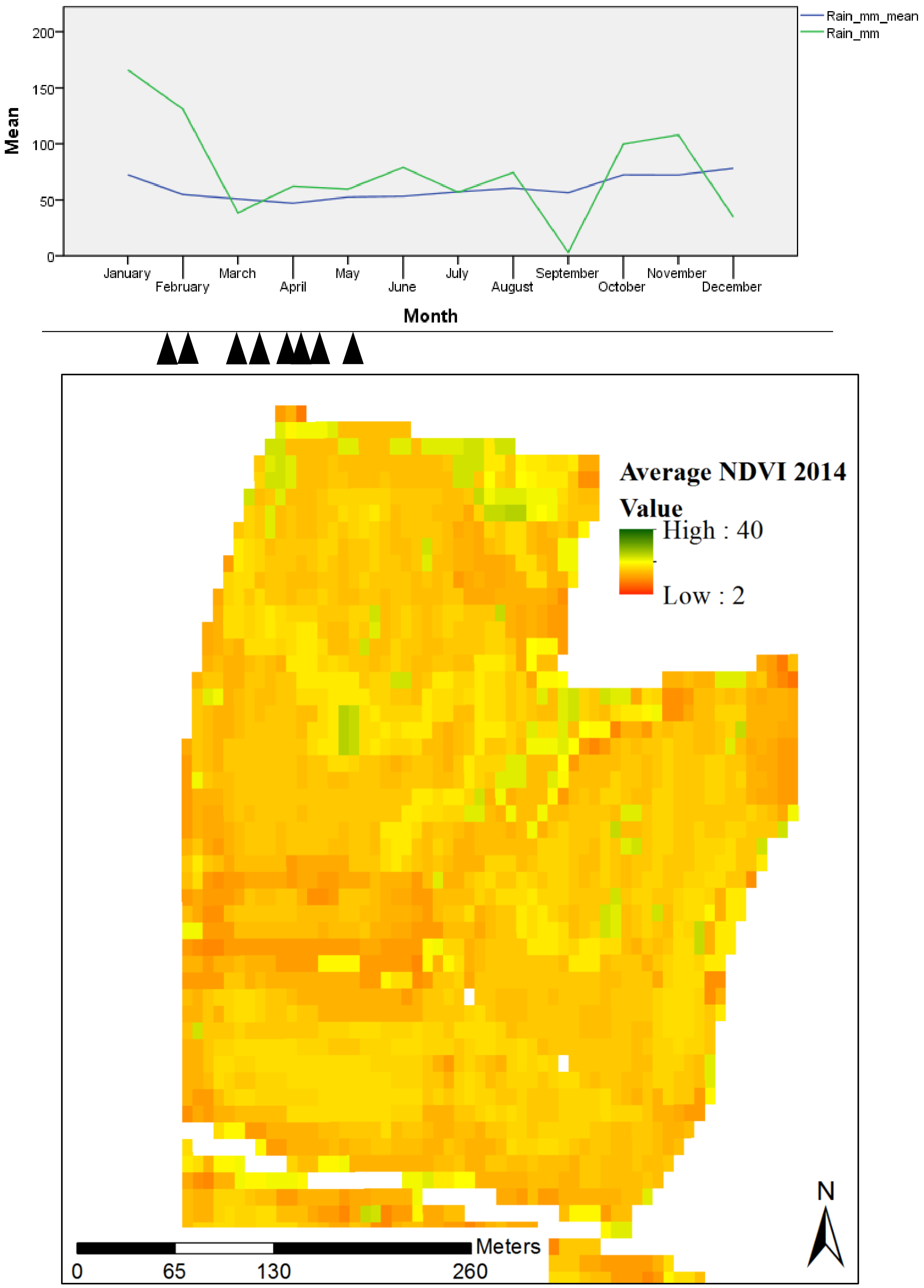


Figure 104: Weighted sum average of NDVI images for 2014 in an oilseed rape crop with weather averages and the timings of images above (courtesy of IPF UK) (© MET Office historic data)

2015

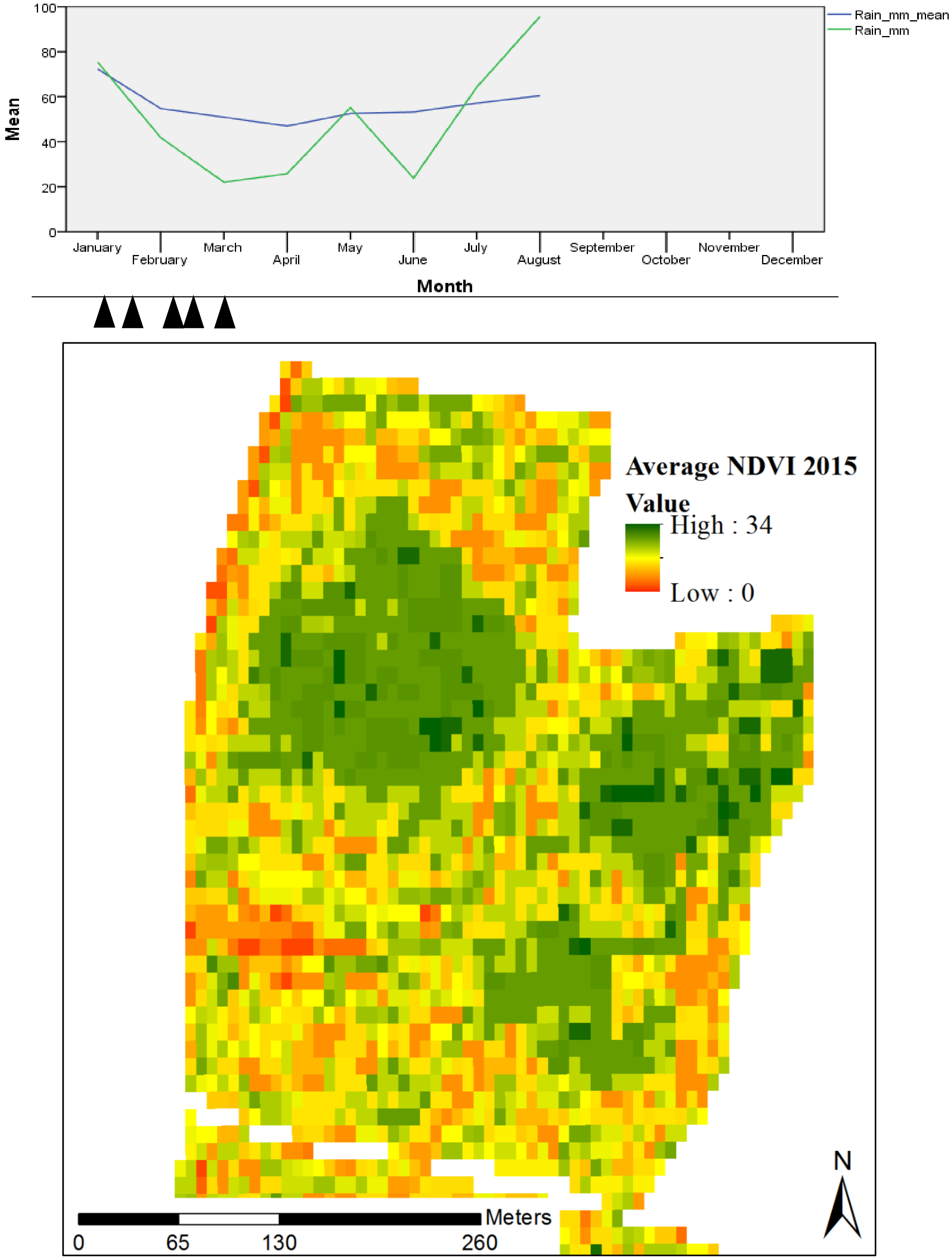


Figure 105: Weighted sum average of NDVI images for 2015 in a spring barley crop with weather averages and the timings of images above (courtesy of IPF UK) (© MET Office historic data)

2013 produced the most variable average NDVI image (Figure 103). The southern part of the field, and especially to the SE, where soils tend to hold more moisture (as seen on multiple aerial images) and where some of the Roman ditched enclosures are located, appears to have the highest NDVI values. The area from the henge and to the N is the poorest, with the footpath clearly having an effect on crop growth and being captured by satellite data. Archaeological features however are not readily visible, although with prior knowledge and an overlaid map of geophysical anomalies, features can be seen in the satellite data, this image would certainly not help identify new archaeological features. The 2014 image (Figure 104) shows subtle variation, again seemingly dividing the field between N and S, although with a few other lines that are not seen on other imagery. These, however, could be artefacts of multiple images of the same data, but with different resolutions, being included in the average sum and appearing as cropmark lines. The 2015 image (Figure 105) shows a high NDVI patch in the centre of the field, but with no seeming links to archaeological features, or coherent variations that match with other datasets.

7.6.3 Agricultural Drone Imagery

Over the course of 2017, when the field was in winter wheat, three drone surveys were conducted over the case study site to collect high resolution (approximately 8cm/pixel) multispectral imagery using the MicaSense Red Edge camera. Flights were on the 27th of March, the 27th of April, and the 13th of May (Figure 106). These survey timings represent a typical PF collection since the spring is when most farmers might consider varying applying nitrogen fertilisers depending on the crop growth.

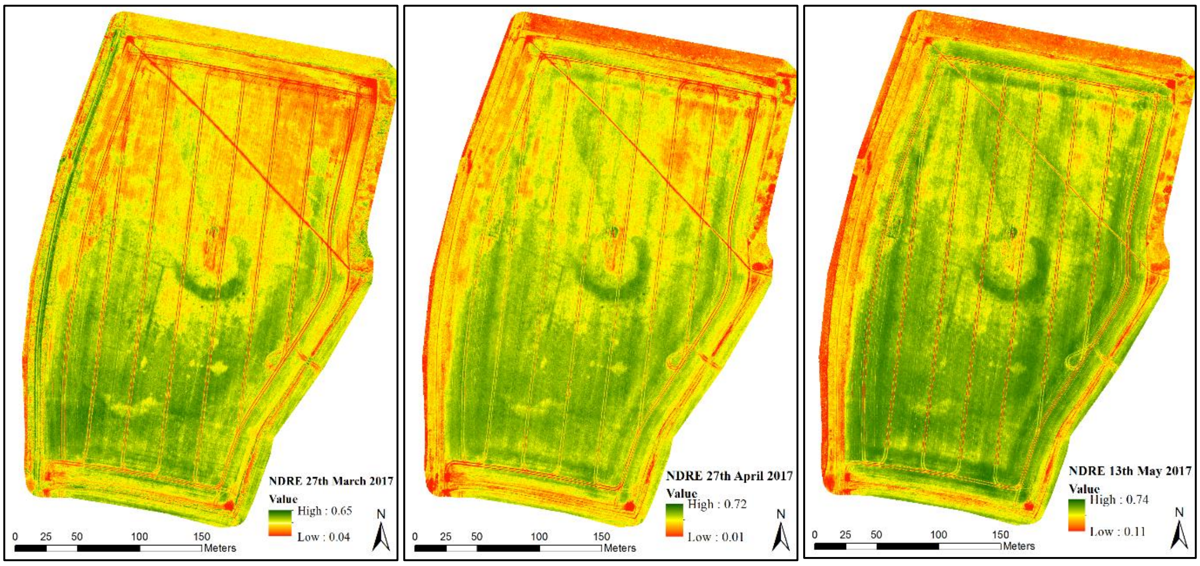


Figure 106: Three sequential drone images of NDRE over Charles Sands field, March (left) > April (centre) > May (right) (© author)

The results show an impressive level of detail, particularly in the NDRE index in comparison to the RGB and the NDVI index. There is a clear difference between the southern half of the field and the northern half, the southern growing much better earlier on in March and the northern half catching up later in May. At the more detailed level there are a number of anomalies appearing in the NDRE data that complement and enhance the archaeological interpretation of features that have only partially been mapped in the existing archaeological evidence.

Figure 107 shows the NDRE image for the 27th of April with the henge clearly defined, but to the NE of the henge is a faint square feature defined on all sides, with a slightly curving inside edge showing positive crop growth and likely to mean slightly deeper and more moisture retentive soils. This feature, when looking at the dashed blue line representing the same area on the magnetic gradiometry survey, appears only in part. This is due to the mixed boundary between the deeper sandy clay soils and the chalky deposits that the henge lies on. Therefore the magnetic contrast, as seen in other areas of the field, is diminished. However, the eastern side of this square enclosure is only half apparent in the magnetic gradiometry, whereas in the NDRE data it is relatively clear.

Often there are modern agricultural management aspects that can interfere with any remote sensing of crop canopies. Overlaps of seeds, fertilisers and chemicals directly in between the tramlines can produce linear, triangular and rectangular cropmarks. So while the eastern part of the enclosure may coincide with this theory, the returning southern side does not. It also sits slightly off from the main tramlines, therefore would not be related to sprayer effects. It is therefore not likely that this square enclosure is an artefact of modern agricultural management of the crop. The question why this magnetic anomaly does not show more of the square could either be because of the changing magnetic contrasts of the soils in that vicinity, or possibly also because the feature, *i.e.* the presumed ditch, is not as continuous as is assumed. It could be slightly truncated by modern cultivations if it is only shallow, or it could contain varied fill deposits that are less magnetic than the other areas, hence reducing the magnetic contrast but still producing the moisture or nutrient variation. The interpretation of this square enclosure is not clear without excavation or any linkage to other more dateable anomalies like the henge ditch or Roman ditches for example. It is most probably some form of Roman enclosure, being more similar and just off parallel with the other Roman ditched enclosures across the field. This said, it is not entirely impossible that it could be a Neolithic enclosure of some type (M. Bell, pers. comm.).

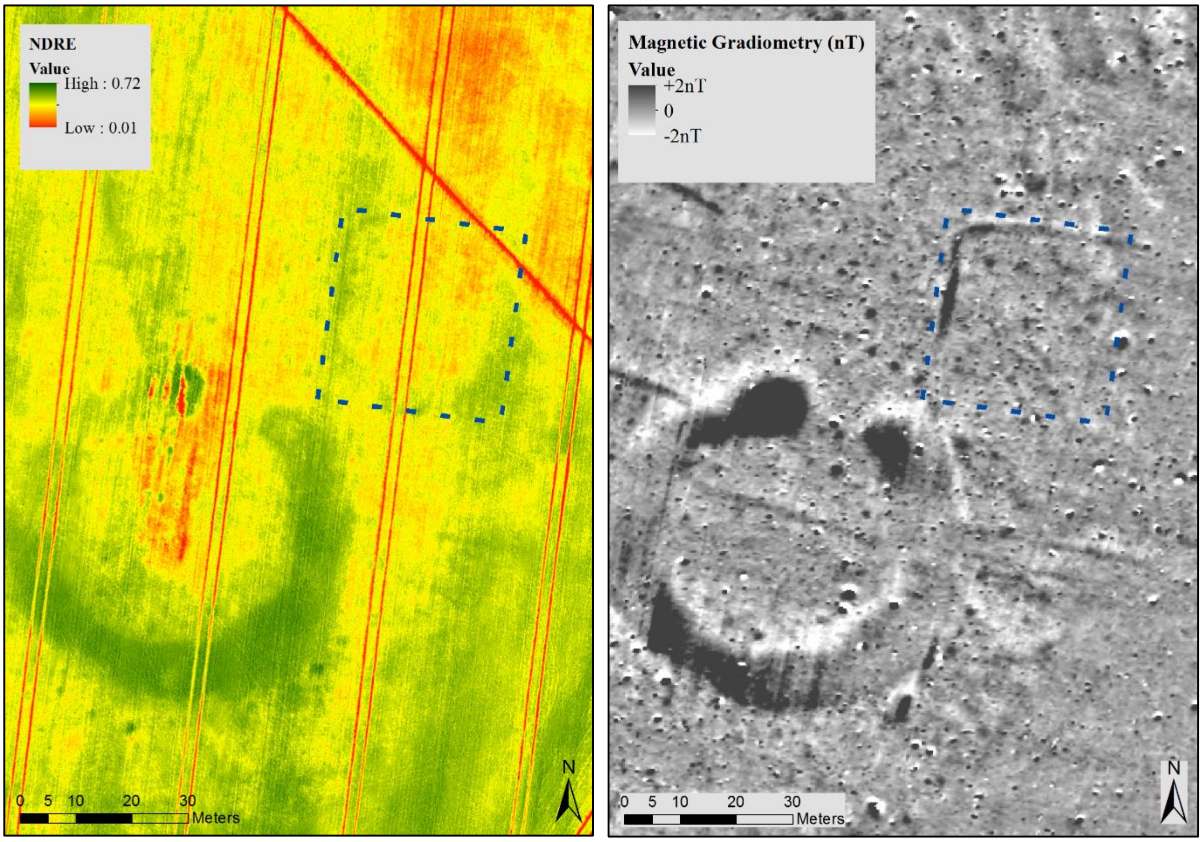


Figure 107: NDRE image of winter wheat (left) in comparison to the magnetic gradiometer data (right) showing a new square enclosure outlined in blue dashes (courtesy of Historic England) (© author)

In addition to the square enclosure, heading NW from the henge is an amorphous positive cropmark that has a very well defined boundary to the W (Figure 107). This anomaly was picked up very faintly in the magnetic survey and interpreted as some sort of geomorphological variation. Unfortunately no soil cores directly sample this anomaly and it can only be said that crop growth in this area is always more positive than the surrounding areas, probably relating to moisture, soil depth or nutrient content. The very straight and defined western boundary does suggest that this anomaly, if of geomorphological origin, does at least have some anthropogenic amendments considering it also ends at the henge entrance.

Further to the possible cultivation lines in the geophysical survey (see example line in red) on Figure 108, more E/W running parallel lines approximately 4m apart have been noted in the drone data. Yet, where the magnetic survey shows these lines turning N with the field boundary, the lines shown in the drone data carry on straight to the field boundary, and are even continuing (or replicated) within the next field. These could be further drainage works, although unlikely on a relatively shallow free draining soil, or other types of cultivation marks.

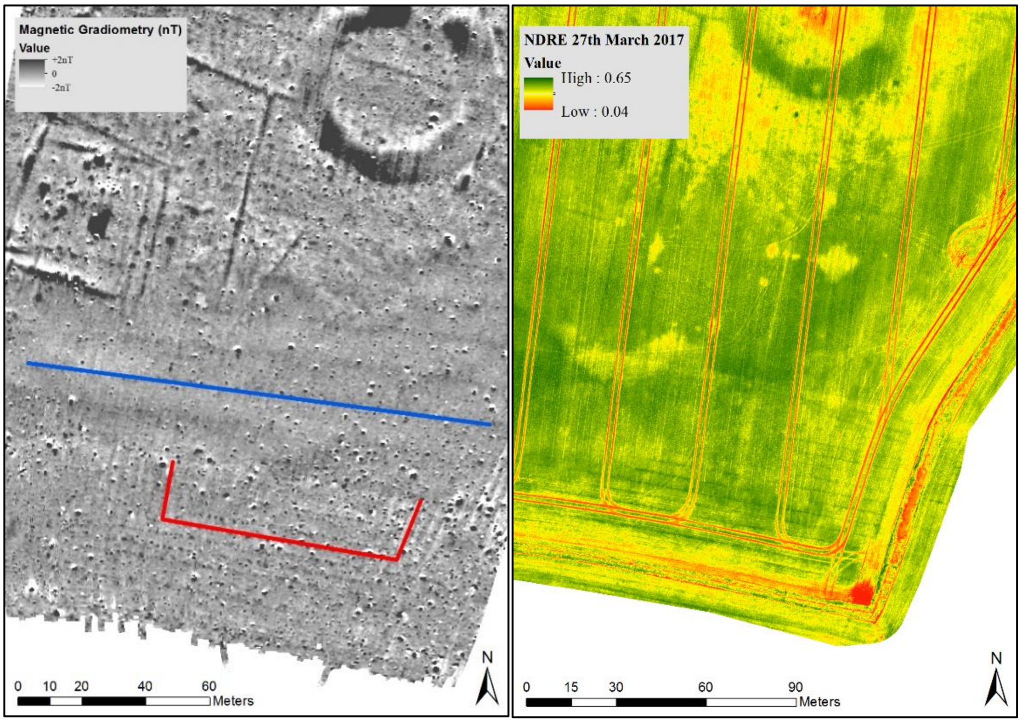


Figure 108: Comparison between the linear features seen in the geophysical survey (left) and the drone data (right) (data courtesy of Historic England) (© author)

7.6.4 Hyperspectral Imagery

Moving from drone-based surveys, to another imaging technique that is not used as regularly by farmers or agricultural companies, but is often used in higher value crops/operations and in archaeological situations, is hyperspectral imagery (Aqdus *et al.*, 2012; Adão *et al.*, 2017). Gathered at approximately 500ft above ground level by light aircraft, a one-off survey was flown to collect hyperspectral data (488 bands between 400nm and 2500nm) over the field for comparison with other datasets. This altitude, and this particular sensor set up, gives a similar ground resolution to the drone surveys (10cm/pixel).

Figure 109 shows two images, side by side, of one particular calculated index from the hyperspectral bands, the Vogelmann Red Edge B Index. In this, there is an open ended rectangular anomaly that appears as a thin positive liner anomaly, and similar to a lot of other observable Roman ditches that can be seen in the S half of the image. This rectangular anomaly has not been observed in any of the other datasets of this field. It is distinguished from the background noise by the fact that this, although being N/S in orientation, is not strictly parallel with any tramlines and therefore rules out modern agricultural operations in the field. It's form, as suggests by the slightly curving eastern edge, and the closed S end, does compare well with other similar shaped anomalies in the area. For example, Figure 110 shows the wider geophysical survey that has not detected any magnetic anomalies in this area, but does show a very similar rectilinear enclosure in the field to the N W of Charles Sands.

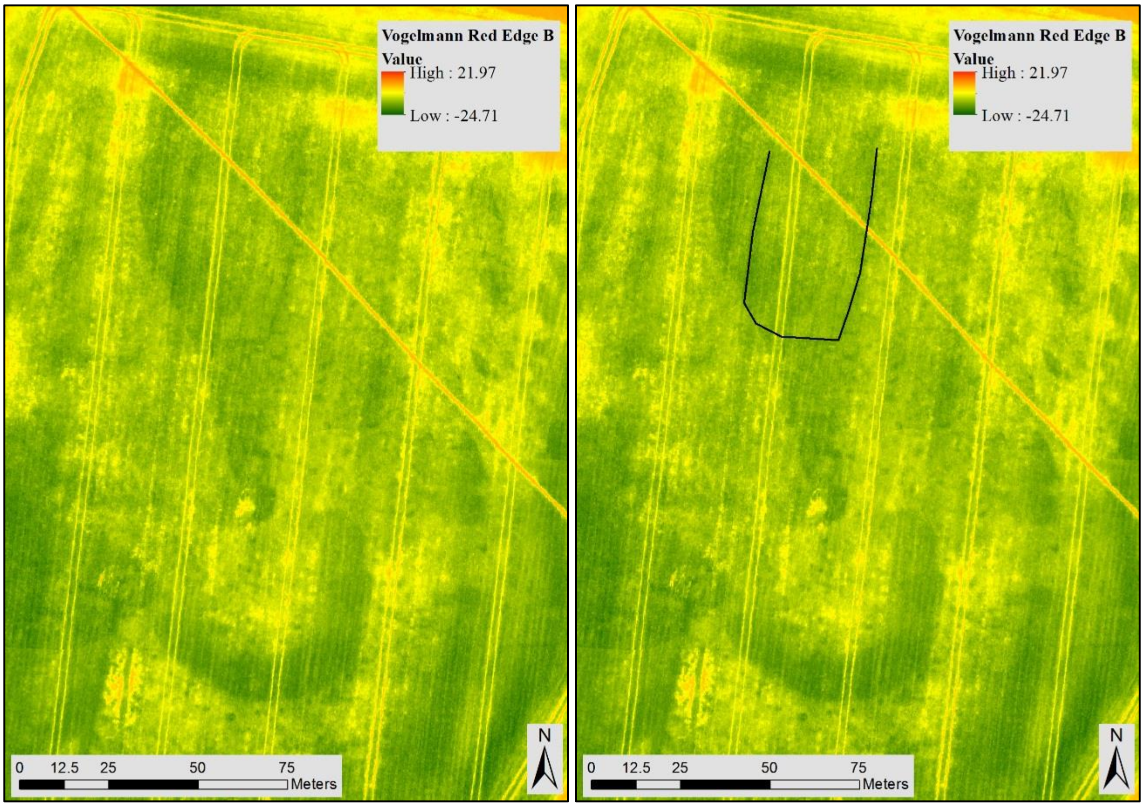


Figure 109: Two images of the Vogelmann Red Edge B Index, showing new rectangular anomaly (courtesy of 2Excel Geopsatial) (© author)

It is questionable whether this anomaly is indeed another enclosure similar to the type already known on the site. If there was a response from this type of geophysical anomaly in one area, on a broadly similar area of soil and geology, then one would expect at least some response to be visible in the geophysical survey. One aspect that may have affected the results of the geophysical survey might be the orientation of the survey lines, with the orientation of the enclosure. However, the closed S end should still have been visible. Other possibilities are again that this anomaly is truncated, and there is too little there surviving to give any magnetic contrast, or that the fill of those deposits are different.

Certainly these datasets and their corresponding anomalies in the growing crop, along with the drone imagery described above, show that there is still some significant contributions to be made from aerial surveys of sites such as this, even with a vast amount of archaeological fieldwork already completed on them.

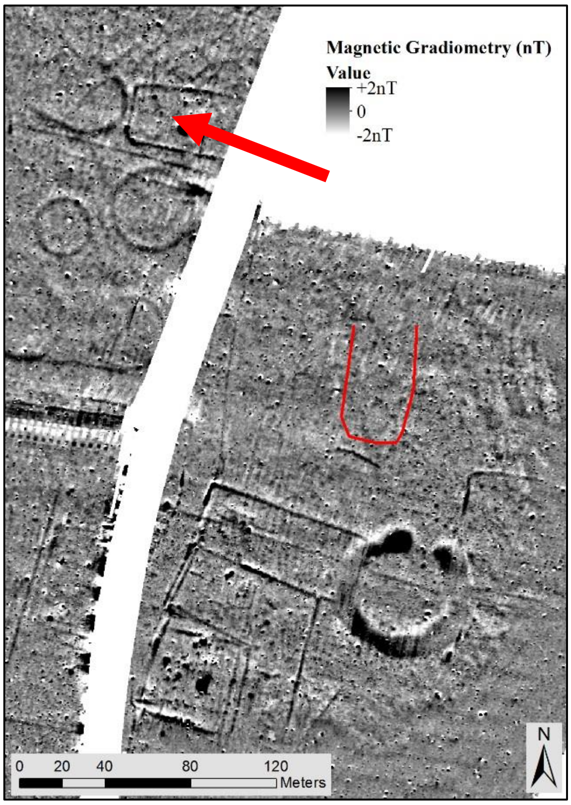
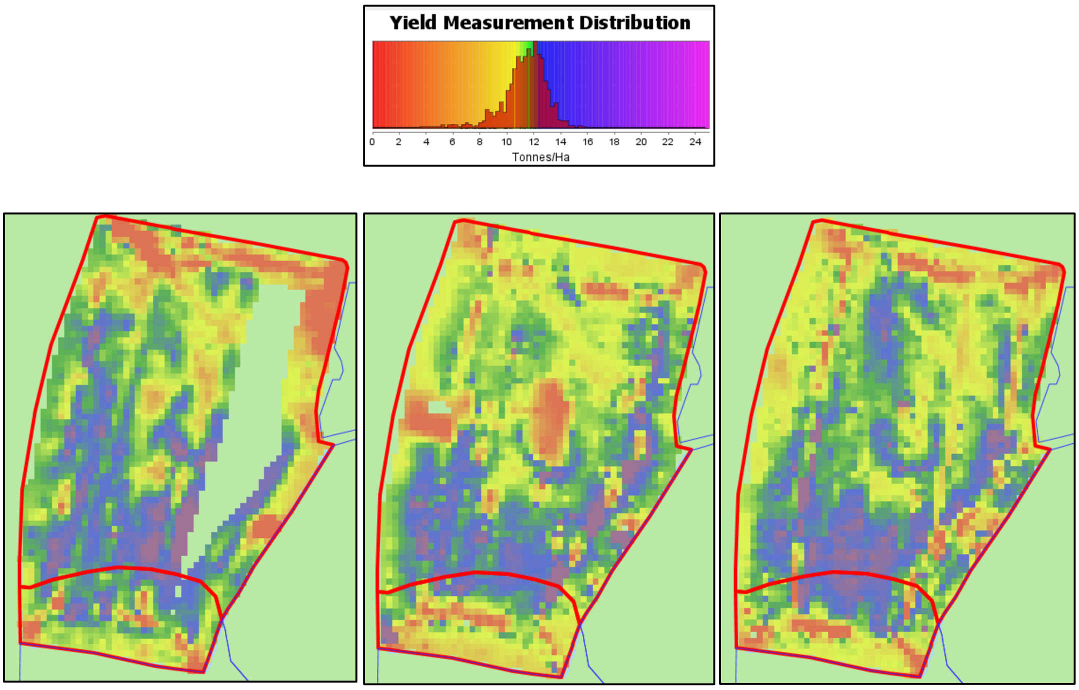


Figure 110: Outline of the new rectangular anomaly on the geophysical data, and an arrow pointing towards a similar shaped a geophysical anomaly (data courtesy of Historic England)

7.6.5 Yield Maps

Wilsford Manor Farm has had yield data collected from the combine harvester used to harvest each year’s crops. Figure 111 shows the yield maps from 2008, 2015 (after the archaeological excavations were completed) and 2017. In general, the yield maps reflect the results of the various imagery of the crop throughout multiple years, the distinction between higher yielding and better growing crops in the S of the field. In comparison to the N part of the field, where the footpath, as well as changes in soils, seems to reduce yields and affect crop growth.

The henge can be seen in all three yield maps (although only partially in 2008 due to a recording error on the combine harvester), and shows the positive (blue/purple) effects on crop yield that the henge provides, with a deep soil profile that retains moisture and nutrients in lower layers than the rest of the field. In 2015, because the excavations occurred over the early summer, the crops were cut in the areas required for the trenches and therefore caused a yield loss that year in those areas shown in red. Post-excavation, in 2017, the yield map shows a more even and average yield in comparison to 2015, however the henge is less clearly visible. The effect of excavating the area, mixing the soils and re-depositing them (even after separation of topsoil from subsoil layers) has effected the yield of this portion of the field, even two years after the excavation. This is partly because of the time it takes for the soil structure to return, but also because of the soils taken away in samples, and the mixing of the backfill deposited back in the trench.



2008 2015 2017

Figure 111: Yield maps from 2008, 2015 and 2017 at Wilsford (data courtesy of IPF UK)

In a similar vein to other PF datasets, no new archaeological features can be seen from this lower resolution data. Both this yield data, and some of the satellite data in Section 7.6.2, can be used as supplementary to the overall analysis of the field and the soils by comparisons to other higher resolution datasets. This allows the testing of hypotheses in relation to why a particular anomaly is having a particular effect, and whether it has the same effect in a similar situation. Yet as with other new datasets, there are pitfalls to be careful of, such as artefacts in the data, error such as data loss due to driver error, and the complications that data exchange brings, especially with yield maps.

7.7 Summary

The field at Wilsford Manor Farm has demonstrated that soils are far more complicated than existing geological and soil mapping suggests. The variability of the background soils can also complicate the interpretation of archaeological impacts on soils themselves, that can be both made up of anthropogenic additions (elements such as Pb, Zn, Ba, Mn) as well as anthropogenic alterations (soils profiles becoming deeper and mixed).

The impact of the various archaeological features, of different archaeological periods, across the field have changed the immediate soil profile (such as ditches, pits, structures) but also can be seen to have affected areas where no archaeological features are known. This highlights how, while using geophysical or aerial anomalies to identify and indicate where archaeological remains are, the impact of those sites might be spread wider into areas of land considered archaeologically empty.

While field-level PF nutrient maps do not offer benefits for understanding archaeological sites currently, if archaeological evidence became part of the PF process, there is potential for soil zones to recognise archaeological features and sample them separately due to an increased likelihood of variability. Alongside this, the application of PF data such as multispectral and hyperspectral imagery at Wilsford has brought new archaeological features to light. Even at a site that has been recorded for over 50 years, with intensive excavations, aerial survey and geophysical survey, there may still be more archaeological features in the field to be discovered.

Chapter 8

8 Perdiswell Farm

Case Study 3:
Perdiswell Farm

Key results:

- Archaeological sites can impact levels of P, Zn, S, Mn, Pb and Cu in soils
- Agricultural trials could be affected by increased soil variability due to archaeological sites
- Geochemical impacts connected to archaeological activity can result in local soil pollution and therefore contribute to future fertiliser choice/nutrient management

Figure 112: Summary of data and results from Perdiswell Farm (© author)

8.1 Site Introduction

Perdiswell Farm, in central Oxfordshire (UK), is a 465ha family run farm on the edge of the Cotswolds. It is made up of a mixture of owned, tenanted and contract farmed land which is primarily arable, although livestock were present on the farm until the 1970s. The farm lies in between Blenheim Palace, the seat of the Duke of Marlborough, and London Oxford Airport at Kidlington. It is sits to the W of the river Cherwell, a significant tributary to the Thames.

8.1.1 Location

The farm (Figure 113) extends between two main roads, Banbury Road and Oxford Road, heading NW from Oxford. The land surrounds London Oxford Airport at Kidlington, and the eastern outskirts of Woodstock village. The case study field itself is called ‘100 Acres’ and is one of the largest fields on the farm, with an area of 45.83ha (113 Acres) (NGR - SP 45855 16181).

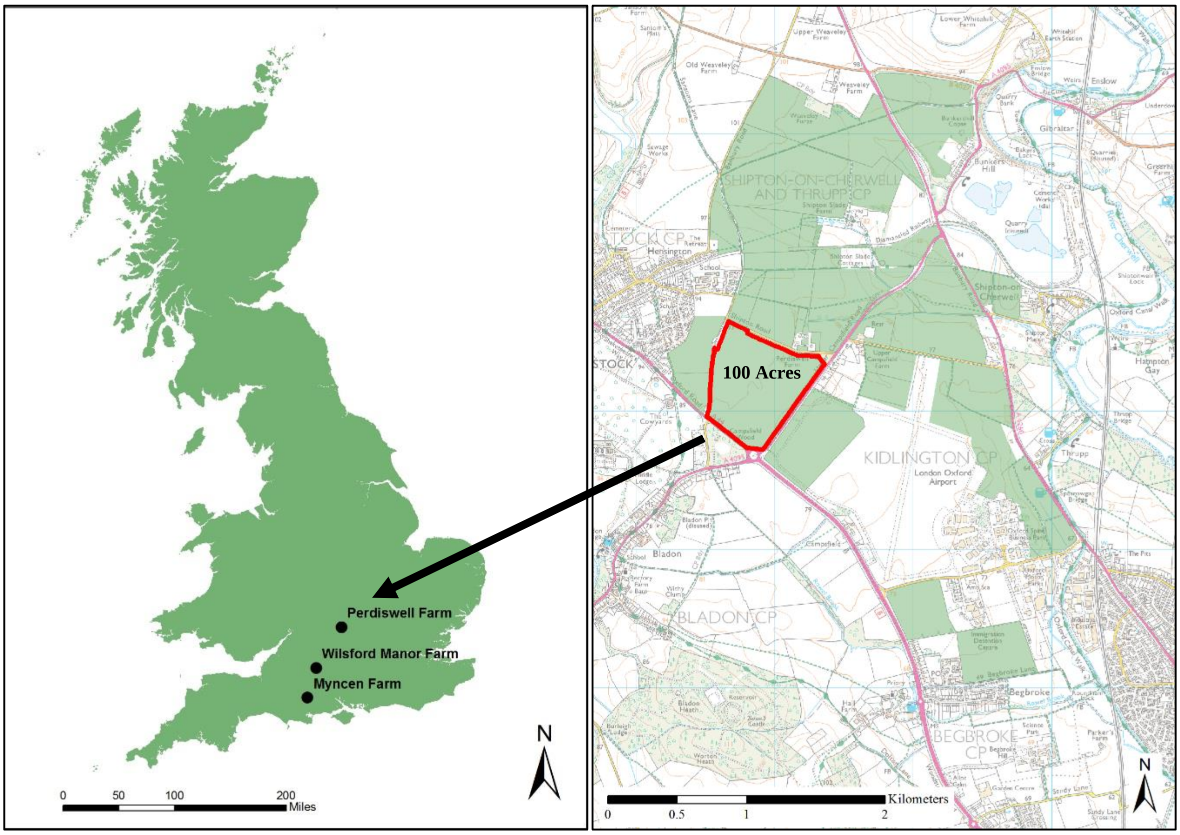


Figure 113: Location of the three case study sites, on the right a map shows the whole farm, with '100 Acres' outlined in red.

(contains OS data © Crown copyright and database right 2019)

8.1.2 Geology

The case study field is predominantly on top of the Cornbrash Formation (a Jurassic Limestone), which overlies the mudstones of the Forest Marble Formation (Bathonian – Callovian Age) (BGS 2018). Within the field itself (Figure 114), the 1:50,000 scale geological maps suggest that the SW corner of the field may exhibit some variability due to a boundary between the overlying Cornbrash Formation and the Forest Marble. For both of these geological deposits, one of the key reference sections used to give an indication of the thickness and stratigraphy of the geological profile was at Shipton-on-Cherwell Cement Works Quarry, about 1km north east of the site. These exposed sections have been described by Allen and Kaye (1973) and although they do not give a good indication of the upper boundary between the Cornbrash and the subsoils, they do give a good idea of the variability of the lower boundary between the Cornbrash and the Forest Marble. The upper parts of the Forest Marble contain very frequent lateral changes in the exposed sections, with recurring layering of limestone and clay. The boundary shows eroded channels that pre-date the Cornbrash, but clearly cut the

Forest Marble. There is evidence of directional patterning caused by the deposition of the beds contributing to the Forest Marble group. The cross-bedding indicating that there is a SW/NW alignment possibly caused by the direction of current flow over the seabed when these deposits were formed (Allen and Kaye, 1973: p. 8).

In the surrounding area, there are some superficial deposits lying on top of these geological units, consisting of sands and gravels, and in the lower lying areas some deposits of head and alluvium (Figure 114). No superficial deposits are noted within the boundary of 100 Acres. Therefore geologically the field itself would seem to be fairly consistent apart from the SW corner.

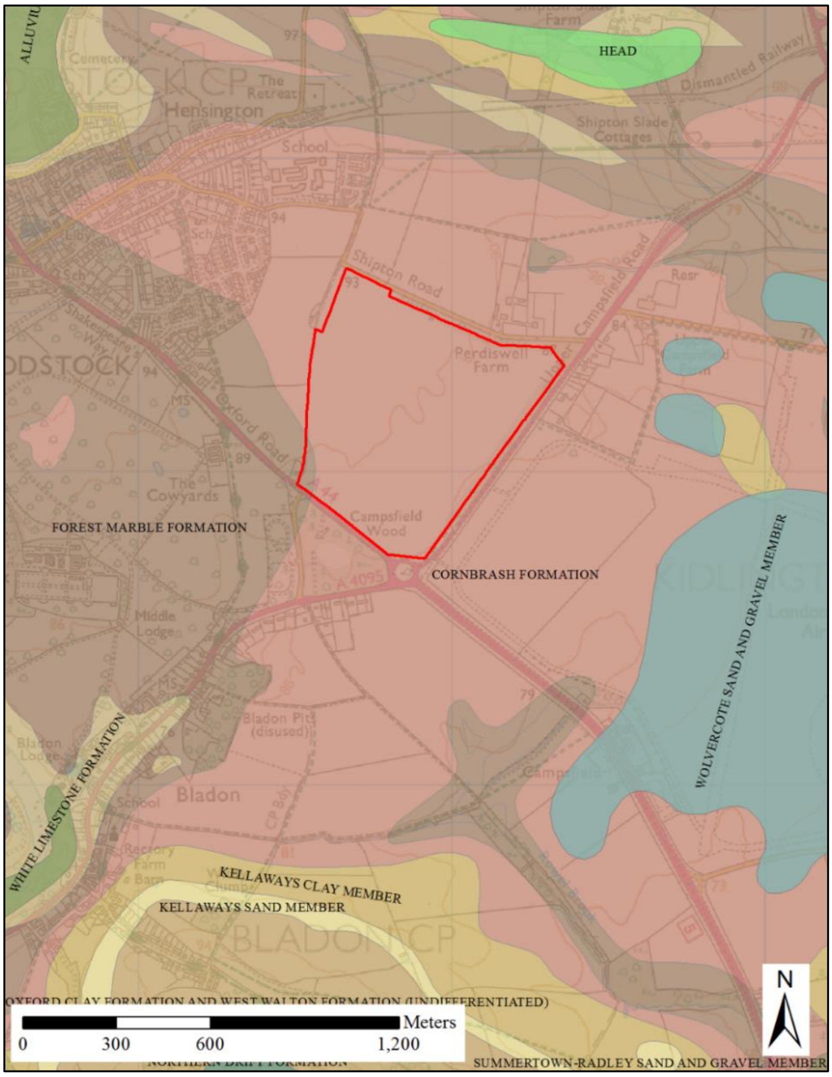


Figure 114: Geological map (1:50,000 scale) of the study area, with 100 Acres outlined in red

(© Crown Copyright/database right 2019. An British Geological Survey/EDINA supplied service) (contains OS data © Crown copyright and database right 2019)

8.1.3 Topography

The field lies at approximately 86-92m AOD with no significant undulations visible. Figure 115 shows the OS terrain data (5m spatial resolution) for the site and the surrounding areas. The highest part of the field is to the western and northern sides, and the land slopes to the SE. There was no available LIDAR data for this site.

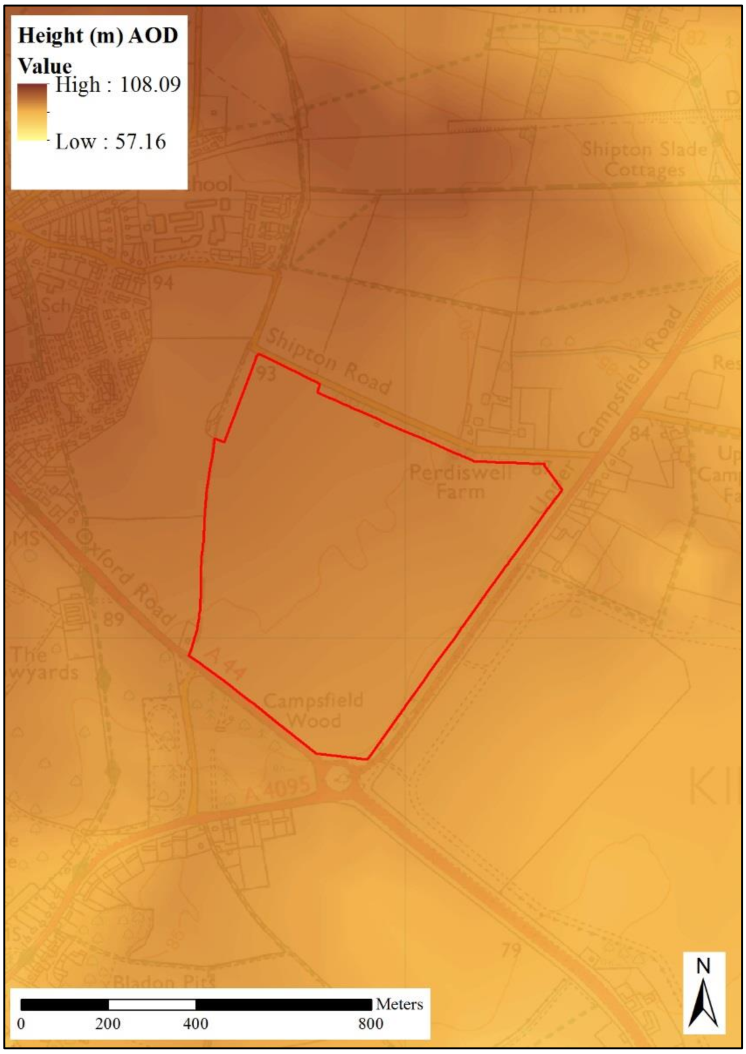
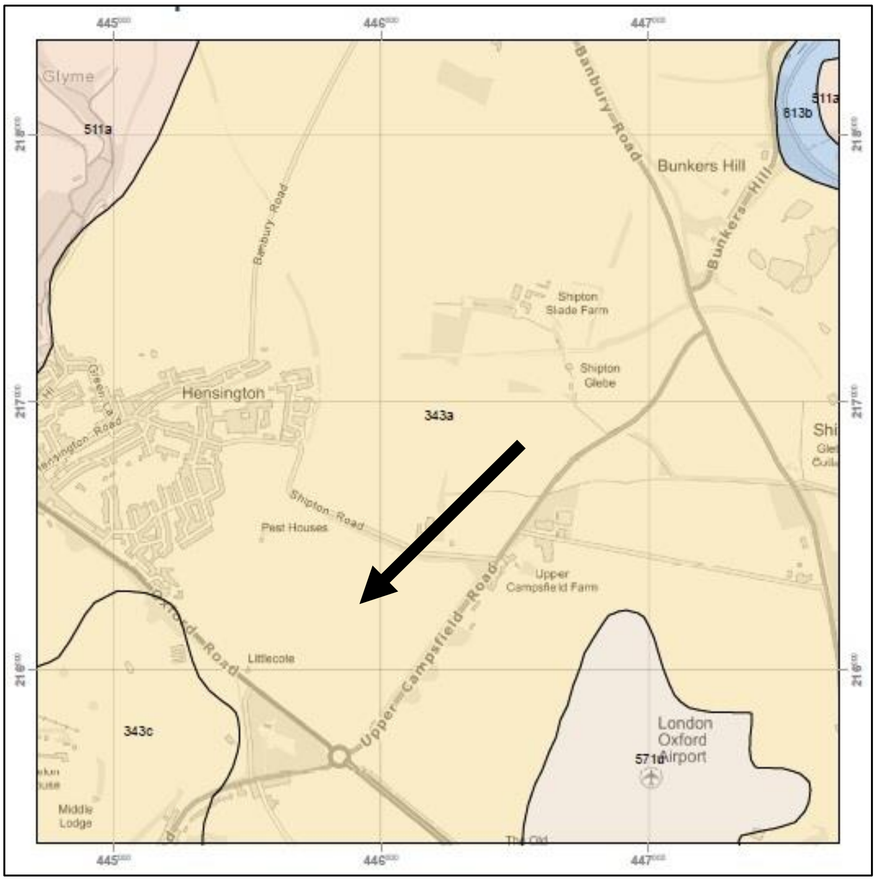


Figure 115: Topographical map of the area surrounding 100 Acres

(contains OS data © Crown copyright and database right 2019)

8.1.4 Soils

As might be expected from the reasonably consistent geology and the broadly level topography of the field, the known soil mapping does not show much variation across the field (Figure 116). In general the soils in the area can be described as shallow, well drained, and brashy calcareous fine loamy soils over limestone. The soil association for the whole area of the case study site is recorded as Elmton 1 (343a), with all soil series within this association having 25-60cm of soil depth before reaching fragmented limestone (National Soil Resources Institute, 2018b). The Elmton series is most common and has a very thin topsoil down to 25cm before reaching Cornbrash. The others (Aberford, Moreton and Shipton) show slightly more horizonation with slightly more blocky structures further down the profile and some yellowish brown horizons in comparison to the dark brown topsoils of slightly stony clay/clay loam.



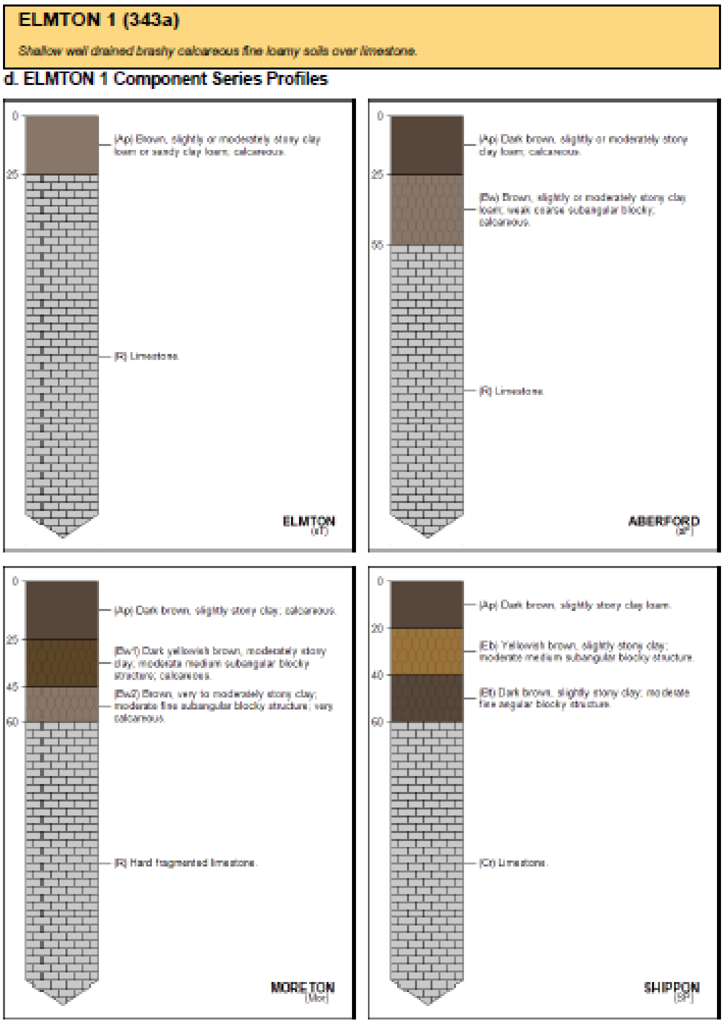


Figure 116: NSRI soil map showing the soil associations in the area (top), with each of the described soil series that could occur in this association (bottom) (National Soil Resources Institute, 2018b)

8.2 Agricultural and PF Background

8.2.1 The Farm

Perdiswell Farm is the base for a family run farming business that has been run by the Price family for three generations (J. Price pers. comm.). It began in 1946 and consisted of a smaller area of land than is currently being farmed. The original farming operation consisted primarily of pedigree Jersey cows and market garden vegetables. This then grew when further land was available, and concentration focused on the arable side of the business. During the 1990s the farm expanded again, when in 2003 Blenheim Estate stopped farming, the Price's took on part of their land and farmed at this point over 1150 Acres (465ha).

The farming business is now run by James Price, and as well as managing all of the farm's owned/tenanted land, offers a number of contracting services such as spraying, drilling, combining, variable rate fertiliser spreading. There is no livestock on the farm, however livestock have been brought in sometimes to graze of cover crops when necessary.

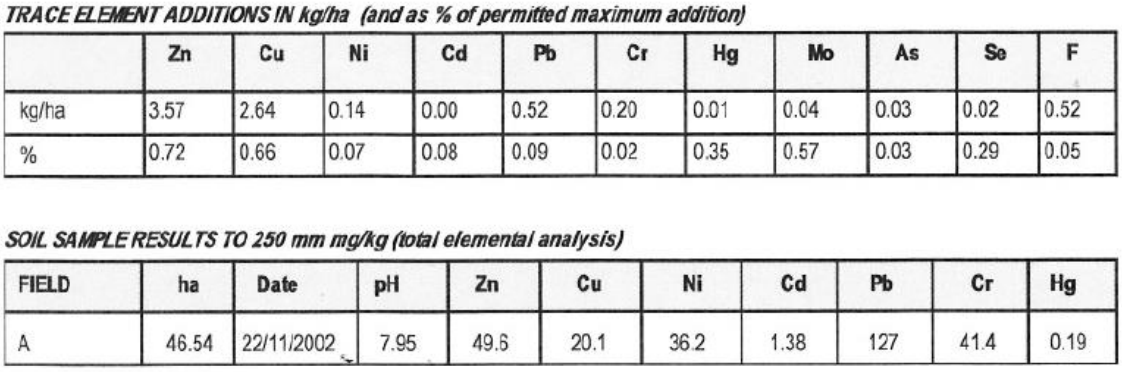
Another important aspect of the farming system at Perdiswell Farm is the participation in agrochemical and fertiliser trials. All agrochemical and fertiliser companies need land and farmers to allow them to trial out new products and set out replicated trial plots in comparison to the normal agronomic system being used. It is beneficial for the farmer to learn as well as for the agrochemical or fertiliser company getting ‘buy in’ from local farmers. The case study field, 100 Acres, has been used for this purpose in the past, and in the duration of this research. The trials were mainly based around new varieties of crops, as well as for agrochemical trials.

The farm has been in Countryside Stewardship agreements from 2000-2010, since then it has been in two Entry-Level Stewardship agreements. Under these agreements, patches within 100 Acres surrounding the Roman villa have been in minimum tillage cultivation zones.

8.2.2 Cropping and Fertiliser

The typical crops grown in 100 Acres over the past 10 years include winter wheat, oilseed rape, spring barley and spring beans with the rotation flexible depending on the soil conditions and other factors. The fertilisers used over the last 10 years have been a mix of organic materials and manufactured fertilisers. The farm has been using biosolids since 2003, which has broadly replaced the need for manufactured P and K fertilisers, although some is still used to top up particular areas. Sewage sludge was applied to 100 Acres in 2011, 2015 and 2016. Digestate from an anaerobic digester was also applied 2012, 2013 and 2014. The mix of nutrients applied also include regular application of available sulphur.

The sewage sludge comes with regulatory requirements for a soil test of the field having sludge applied to it, to ensure maximum levels of PTEs are not exceeded. Table 12 shows the historic soil test (one bulked sample) analysed for heavy metal contents of 100 Acres, with the concentrations of those metals in the sludge. This is an example from the 2015 sludge specifically, however applies broadly to the other years because product was from the same company and relatively consistent.



TRACE ELEMENT ADDITIONS IN kg/ha (and as % of permitted maximum addition)

	Zn	Cu	Ni	Cd	Pb	Cr	Hg	Mo	As	Se	F
kg/ha	3.57	2.64	0.14	0.00	0.52	0.20	0.01	0.04	0.03	0.02	0.52
%	0.72	0.66	0.07	0.08	0.09	0.02	0.35	0.57	0.03	0.29	0.05

SOIL SAMPLE RESULTS TO 250 mm mg/kg (total elemental analysis)

FIELD	ha	Date	pH	Zn	Cu	Ni	Cd	Pb	Cr	Hg
A	46.54	22/11/2002	7.95	49.6	20.1	36.2	1.38	127	41.4	0.19

Table 12: Analysis of the sewage sludge applied to 100 Acres in 2015, elemental content of the sludge (top) and soil analysis of 100 Acres in 2002 (bottom) (courtesy of J. Price)

8.2.3 Cultivations

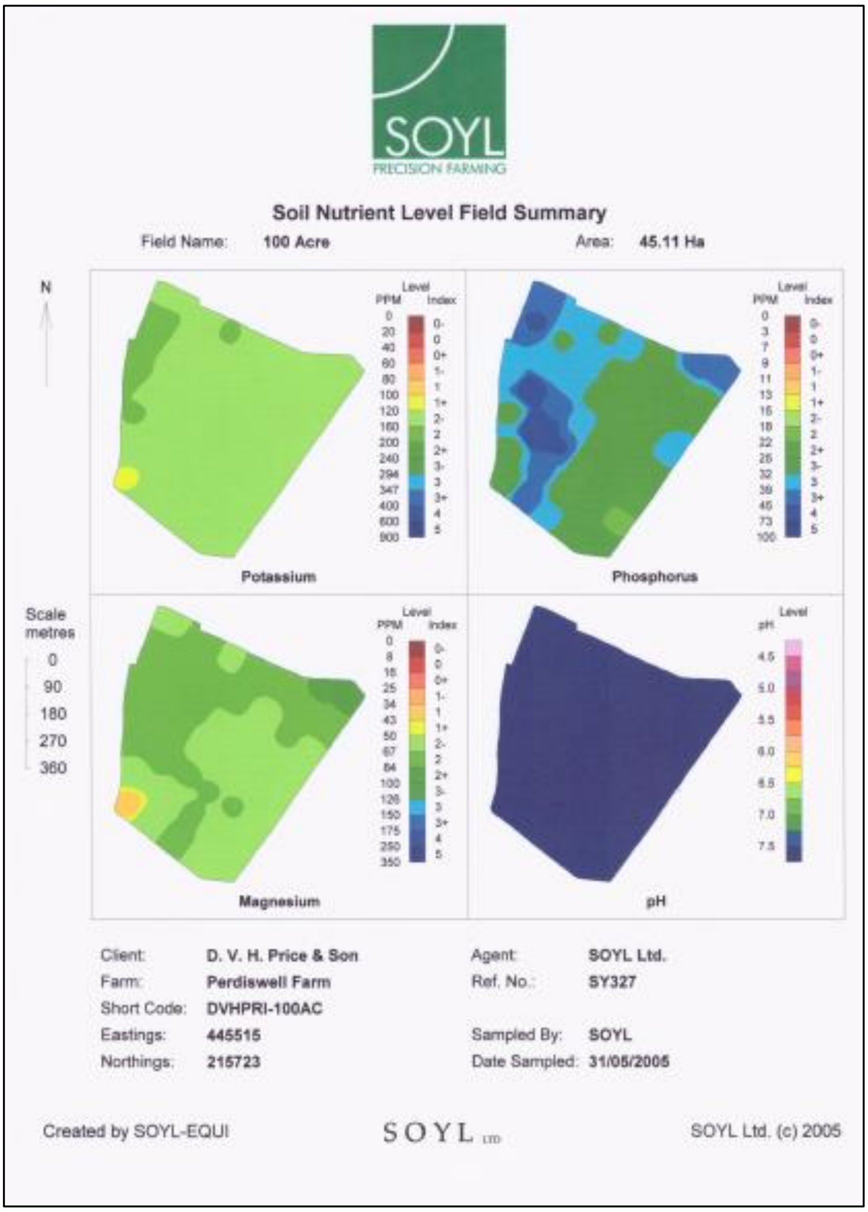
Broadly, the cultivation system is min-till across the farm, but with rotational ploughing when necessary (most often after organic material applications that need burying within the soil).

8.2.4 PF

As the farming system at Perdiswell Farm has grown, a future looking approach was taken to ensure the farm was equipped with the most up-to-date techniques and machinery. The farm has not followed the route of one PF company, but has instead tested datasets, been involved in trials, and worked with advisers in many PF companies, meaning there is no single piece of software that contains all the farms' data, and no set soil zones in comparison to the other two case study sites. Instead of mapping the soil types, the approach at Persdiswell focuses on managing the variability that is measured, and this may not always relate to rigid boundaries drawn between varying soil types.

One of the key areas of involvement with PF has been the development of the N-Sensor, a key tool used to detect the biomass of the crop in front of the tractor, in real time, to allow variable rate application of nitrogen fertiliser on the go. Perdiswell Farm has been using the N-Sensor for nearly 10 years, having been heavily involved with the first trials of the N-Sensor in the UK, and has been varying the rate of nitrogen applied since 2011.

The PF company SOYL, mapped some fields of the farm with conductivity survey and completed a grid-based soil analysis of within field variation in 2005 (Figure 117). Another company, Precision Decisions, completed a grid sampling P,K, Mg, pH and OM analysis of the whole farm on a semi-systematic grid-basis in 2013 and then again in 2017. The farm has yield maps from 2009 onwards from their combine harvester.



Soil Nutrient Level Field Summary

Field Name: **100 Acre**
Area: **45.11 Ha**

Client: **D. V. H. Price & Son**
Farm: **Perdiswell Farm**
Short Code: **DVHPRI-100AC**
Eastings: **445515**
Northings: **215723**
Agent: **SOYL Ltd.**
Ref. No.: **SY327**
Sampled By: **SOYL**
Date Sampled: **31/05/2005**

Created by SOYL-EQUI

SOYL Ltd. (c) 2005

Figure 117: An example soil analysis sheet from a PF company for 100 Acres (courtesy of J. Price)

8.3 Archaeological Background

Where Chapters 6 and 7 focused on the chronology of archaeological investigation across the site, at Perdiswell there have only been two investigations that have provided a large amount of background to the site, hence the archaeological background will be separated by archaeological period instead.

8.3.1 Prehistoric

As has been noted in multiple archaeological reports by Thames Valley Archaeology Services (TVAS) (Bray and Taylor, 2014; Dawson and Bray, 2014; Preston, 2014), this area has been an attractive site for settlement in all periods, being in between three tributaries to the Thames (the Evenlode, Glyme and the River Cherwell). In a DBA by TVAS in 2014, there were some flint scatters found in the field to the W of 100 Acres and some further NE of Woodstock (Preston, 2014: p.6). These do not represent significant scatters and therefore have not been linked with any prehistoric settlement. One and a half kilometres to the NW of the site lies a long barrow (scheduled monument 1021413), which still survives as a low mound but has been degraded over the past 50 years from cultivation. Two further long barrows are suspected to the W and NW of the scheduled barrow, and a possible Bronze Age round barrow to the S, however the evidence for these is less substantial (Preston, 2014).

8.3.2 Roman

The area surrounding Perdiswell Farm was used significantly in the Roman period, with a number of areas of settlement, as well as proximity to a major Roman road (Akeman Street). A Roman villa is known at Dog Kennel Hill (3km W of the site); a Roman ditch-enclosed farmstead at Hensington (1km N of the site); a small square Romano-British temple (scheduled monument 1009417) with surviving bank and outer ditch, lays within the grounds of Blenheim Palace (2km W of the site) and a late Roman habitation site identified while widening the A44 where many Roman ditches, pits and corn-drying ovens were excavated (0.5km SE of the site).

8.3.3 Early Medieval, Medieval and Post-Medieval

The site lies at the junction of a number of English parishes that are recorded at the time of the Domesday Book in 1086 CE (Preston, 2014). The most significant parish is that of Woodstock itself, which was previously part of the royal forest. The parish was carved out of other existing parishes by Henry I to become a royal park with a hunting lodge in the early 12th century. This was then turned into a royal palace under Henry II and became a long term centre for royal activity until the English Civil War (1642-1651). Queen Anne in 1705 granted the palace to John Churchill, the 1st Duke of Marlborough after his victory at the battle of Blindheim. The remains of the old palace were pulled down, and the new palace of Blenheim was built in 1705-22. With this shift of the palace S of the Glyme, came the shift of the village of Woodstock to its current position. Blenheim Palace, now with its 18th, 19th and 20th century additions and landscaping, as well as its historical connections to the Dukes of Marlborough and Sir Winston Churchill, was listed as a World Heritage Site in 1987.

Other elements of Medieval history in the landscape surrounding 100 Acres are fishponds and ridge and furrow earthworks to the N of the site towards Hensington. In addition a plot of land immediately NW of the field has been recorded as a pest house on the First Edition OS of 1880. This plot and the existence of a building is shown on previous maps from 1794 and 1818 and indicated by the Victoria County History as possibly in existence by 1750. The term ‘pest house’ is used to describe a hospital for infectious diseases (Preston, 2014: p.20).

8.3.4 Modern

OS mapping since the First Edition in 1883, shows the development of the area over the last century and a half (Figure 118). In 1890 a railway was constructed by the Duke of Marlborough connecting Woodstock to Shipton-on-Cherwell (mainline), and running to the N of the site but was disused by 1954. A few hundred metres to the E of the site, at Kidlington, in 1935 a civil airport was opened by Oxford City Council. This was requisitioned by the Royal Air Force during the Second World War, but returned to a civil aviation post-1946, and by 1969 housed the largest civil pilot school in Europe and is still in use today (Preston, 2014: p.13).

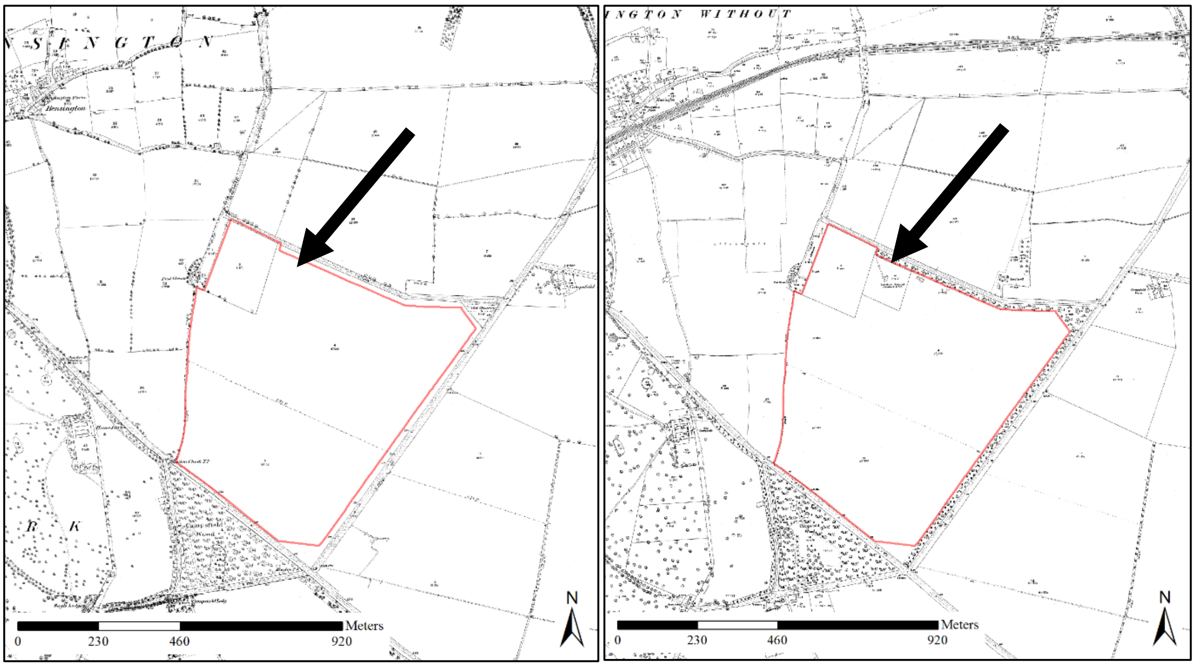


Figure 118: First Edition OS map published 1883 (left) and 3rd Revision published 1923 (right) with location of Isolation Hospital marked

(© Crown Copyright and Landmark Information Group Limited (2019). All rights reserved. (1883 and 1923))

8.3.5 The Field: 100 Acres

The reason for the detailed, commercially-led, DBA which has provided a lot of background material for the site, is due to a proposed development of the field immediately W of 100 Acres, and potentially including 100 Acres itself. After the DBA was completed, a geophysical survey of the proposed area and trial excavation of this area was recommended. These reports can be read in full if the reader wishes more detail than the summary presented here (Preston 2014; Bray and Dawson 2014; Bray and Taylor 2014).

Previous to the TVAS work, one of the most significant archaeological sites within this field is the Blenheim villa or Begbroke villa (scheduled monument 1021367)(Figure 119). First recorded by aerial photography in 1971, and confirmed with limited trenching across the site in 1985, the villa comprises of buildings, a simple cottage form with six rooms, an apsidal end and corridor, all enclosed by a number of ditched enclosures. Subsurface preservation was relatively good, with a layer of decorated plaster still surviving above the floor surface and at least three courses of stonework beneath the plough soil. From pottery found within the excavated areas, the villa is thought to relate mainly to the 3rd and 4th centuries CE (https://historicengland.org.uk/listing/the-list/list-entry/1021367 accessed 03/11/19).

A geophysical survey (magnetic gradiometry) was completed by TVAS in 2014 for the whole of the field (Figure 119), and produced a large number of magnetic anomalies. The most significant cluster surrounding the villa itself, and spreading to the N and S of the scheduled area, showing that the relating enclosures were more extensive than previously thought, and that there is a possibility for further small ancillary buildings connected to these. In the northern end of the field, there are some magnetic disturbances that relate to an area marked as an Isolation Hospital on the Third Revision OS map, but was short-lived and removed by the Fourth Revision. Further to the NE there were a number of linear and circular geophysical anomalies that likely relate to past quarrying, as well as older field boundaries within the field. Again the First Edition OS (Figure 118) shows the wooded area in this north eastern corner was a site of old quarrying. There are some linear anomalies forming an exact cross aligned with the points of the compass, connected by a linear anomaly running towards the airfield to the east. This has been interpreted as a navigational aid and has been seen in aerial photographs from the 1940s (Dawson and Bray, 2014: p.7). The other main anomalies outline a number of previous field boundaries, some presumed to be modern and some post-Medieval, and a small rectangular enclosure to the SE of the site that is of unknown date.

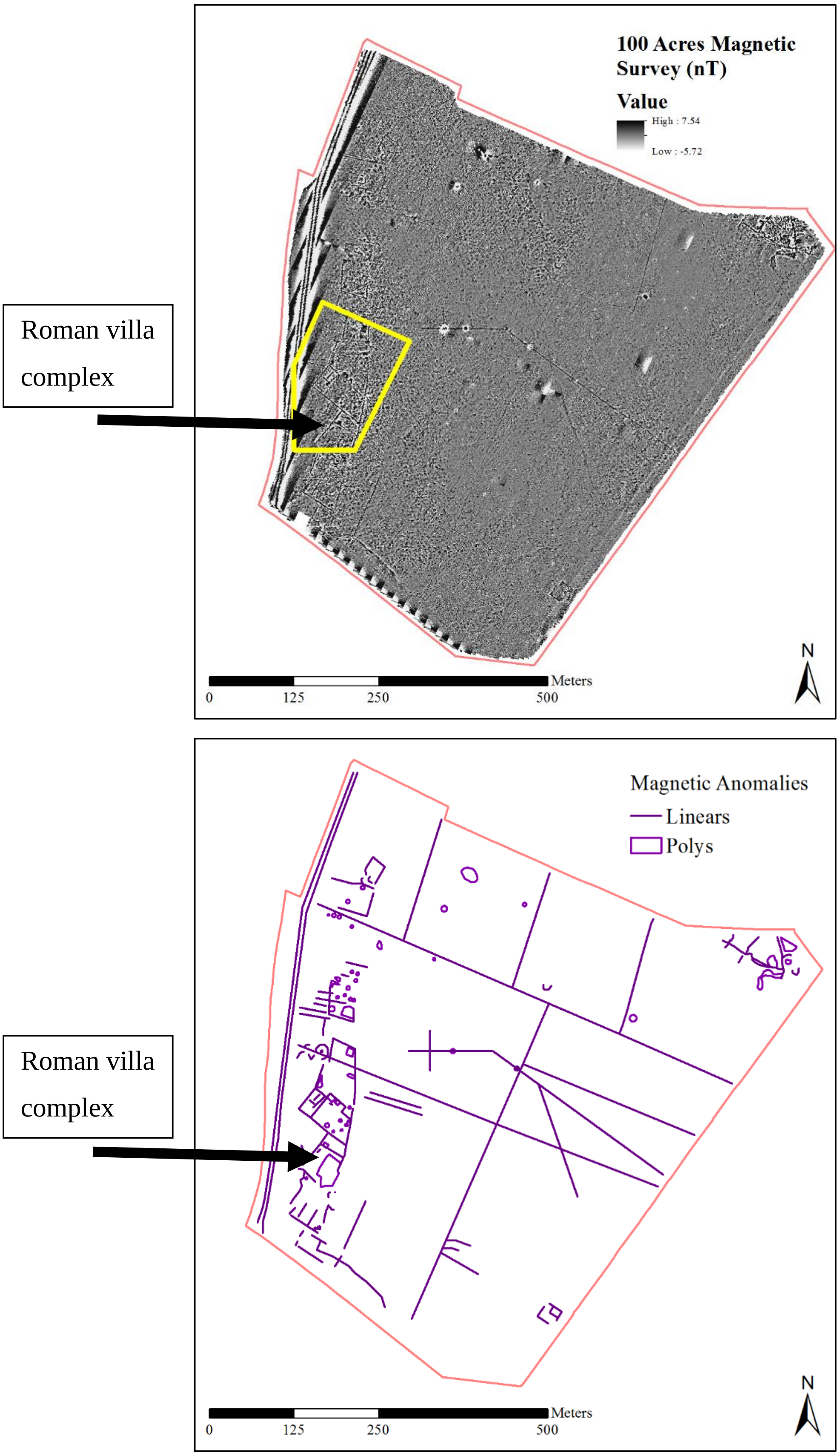


Figure 119: The data of the magnetic survey (top) and the interpreted archaeological anomalies (bottom) with arrows marking the scheduled Roman villa and yellow polygon marking edge of scheduled area (courtesy of TVAS)(Dawson and Bray, 2014)

Following this geophysical survey, an evaluation was carried out across the whole site, including 100 Acres. There were 265 trenches, machine-excavated across the whole site, but excluding the area surrounding the scheduled area of the Roman villa.

199 trenches were excavated to varying depths depending on the soil variations across the field, but were all in between 0.23m and 0.59m. The archaeological features encountered across the site were, in nearly all cases, shallow (due to the underlying geology) and therefore heavily truncated by modern cultivation. The features excavated consisted of shallow gullies formed from truncated ditches, some deeper ditches and pits, and one crouched burial. Most of these are dated to the late Iron Age/Roman periods. Many features correlated well with the geophysical results, and some areas previously undated could be identified as further Roman occupation, and some as modern 19th-century features. The site of the Isolation Hospital yielded no significant subsurface remains highlighting either its short lived use/temporary structure, or its complete recycling. It is noted that other than the 34 trenches that had archaeological features of a pre-modern date, the rest of the trenches had relatively little in them, suggesting perhaps that other than this major period of use in the late Iron Age/Roman period, the landscape of enclosed fields and trackways is probably relatively recent (post-Medieval).

8.4 Fieldwork Results

8.4.1 Soil Geochemistry

This field, being considerably larger in area than the other two case study sites, and with a comparatively shallow soil profile before reaching geological horizons, was only sampled for topsoil variation within the upper 20cm of topsoil. The resolution of the topsoil sampling was the same as at other sites, a grid of 20x20m squares, producing 1087 soil samples for pXRF analysis (Figure 120).

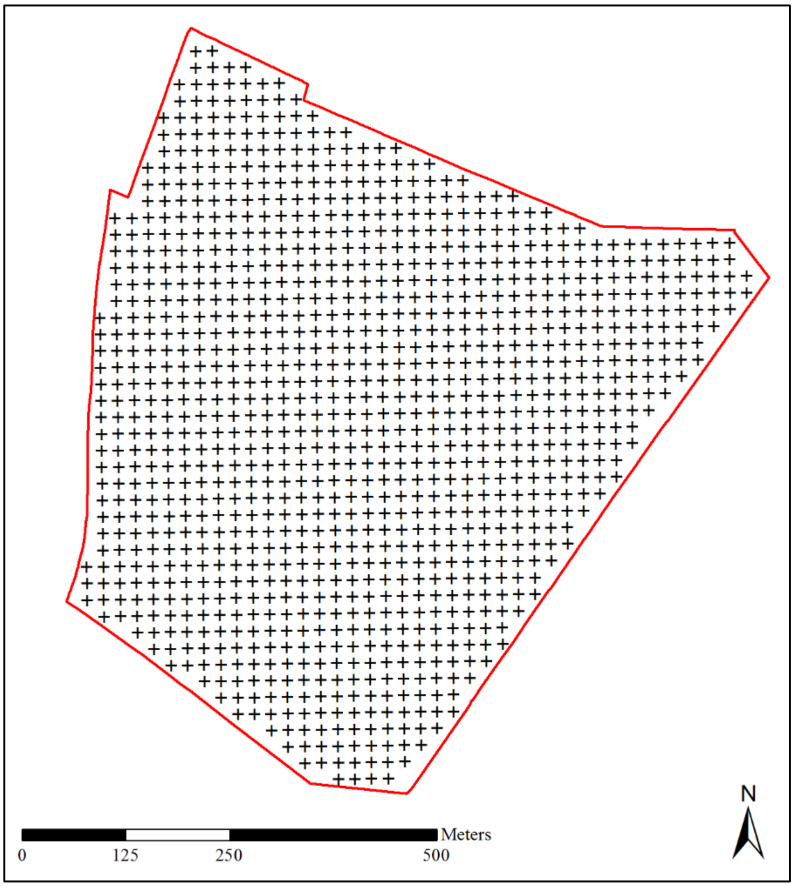
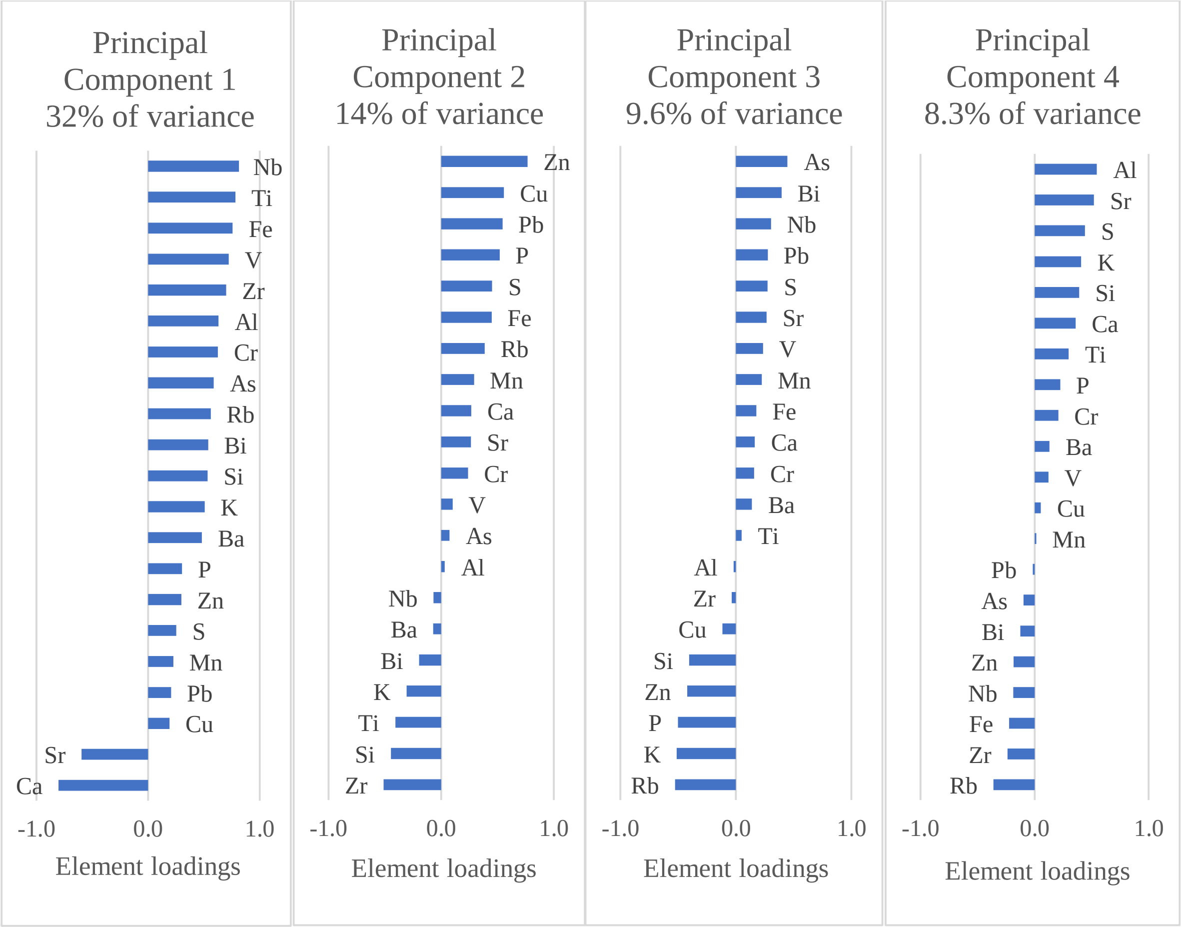


Figure 120: Location of all topsoil soil samples at Perdiswell

Out of the total 34 elements analysed by pXRF, 13 elements were below the limit of detection, leaving 21 elements with consistent detection apart from Cu, which is still included due to its archaeological potential (Cu was detected in 499 samples out of 1087). The PCA resulted in five components, explaining 70.5% of the variance of the entire dataset, but only the first four will be discussed, since the 5th only related to 5% of the variance of the entire dataset.

The elemental loadings are shown in Figure 121 for each PC with the percentage variance that it relates to within the entire dataset. PC1 shows a result that is similar to the other two case study sites, with a clear differentiation between Ca and Sr (group A on Figure 121), in comparison with most other elements (group B on Figure 121). This is expected due to the varying types of limestone/chalk geologies that underly all three case study sites. Elements that lie within group C (elements P, Zn ,S ,Mn ,Pb and Cu) have very similar loading values close to zero and appear to be less associated with the major positive/negative groupings (especially in PC1), suggesting that these do not relate strongly to groups A or B. This same group (apart from Mn) in PC2 has a positive loading that is separate from the negatively loaded elements such as Zn, Si, Ti K, as well as Ca and Sr, which instead sit in the middle of PC2. PC3 and PC4 show less significant differences between the elements, as well as only representing around 9% of the variation of the entire dataset and are not considered further.



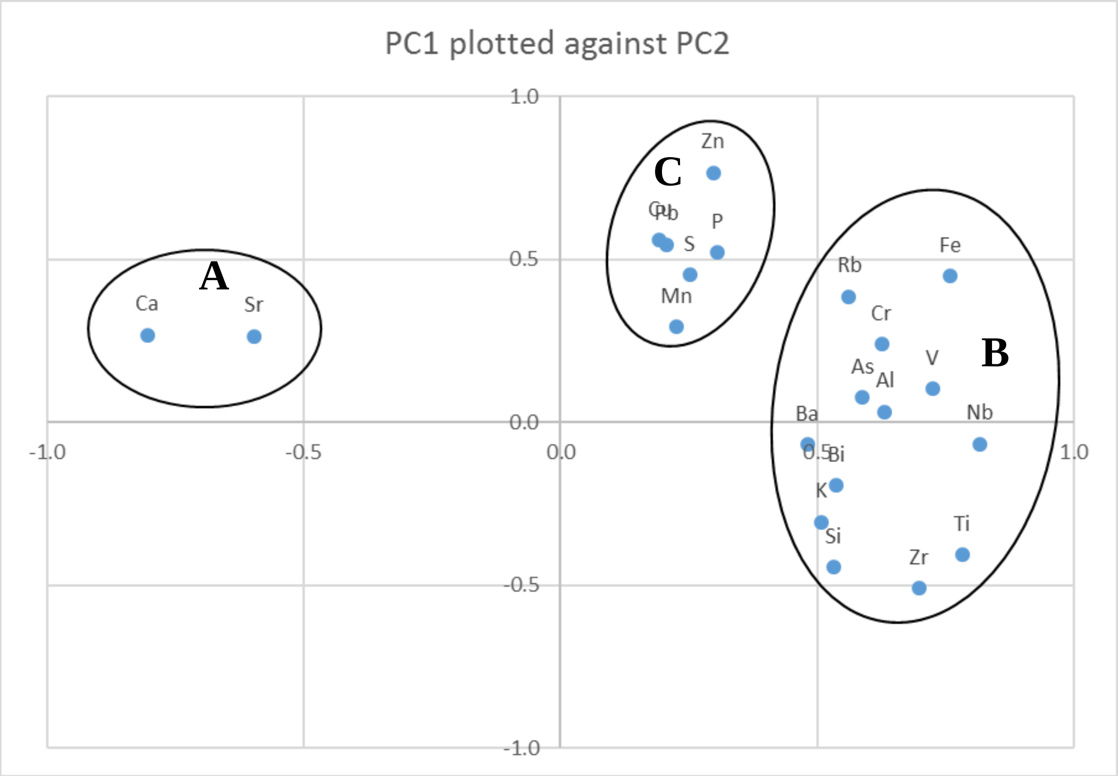


Figure 121: Elemental loadings for four Principal Components (top) and graph of PC1 plotted against PC2 (bottom) (© author)

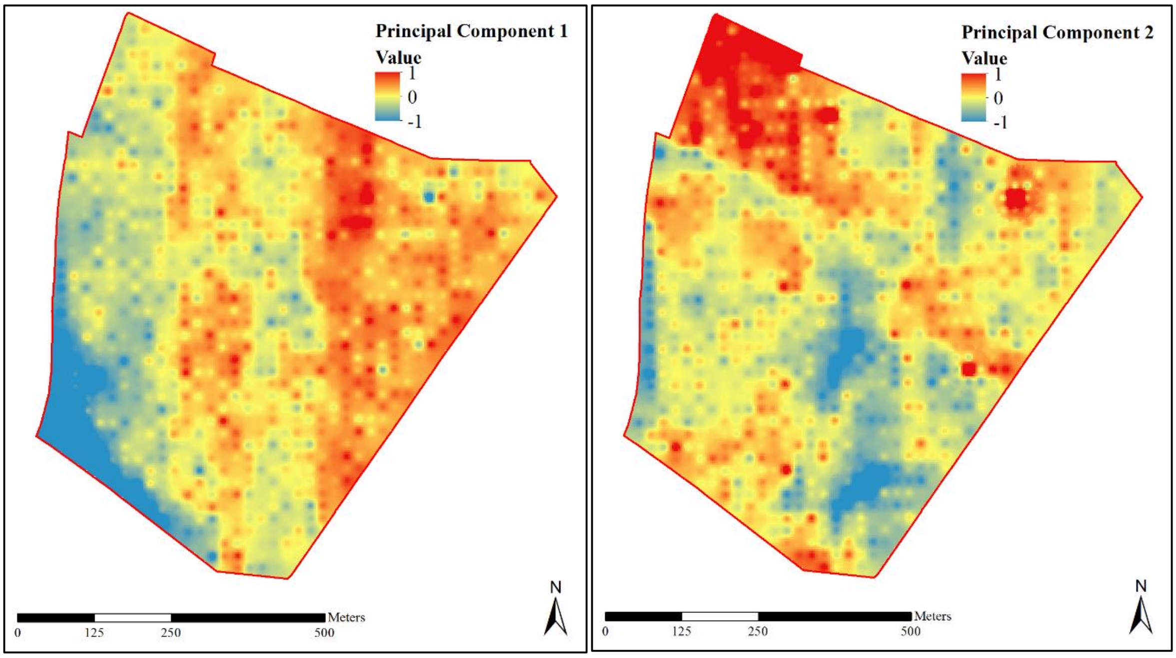


Figure 122: Colourmap showing PC1 (left) and PC2 (right) distributed spatially (© author)

The negative elemental grouping in PC1, Ca and Sr, show up well in the spatial distribution of PC1 in Figure 122 at the S and SW edges of the field. In comparison, the majority of the rest of the field has a positive elemental grouping, matching group B. There are some vertical N/S orientated striping in this dataset, which after further investigation appear to originate from two elemental maps, Al and Ti. Due to the time taken to sample the large number soil samples, two soil sampling augers were used, one 'dutch' type auger and one small hand corer. The differences in Al and Ti relate to the sampling lines and approximately to a day's work, therefore the use of a different sampling auger must have affected the pXRF data. This highlights how important it is to ensure sampling is consistent for detailed elemental analysis. Figure 123 shows another replica of PC1 created without using the Al and Ti data to show the distribution of the major positive and negative PC1 elemental groups without the striping caused by sampling errors. This image provides evidence for soil variability over the field with a clear SW boundary, where the topography dips down towards the road (A44) defined by high Ca and Sr values. The rest of the field is more consistent, but still with a mottled variability.

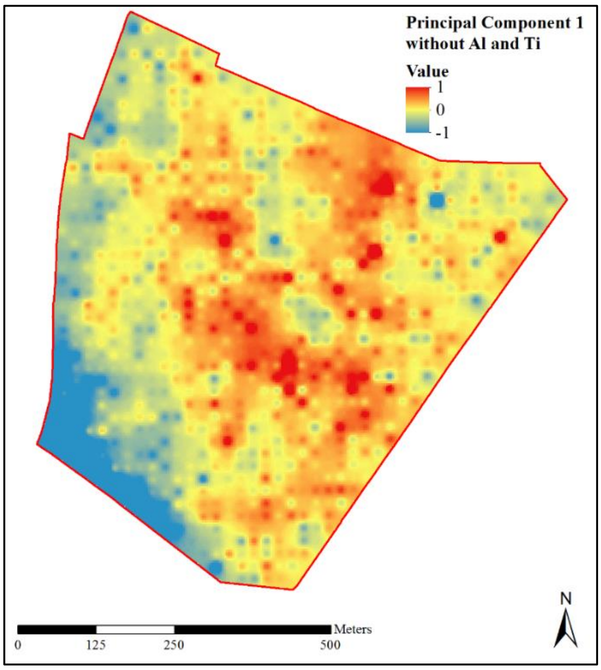
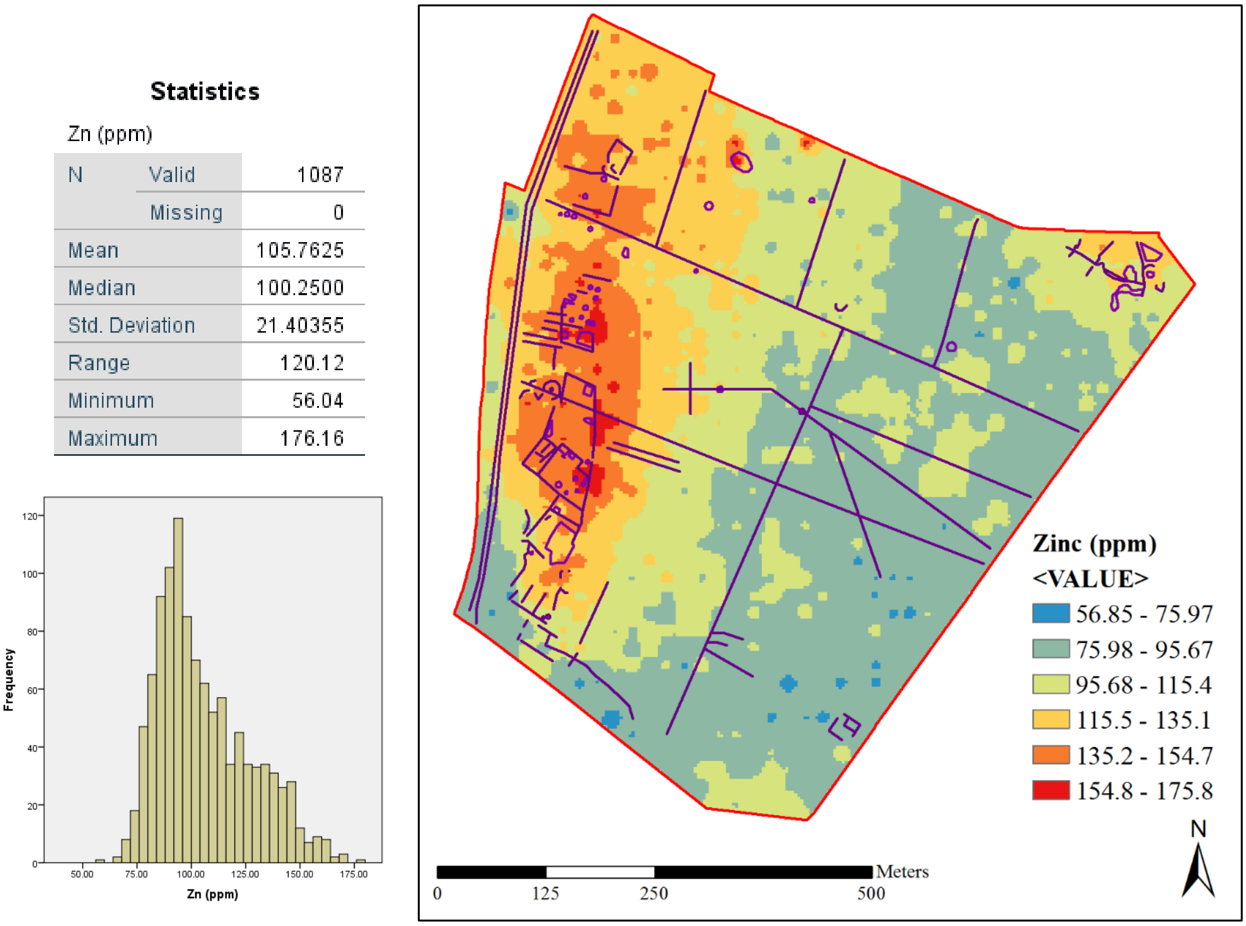


Figure 123: Colourmap of PC1 with Al and Ti data removed to address the striping in Figure 122 (© author)

Moving to PC2 (Figure 122 right), the positive elemental loadings should represent the spatial distribution of the group C (P, Zn ,S ,Mn ,Pb and Cu). The image shows a stark difference in the NW corner of the field that is substantially different from the rest of the field. It's form aligns to linear boundaries linking to previous field boundaries shown in Figures 118 and 119. There is a broad area in the NE of the field, as well as two negative (blue) patches in the central and S part of the field.

While the multi-element analysis shows broad variation in groups of elements, it is important to relate those to the distributions of individual elements. Group C presents a number of elements of interest because of their lack of correlation with the major soil groups, and relation to archaeological activities (Section 3.1.6). Each element will be compared using the magnetic anomalies in Figure 119 as a starting point for interpretation.

The variation in Zn in the topsoil is very clear (Figure 124). There is an elongated oval area surrounding the known Roman villa site, and the associated enclosures spreading N and S from it, containing elevated levels of Zn, approximately 30-70ppm over the average of 106 ppm. These general elevated levels carry on into the NW corner of the field, and spread across the two western-most historic field boundaries that have an uncertain date of origin but were in use until at least the Second World War. There are slightly elevated relating to previous quarrying and ditch features dated to the late Iron Age/Roman period. There are some very isolated elevated levels over the exact location of the Isolation Hospital. The sum of these elevated levels of Zn that all correlate with one archaeological feature or another, adds a noticeable positive skew to the histogram for the whole field.



Statistics

Zn (ppm)

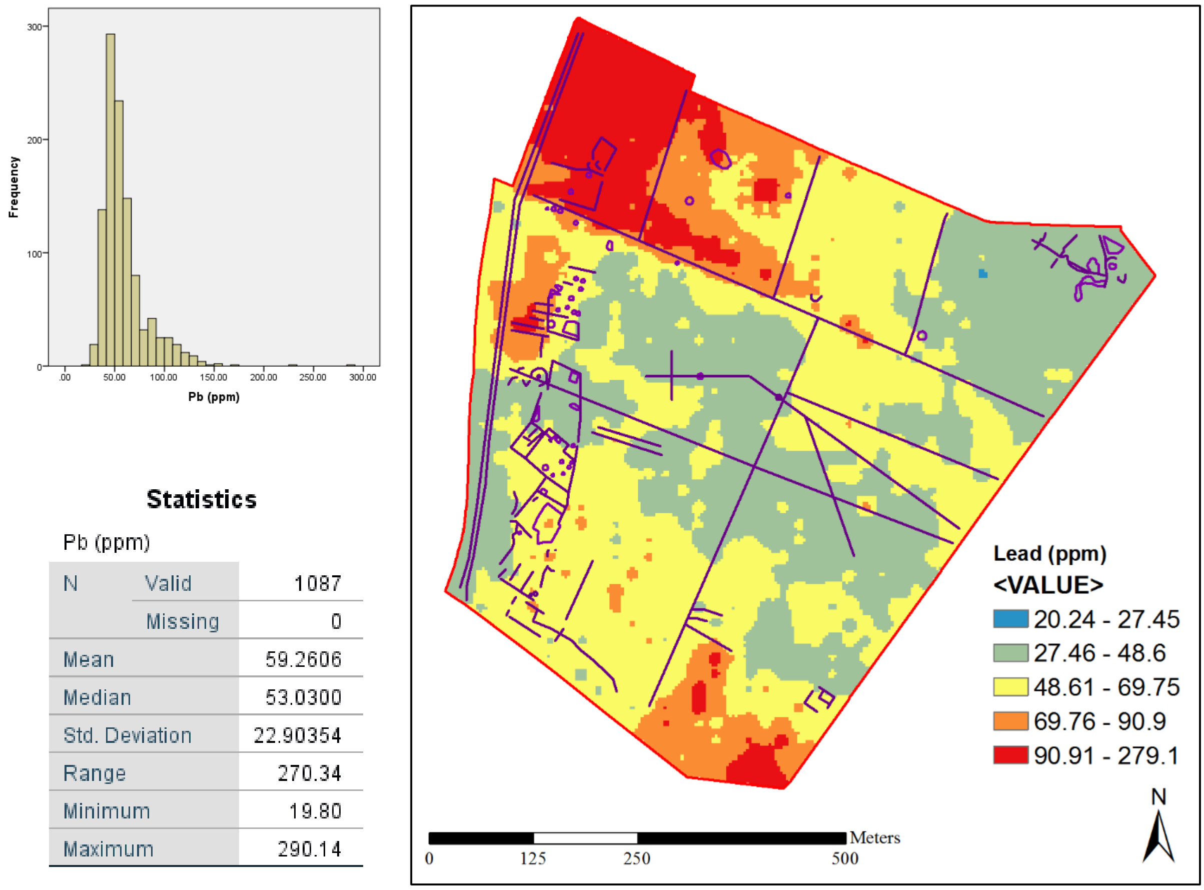
N	Valid	1087
	Missing	0
Mean		105.7625
Median		100.2500
Std. Deviation		21.40355
Range		120.12
Minimum		56.04
Maximum		176.16

Figure 124: Basic statistics for Zn in the topsoils (left top), frequency histogram (left bottom) and map of Zn variation in relation to magnetic anomalies (right) (geophysical anomalies courtesy of TVAS) (© author)

The levels of Pb over the site are substantially variable (Figure 125) and it is clear that Pb has contributed quite significantly to the overall distribution of in PC2 (Figure 122). The NW corner, within the historic field boundary, exhibits the highest levels of Pb (the whole area >90ppm). While the second historic field to the E does have elevated levels of Pb, the distribution only covers around 50% of the area and is of a lower concentration. It does interestingly follow the E/W the magnetic anomaly of a field boundary which does not appear on any of the OS maps making it pre 1890 in date at least.

Figure 126 shows the location of the Isolation Hospital, with a track leading to it, and a field boundary surrounding it which does not appear on the geophysical data (meaning it was most likely just a fence with no ditch at all). The track way leading to the hospital correlates with the linear and similarly aligned elevated level of Pb and it is known that Pb can be deposited in quite high levels from vehicle emissions of leaded petrol (Kabata-Pendias, 2011: p.342). Other possible sources, especially being near an airfield, could come from aircraft fuel but this is unlikely at such a localised level within the field. Since the enhancements runs along the length of a trackway or entrance way to the Isolation Hospital, it may also relate to materials making up that trackway, or something to do with the destruction and clean-up of the site (for example paint can contain high levels of Pb) (Kabata-Pendias, 2011: p.342).

These results demonstrate that geochemical enhancements can be chronologically identified if there are enough enhancements relating to different events in time. The Pb additions along the trackway, if caused by the trackway and not another type of addition before that date, likely dates from *c.*1900-1950. While Pb additions aligning with the field boundary not shown on OS mapping likely date to pre-1884. One sample that produced the most extreme level of Pb is also within this area, SE of the site of the Hospital. If extreme outliers in the statistical distribution were discarded before analysis, as is often the case in many statistical studies, locations of anomalies such as this may be deleted. However, with knowledge of the Isolation Hospital and the various other Pb variations in this area, it is quite likely this high outlier also represents some anthropogenic enhancement.



Statistics

Pb (ppm)

N	Valid	1087
	Missing	0
Mean		59.2606
Median		53.0300
Std. Deviation		22.90354
Range		270.34
Minimum		19.80
Maximum		290.14

Figure 125: Basic statistics for Pb in the topsoils (left top), frequency histogram (left bottom) and map of Pb variation in relation to magnetic anomalies (right) (geophysical anomalies courtesy of TVAS) (© author)

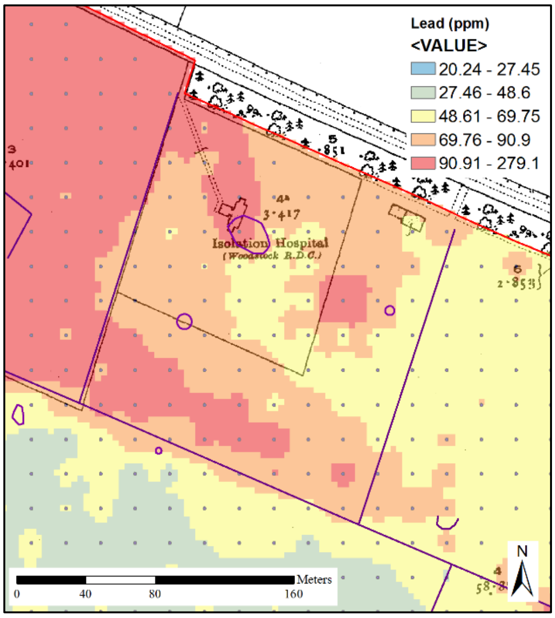
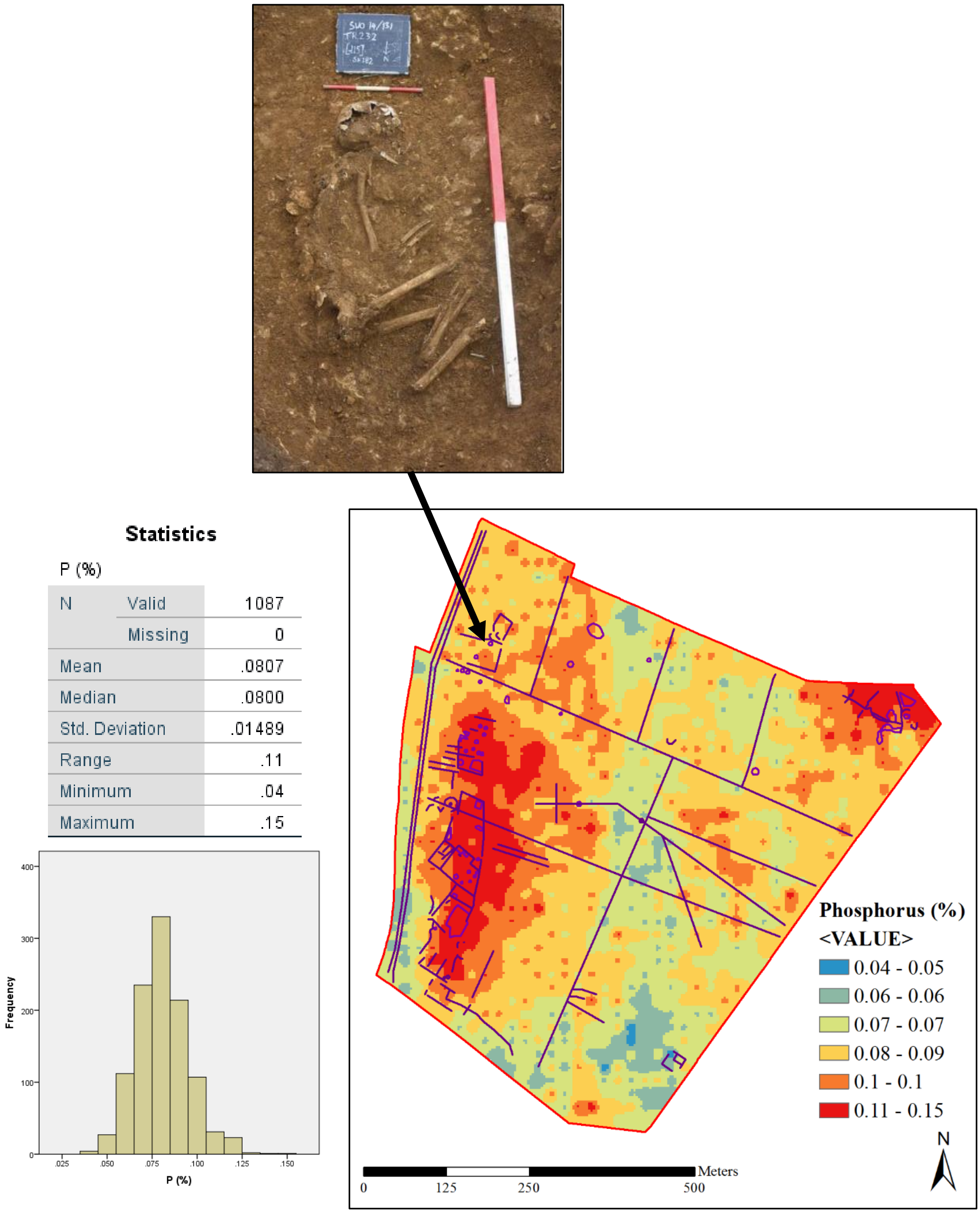


Figure 126: Pb levels across the Isolation Hospital and historic field boundaries. (geophysical anomalies courtesy of TVAS) (© author) (© Crown Copyright and Landmark Information Group Limited (2019). All rights reserved. (1883))

Separate areas of Pb enhancement are shown to the W of the field, relating not to the whole spread of Roman activity like Zn, but to one smaller area just W of a group of geophysical anomalies that represent further Roman enclosures and possible structures. The conclusion that this deposition was caused by Roman period activity however is far from certain. In addition to this another area of elevated Pb levels lies to the SE corner of the field covering a relatively larger area. The only archaeological features noted in this area are a small rectangular structure and a short linear anomaly (not a ditch) that corresponds with the end of the slightly elevated levels of Pb. This could be part of another historic field boundary or partition in land use.

P levels across the field vary from 0.04% to 0.15% with an average around 0.08% (Figure 127). P variation correlates well with the Zn distribution, with two main clusters of high levels surrounding the Roman enclosures and the late Iron Age/Roman enclosures in the NW of the field. There is again a clear distinction between the P distribution and the combined PC1 map showing the predominant elemental groupings, being very different from PC1. P variation is therefore very well correlated to the historic features in the field, and especially to the late Iron Age and Roman features. The reasons for this are likely to be because of the intensive land use over a significant period of time. Excavation evidence suggests that the site was predominantly in use from the 3rd to the 4th centuries approximately, although with some late Iron Age material appearing, it is likely the site would have been in use before the 3rd century CE. Within the enclosures the P sources are likely to be from human and animal wastes deposited in ditches as well as in midden areas or even pits. The elevated P levels extend significantly to the E which could indicate that this area had been intensively used in some form to deposit high levels of P there. Despite there not being any clear geophysical anomalies suggestive of ditches that could form boundaries, it is certainly possible more temporary structures could have been used for keeping animals close to the main villa which could explain this wide spread on the higher ground.

The small group of geophysical anomalies to the N of the main set of Roman enclosures, within the NW historic field boundary, do not have the similar elevated levels of P even though it did show higher levels of Zn. Excavations show that these enclosures are of the Roman period, from large amounts of pottery and oyster shell recovered from the fills of the ditches. One trench (no. 232) contained a crouched burial cut into an earlier ditch, the burial was not fully excavated and so is of uncertain date. Therefore if these features are of a similar date to the rest of the Roman enclosures to the S, there was certainly less intensive use of this area due to less P additions.



Statistics

P (%)

N	Valid	1087
	Missing	0
Mean		.0807
Median		.0800
Std. Deviation		.01489
Range		.11
Minimum		.04
Maximum		.15

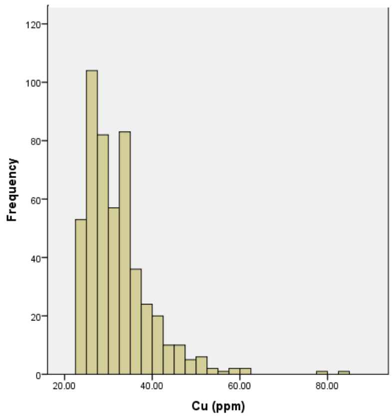
Figure 127: Basic statistics for P in the topsoils (left top), frequency histogram (left bottom) and map of P variation in relation to magnetic anomalies (right) and photograph of crouched burial (top) with arrow pointing to its location on the map (data courtesy of TVAS) (© author)

Cu was not detected consistently across the whole field, due to levels approaching LOD of the pXRF, but did appear within the same grouping in the PCA as other potentially interesting elements. Therefore with 499 samples that were detected accurately, the spatial distribution map was produced (Figure 128). This shows that there are two clearly elevated areas of Cu that link with existing distributions. The first being the NW corner, and specifically only within the first historic field boundary. The second area of high Cu levels is over the central area of the villa complex, concentrated around the middle of a number of linear enclosures immediately N of the villa. The enclosures within this area do have a number of small square positive magnetic anomalies, along with some pit type features. Together these results could suggest some form of metal working activity for example. There are some low, but consistent areas of detection in the NE corner of the field, relating to the late Iron Age/ Roman activity.

Statistics

Cu (ppm)

N	Valid	499
	Missing	588
Mean		32.0708
Median		30.2700
Std. Deviation		7.45543
Range		61.31
Minimum		23.11
Maximum		84.42



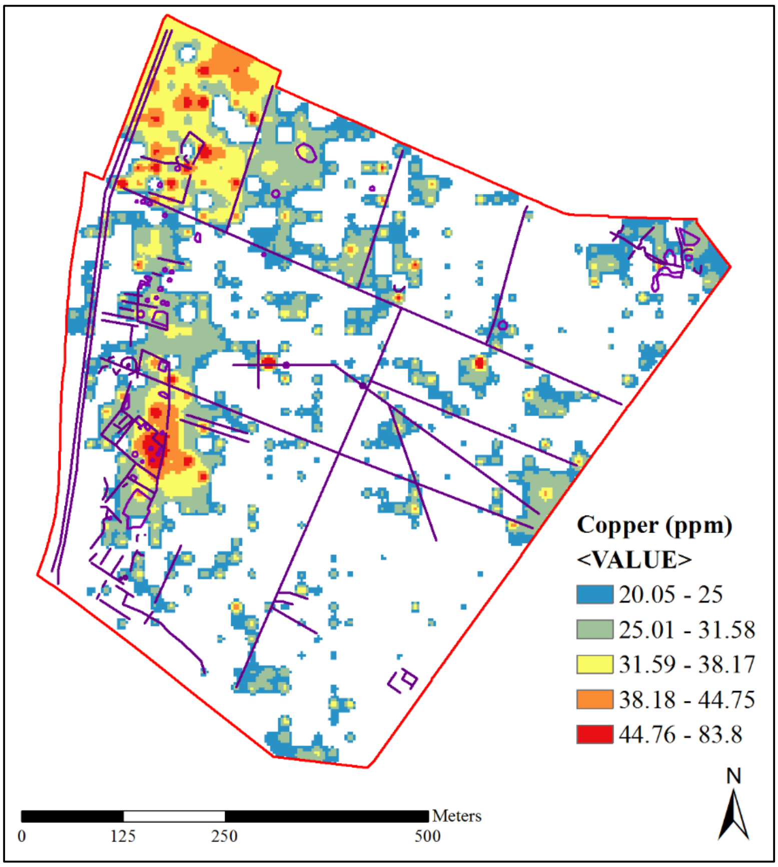
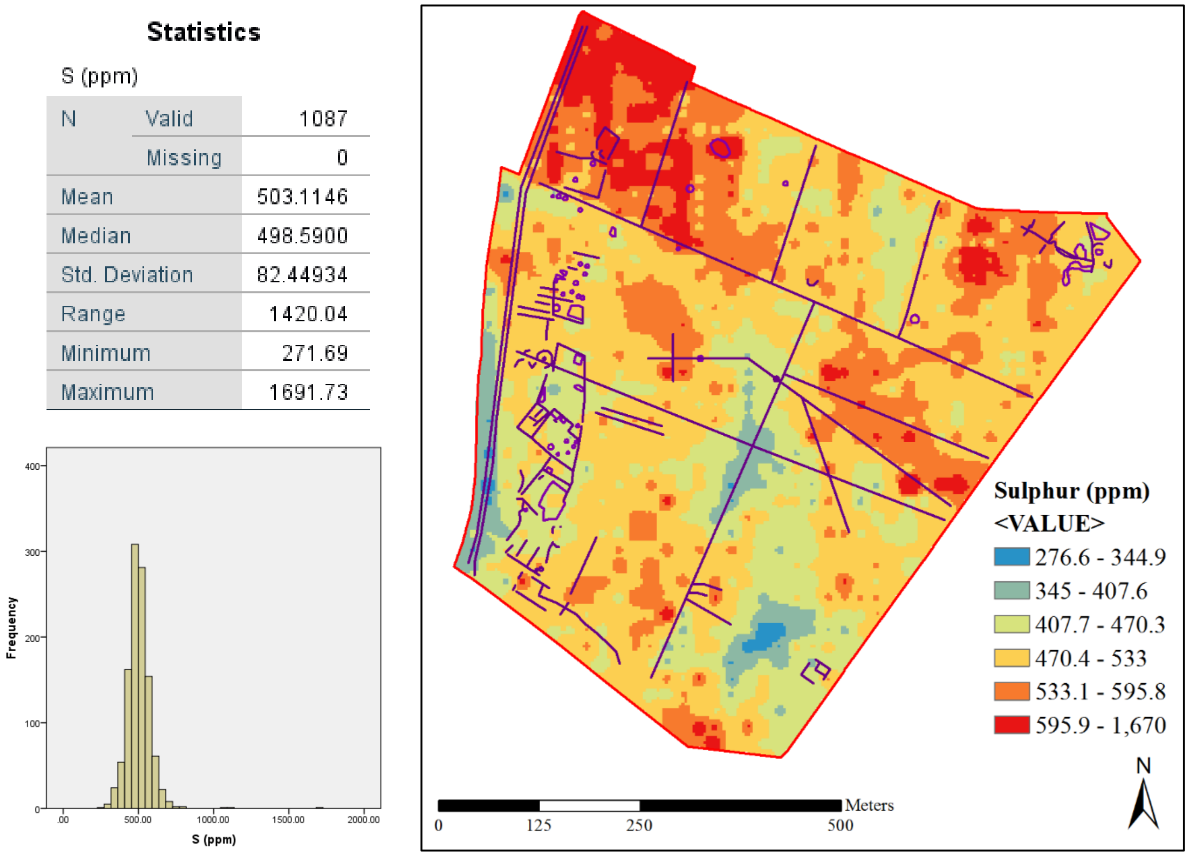


Figure 128: Basic statistics for Cu in the topsoils (left top), frequency histogram (left bottom) and map of Cu variation in relation to magnetic anomalies (right) (geophysical anomalies courtesy of TVAS) (© author)

Mn, although linked with the other elements focused on here as being of potential archaeological origin, shows no real distribution that relates to any of the geophysical anomalies or existing elemental distributions and so is not discussed.

The S distribution (Figure 129) reinforces the distribution shown in PC2. A very clear area of elevated levels of S lie in the NW area, this time spreading across both historic field boundaries in that corner of the field, but similarly variable across the second field surrounding where the Isolation Hospital was sited. The average levels of S being around 500ppm, and the elevated areas mostly being in the range of 600-700ppm. There are a couple of very high values in the NE corner, outside of the group of geophysical anomalies, but in an area that has not exhibited similar responses in other elements analysed.



Statistics

S (ppm)

N	Valid	1087
	Missing	0
Mean		503.1146
Median		498.5900
Std. Deviation		82.44934
Range		1420.04
Minimum		271.69
Maximum		1691.73

Figure 129: Basic statistics for S in the topsoils (left top), frequency histogram (left bottom) and map of S variation in relation to magnetic anomalies (right) (geophysical anomalies courtesy of TVAS) (© author)

Figure 130 shows a higher concentration of As in the central northern area of the field, but not to such an extent in the NW corner, as most other metals have. This spread does not seem to relate to any historic field boundaries as clearly either. The values are all above levels expected from the broad scale NSI topsoil data which suggest an average of 23ppm. So there is build up within the field, possibly from the spreading of fertilisers, spraying of agrochemicals, or industrial wastes that are likely to contain As (Kabata-Pendias, 2011: p.357). Yet the spatial variation and correlation with particular archaeological anomalies is less certain than in comparison to some of the other elements mapped.

Statistics

As (ppm)

N	Valid	1087
	Missing	0
Mean		48.8711
Median		48.9300
Std. Deviation		8.27972
Range		53.38
Minimum		19.84
Maximum		73.22

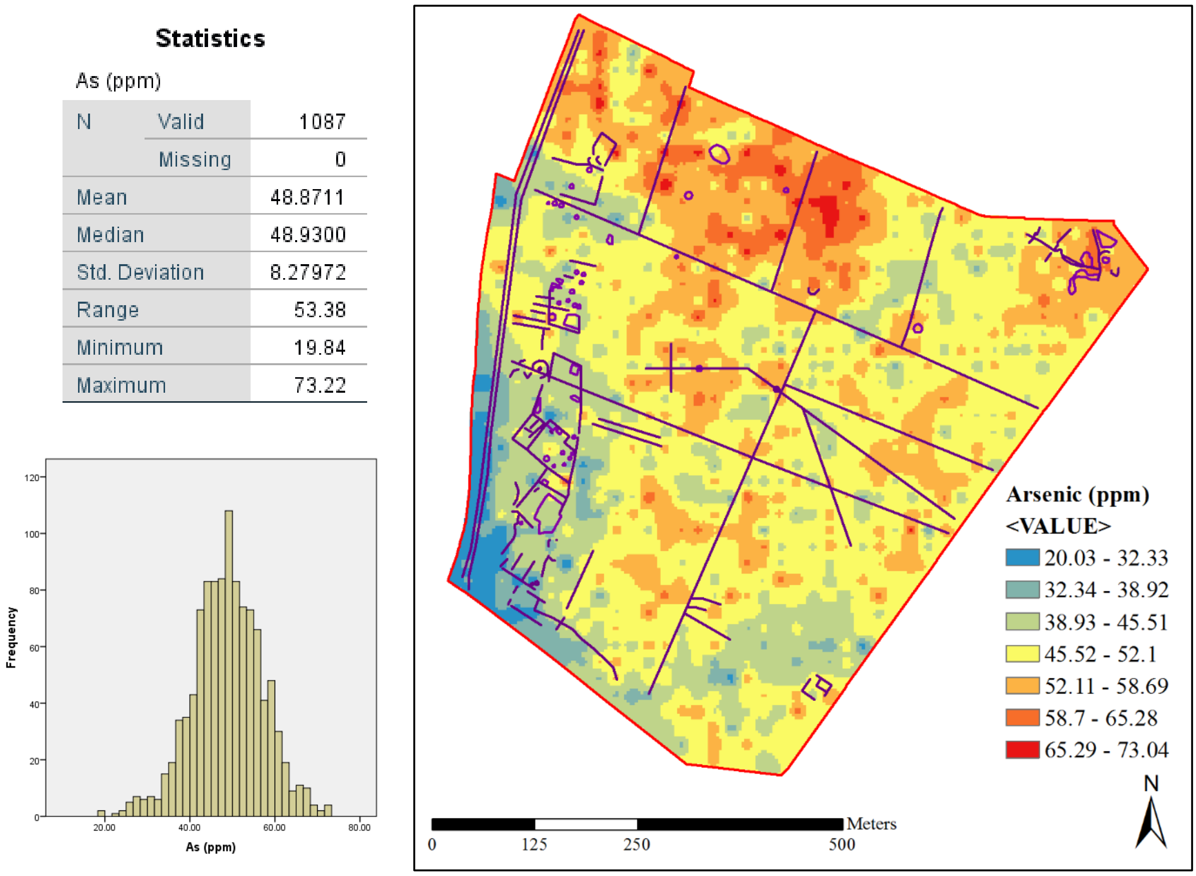


Figure 130: Basic statistics for As in the topsoils (left top), frequency histogram (left bottom) and map of As variation in relation to magnetic anomalies (right) (geophysical anomalies courtesy of TVAS) (© author)

8.4.2 Soil Stratigraphy

At this case study site, detailed vertical coring was not undertaken due to the size of the field, the relatively shallow nature of the soils and the difficulty of getting complete cores in such a stony/brashy soil profile. This does not mean there was no data available to assess the variation in soil depth across the site and any possible connections with archaeological features. Evidence from excavations across the field carried out by TVAS contain soil depths and relevant archaeological features from each of the 199 trenches excavated across the field.

Using this data, the average depth of soils were between 0.23m to 0.59m to the natural soils/geology. These measurements therefore are a mixture of; topsoil to limestone bedrock, topsoil to subsoil to bedrock, topsoil to subsoil to further subsoil mixing to bedrock, depending on the soil profile and how deep it was recorded in excavation. This does limit the exact depths of sediments to bedrock and the assessment of the whole soil profile, with many trenches only evaluating down to the clayey or sandy silts mixed with high frequencies of limestone brash, but never the less gives an indication to the normal soil depths across the field.

Figure 131A gives an indication of the various depths of each trench within the case study field by collating the frequencies of trenches excavated to a certain depth. The majority of the trenches (174 out of 199) reached a depth of between 0.23m and 0.32m, with 23 reaching 0.41m and only 1 reaching 0.6m. The number of archaeological features found within each trench depth category (Figure 131B) shows a similar response, with the majority of features (44 out of 60) in the upper 0.33m. There are a higher proportion of archaeological features in relation to the number of trenches, in the lower part of the profile below 0.32/0.33m.

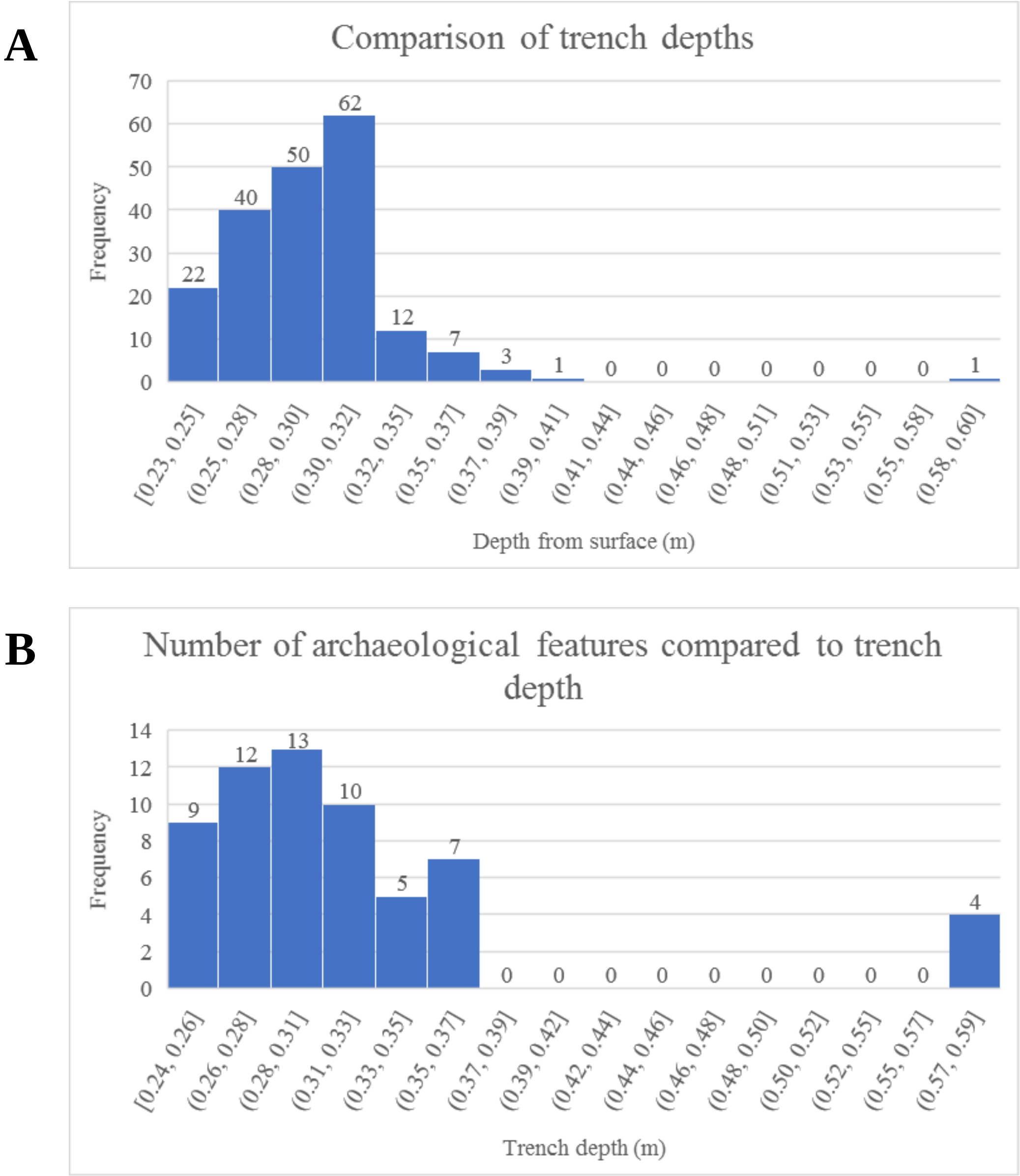


Figure 131: Histogram A showing frequency of trenches reaching particular depths (top) and histogram B showing frequency of archaeological features with trench depth (bottom)(data courtesy of TVAS) (© author)

At this site these results are to be expected, the soils are generally very thin and sit directly on top of limestone geology, which itself is a hard material and therefore not easy to dig into. This means that the majority of the archaeoolgical features are shallow in nature to begin with, but that truncation due to agricultural use of the land is quite likely to have disturbed much of the archaeological features' into the plough soil. In addition, because the trenching is aiming at identifying archaeological features, it is therefore expected that the deeper the trenches are the more likely they are to contain deeper archaeological deposits.

Despite the limited amount of understanding that can be sought from the data above, the spatial distribution of the trenches that are deeper than 0.32m is worth considering along with the knowledege of whether they contain archaeological features or not. Figure 132 shows this distribution, which is spread over much of the field with no particular correlation to a single patch of deeper soil, or even to particular areas of archaeological features.

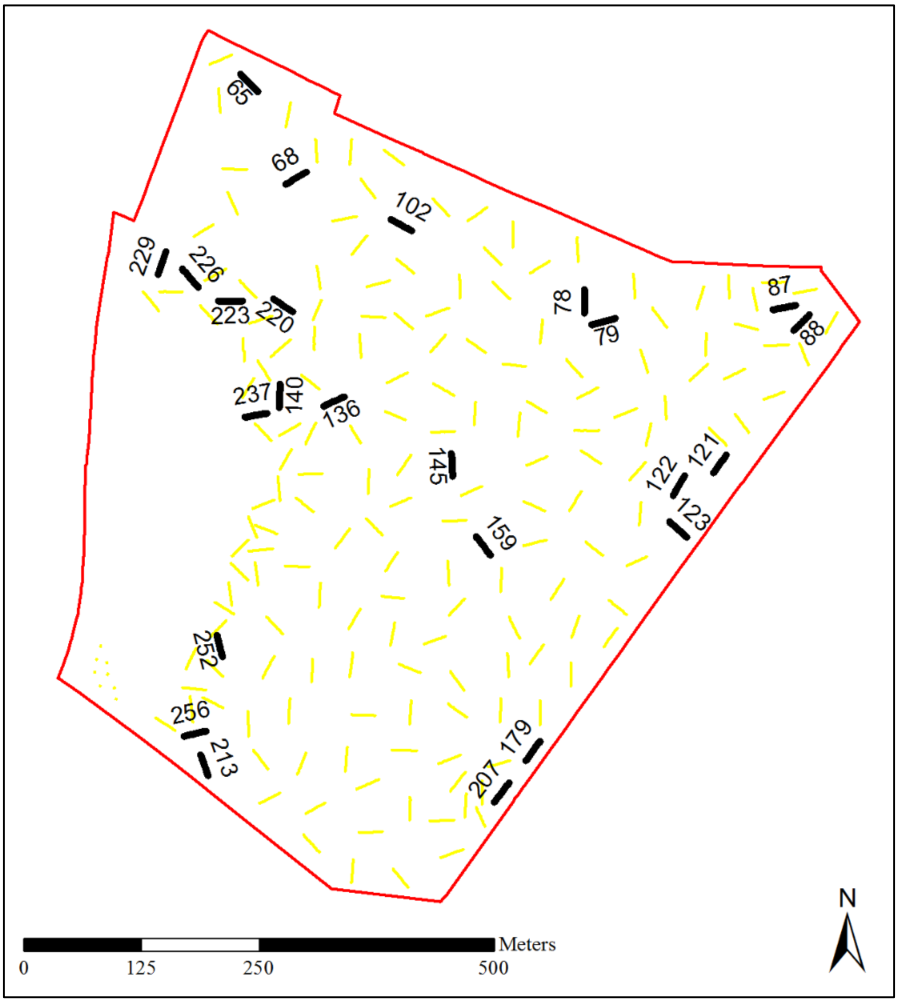


Figure 132: Location of all 199 excavated trenches, with the black trenches and their corresponding number representing trenches that were deeper than 0.32m (data courtesy of TVAS) (© author)

Out of the 24 trenches that have deeper soils, only seven have excavated archaeological features within them, meaning the other 17 do not appear to link to any recognised archaeological features but still were approximately 10cm deeper than the average. Overall the archaeological impacts on the soil depth within ‘100 Acres’ are insignificant and quite limited to the shallow and local effect of specific archaeological features. There does not appear to be any considerable variability in the thickness of the topsoil, or any major subsoil horizons above the fragmented limestone bedrock either that are likely to have a significant effect on the soil profile as a whole.

8.5 Archaeological Data in a PF Context

8.5.1 Remote Sensing and Aerial Photography

The aerial photographic evidence for 100 Acres show the multiple uses this field has had throughout the past century, and the multiple internal divisions that have only recently been merged into a single field made possible by agricultural mechanisation. Figure 133 shows an aerial photograph from 1944, from which the navigational aid can be seen quite clearly in the centre of the field. The remains, or structure of, the Isolation Hospital and track leading to it can also be seen along with the many field boundaries showing varying states of cultivated land, implying the cropping and therefore fertilisation of these smaller fields was variable as well.

Unfortunately the Roman villa itself, although reported to have been found in the first instance by aerial photography (Preston, 2014), is not regularly seen in imagery. It is noted that surprisingly few aerials, out of around 50 vertical photos, have actually recorded the villa footprint accurately. Some reason for this could be continued truncation as a result of cultivation, but this does not explain why it was also not visible on many early photographs. It has also meant that no transcription has taken place to record the villa, surrounding enclosures, aerial anomalies, and later archaeological features. This, plus the limited availability of some of these photographic records (not being available online) has the effect of limiting any use of this data within a PF context.

Figure 134 shows another aerial photograph, at an oblique angle, of the S portion of 100 Acres during the Royal Agricultural Show in 1950. This demonstrates that the field has also been used for events, car parking, and camping in the recent past. Although this is unlikely to have a significant impact on the soils, it is another layer of use that must be considered when interpreting various datasets in the search for soil variations.

Figure 133: Vertical aerial photograph from 1944 showing 100 Acres with an arrow (© Historic England NMR 6915)

Figure 134: Aerial photograph of the Royal Agricultural Society show in 1950, with parking and camping areas spilling out into the south half of 100 Acres (© Historic England sourced https://www.britainfromabove.org.uk/)

Figure 135: Selection of freely available satellite imagery; Google Earth 2003 (top left), Google Earth 2008 (top right) and Bing undated (bottom) (© Google and © Bing)

Freely available satellite imagery, such as those in Figure 135, provide additional layers of imagery into both archaeological investigations and PF assessments of fields. Archaeologically, although none have captured the Roman villa in detail, images have captured many historic field boundaries shown by the geophysical anomalies, as well as additional soil variations. A rectangular dark patch of soil in the NW of the field, appears in each image and is marked by an arrow in Figure 135. This data has also been used in a PF context already. Since it is freely available, provides high resolution images and is spatially referenced, the farmer has used this data to help identify where soil samples should targeted and to evaluate anomalies in other PF data (J. Price, pers. comm.).

8.5.2 Archaeological Evidence and Agricultural Trial Plots

Archaeological evidence and agricultural trial plots are not often studied together, however the location of various trial plots within 100 Acres during the period of this research, enabled some initial comparisons and data to test whether archaeology could be relevant for agricultural trials. Agricultural field trials are becoming more popular on everyday farms because of the growth in digital agronomy (Section 2.5), enabling farmers to create their own split field trials and record the data using satellites, drones and yield maps. One of the key requirements for setting up a field trial is to site the trial plots in a relatively even and consistent patch of soil to reduce any inherent variation (ADAS, 2018).

In 2017, there was one small group of trial plots for new crop varieties within ‘100 Acres’ that can be seen in a drone survey image taken on the 13th May 2017 in a winter barley crop (Figure 136). This small trial plot (25x20m) is situated in the N part of the field, and sits immediately next to the site of the Isolation Hospital and within the historic field boundaries that have shown considerable geochemical variation from previous land uses. Figure 136 shows the proximity of the trial plots to these archaeological areas and selected elemental variability in those soils. Out of all elements measured, the values of S, Cr, Pb and Zn show significant variations within this part of the field, and specifically variation within the 20x25m rectangle.

The levels, in the cases of Zn and Pb, produce a percentage increase of 44% and 57% respectively from the highest to the lowest values within the trial plots. Whereas the range of Cr and S levels are much lower. The real impact that these elemental variations, or any physical variations in the soil profile itself is questionable. It would depend on the exact purpose of that trial, whether it was looking at Zn content of those plants for example, or whether it was on general crop yield (in which case these effects are unlikely to be seen). It may also depend on what year the trial is run, in some year’s crop variability might be low in a certain area of a field, yet in another it could show significant patterns of change. It may be the case that these underlying soil variations do not affect the robustness of this particular trial, however it is certain that this level of geochemical, and potential physical, variation was not taken into account when planning the plot location.

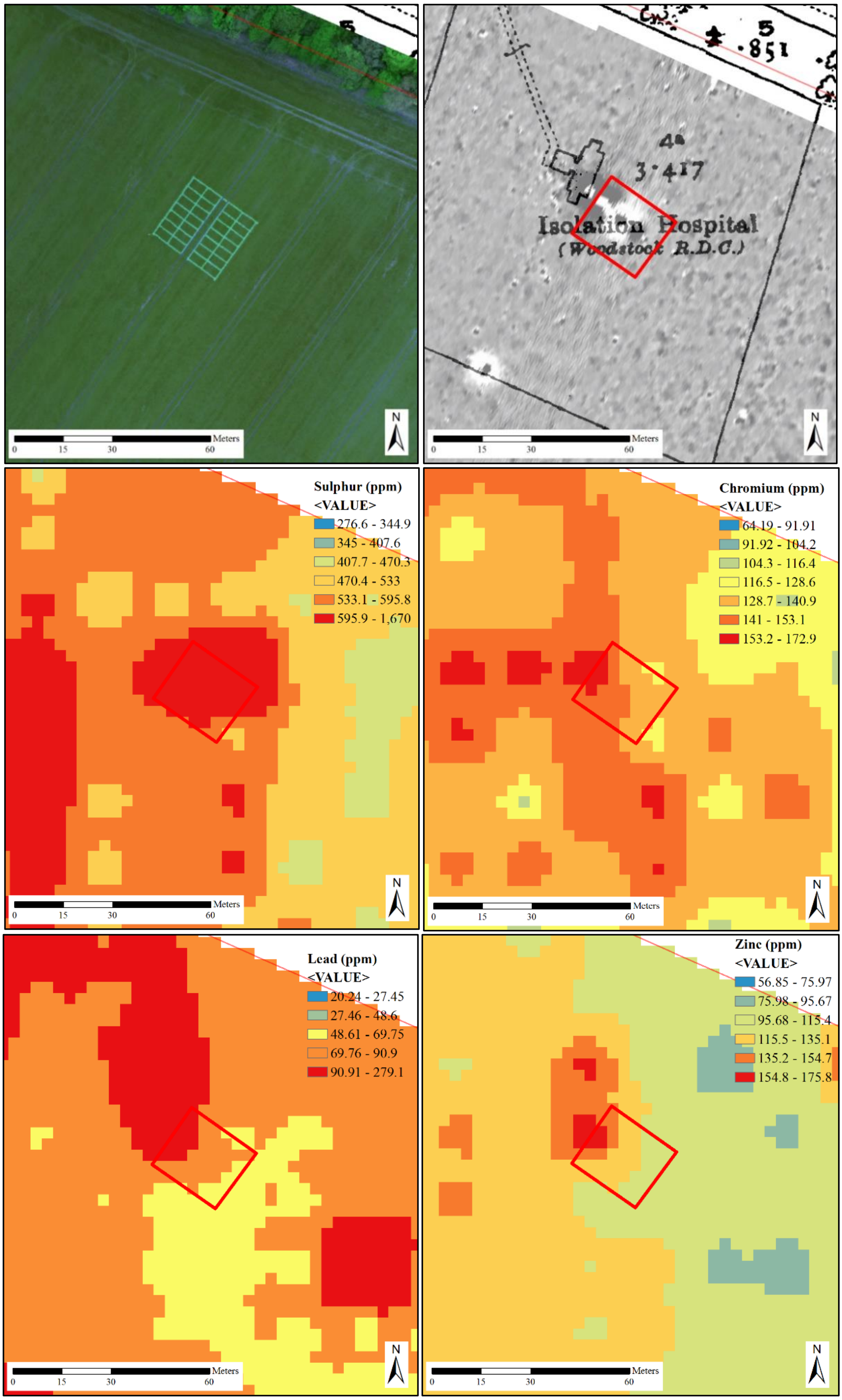
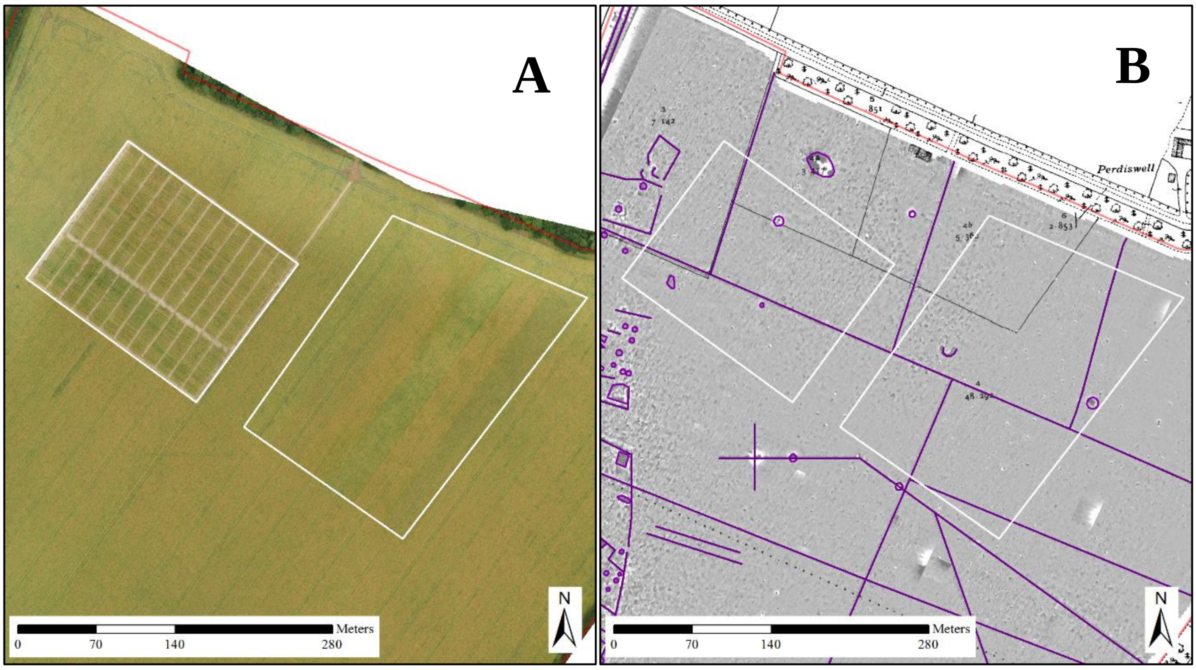


Figure 136: showing the location of the trial plot, OS mapping and magnetic gradiometry as well as the geochemical maps for S, Cr, Pb and Zn (data courtesy of TVAS) (© Crown Copyright and Landmark Information Group Limited (2019). All rights reserved. (1883)

The following year, 2018, two other trials took place in a similar area within ‘100 Acres’ (Figure 137 A and B). These trials were much larger than 2017 and involved at least two different trials. The intensively plotted area in the W covers 2.85ha and is made up of many 12x2m strips which are treated separately across the year with various agrochemical products and then harvested separately. The second plot area to the E covers 4.4ha and is trial that is completed with the farmers’ own machinery, allowing more realistic results and taking into account a larger area, and therefore a greater amount of inherent (soil) variation.

Both areas, as can be seen in Figure 137, cover archaeological anomalies, identified from both geophysical measurements, boundaries from OS mapping and visible soil colour changes from Google Earth imagery. Amongst the eastern trial plot there is a broad area of greener crop that is clearly growing better than the rest of the plots. Figure 137 (C and D) shows that there is a patch of darker soil relating to the area of greener trial plots that is likely to have a higher OM, possibly relate to deeper soils or be more moisture retentive, hence more positive crop growth. These trials may be replicated many times across the whole area, possibly negating the effects of some of this variation, but in attempting to reduce the inherent variation covered by agricultural trials, there are certainly more consistent areas of this field that could have been chosen instead. Hence in these two examples, archaeological evidence demonstrates its usefulness in placing agricultural trials in more suitable locations and possibly highlighting variability that neds to be taken into account when analysing large trial datasets.



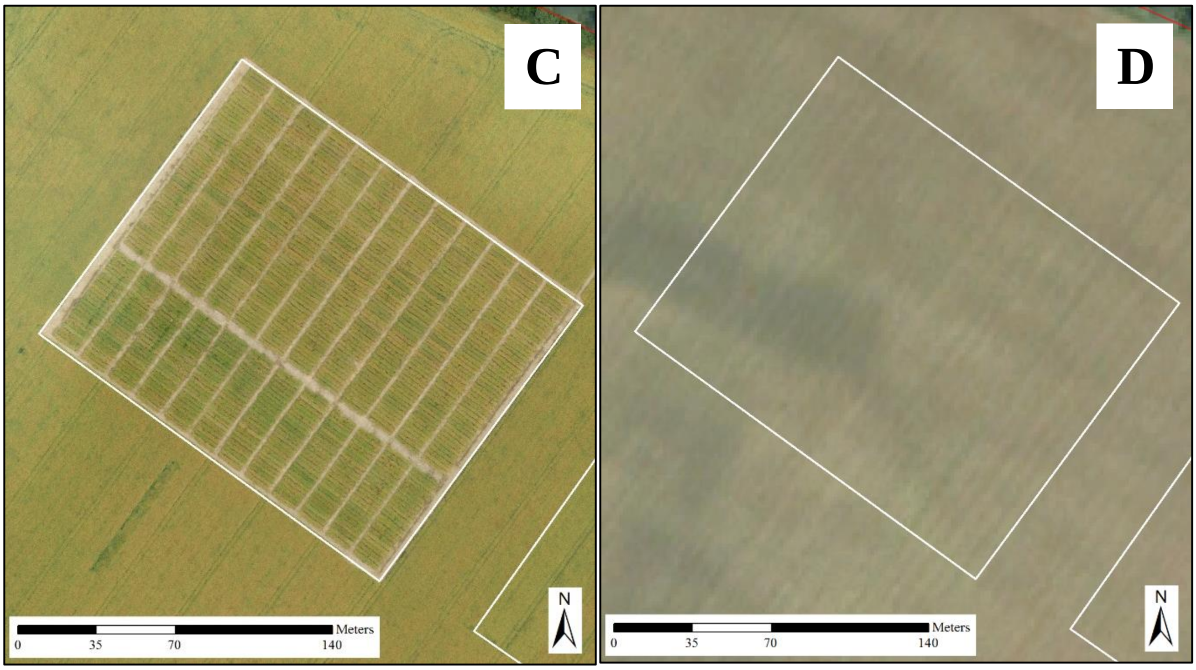


Figure 137: Location of both trial plots in 2018 from a drone image (A), alongside the same area with OS mapping and geophysical data (B), showing the eastern trial plot (C) alongside a Google Earth image from 2006 showing darker areas of soil (D)

(Data courtesy of TVAS)(© Crown Copyright and Landmark Information Group Limited (2019). All rights reserved. (1883)) (© author)

8.5.3 Historic Environment Records

The HER data for the area surrounding Perdiswell Farm was retrieved from the local county HER team, and plotted along with the field and farm boundaries (Figure 138). The records surrounding 100 Acres and including the wider area of the whole farm (both shown in Figure 138) are divided, as is standard practice in HER procedures, into monuments and events. Monuments includes any recorded archaeological sites, archaeological features, or even as small as individual find spots of importance. The events category covers any archaeological fieldwork that has been recorded in the area along with ancillary details.

This set of HER records only had point data for each monument or event record, along with a string of attributes such as dates, details of work, time period of the relating monument and the type of that monument (find spot, feature, site). This does immediately limit the use of any HER data for actually informing the shapes or areas of archaeological activity within a field and for linking directly into any PF context that is based on polygons delineating specific areas for specific reasons.

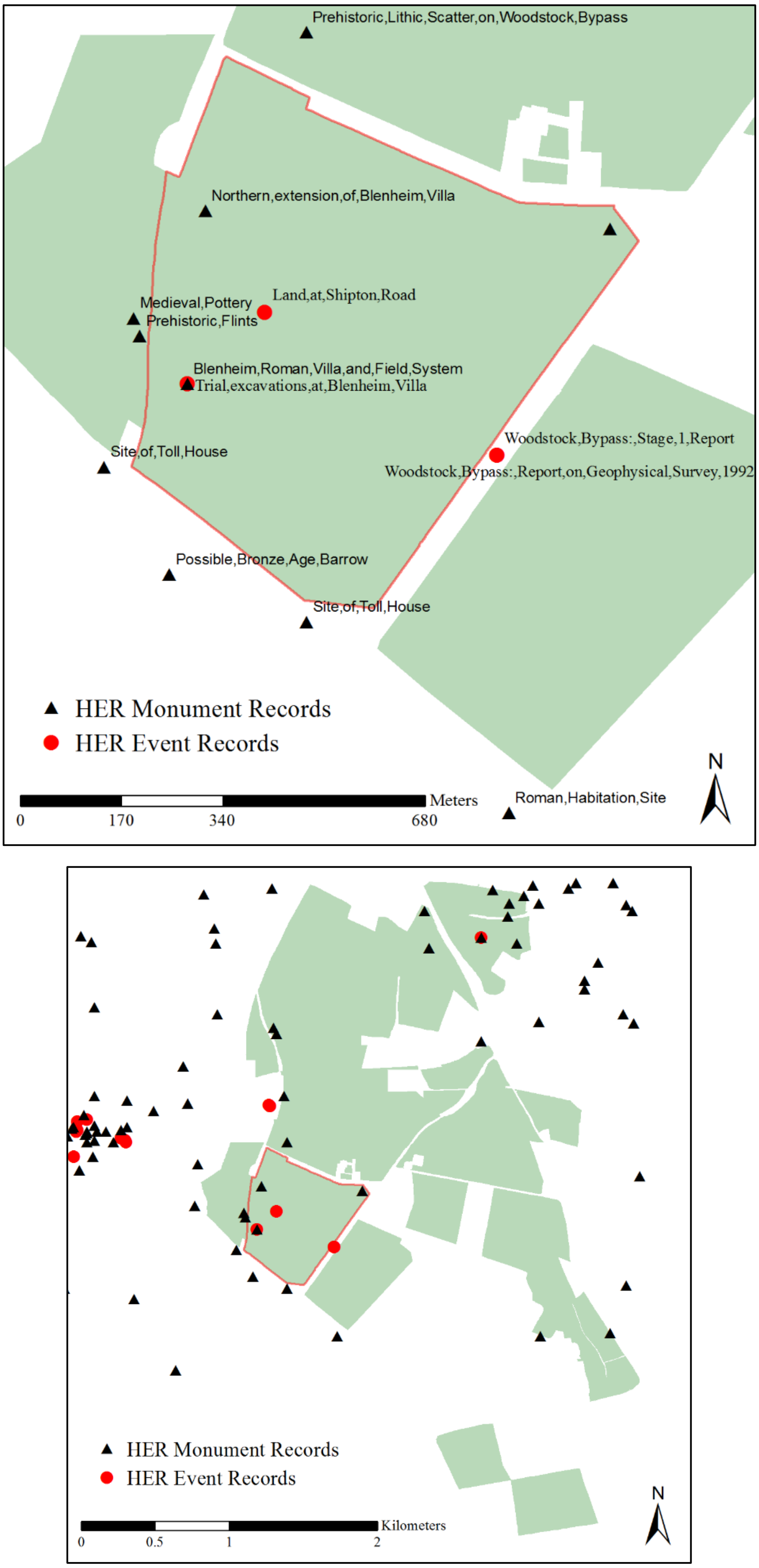


Figure 138: Monument records and archaeological events taken place immediately near the case study field (top) and across the whole farm (bottom)(data courtesy of Oxfordshire HER) (© author)

Yet value of point data, and the various attributes that go along side it, can still aid the PF process. Especially when assessing the variation of the soils within a field with no prior knowledge of the archaeological activity in that field. In this case study, the Roman villa is recorded. In addition the enclosures to the N of the villa are noted as a separate 'monument'. The quarrying and other small enclosures in the NE corner of the field were recorded. The surrounding point data shows that Medieval pottery and prehistoric artefact scatters, as well as a possible Bronze Age barrow, lie immediately outside this field boundary. These, while not directly relevant, do give evidence as to the wider archaeological activity in the landscape, and that could potentially impact the case study field itself if, for example, there were possible cropmarks that looked like a barrow.

The event data that lies within '100 Acres' gives details of two different pieces of work that cover, or are within, the field. The evaluations (DBA, geophysics and excavations) by TVAS are listed within the attributes, as well as the initial trial excavations from 1986 that identified the villa itself and established its scheduled monument status. The value of the data point itself is of limited value to one interested in mapping the soil variation of the field, but it is the reference that could allow far more valuable information to be found concerning the site from the grey literature. For example, the reports to the geophysical surveys and the excavation reports are available online and therefore spatial images can be accessed, alongside the interpretation of those geophysical anomalies which could impact on the soil variations within the field as have been demonstrated in this chapter.

In the wider area (Figure 138 bottom) of the whole farm, the HER data shows that it is perhaps more beneficial when applied to a larger area. With the whole farm outlined, it is quick and easy to pinpoint certain fields, and certain parts of fields, that might have archaeological monuments or activity within those areas. Once again, on farms where there is little or no knowledge of archaeological features, or as part of the soil zoning process used by any PF company, being able to consider quickly and over a large area where archaeological sites may be could be immediately useful in the wider soil zoning and crop management process.

8.5.4 Archaeological Geophysics

The magnetic gradiometer survey completed by TVAS in 2014, over the whole of 100 Acres field represents another detailed dataset that has been invaluable for interpreting geochemical variations and other remotely sensed soil changes. One of the key elements of this dataset that make it immediately useful is its spatial coverage. If parts of the field were not surveyed, as can be the case where archaeological surveys focus on specific sites, then there would be a lack of consistent data and from an agricultural perspective, this severely limits the usefulness of that data for interpreting the soil variability of the field as a whole (because it is being managed as a whole). At 100 Acres, the whole field has been surveyed, meaning it can be used to help understand any soil variation across that field, rather than being limited to a particular area (such as the Roman villa).

The second key element is whether this geophysical data can inform a PF specialist about the soils' variability. The magnetic gradiometer method can give information about soil depth, for example the network of historic field boundaries, Roman and earlier enclosures all represent deeper topsoils, and mixed subsoil horizons filling in old ditches that are very different form the surrounding natural soil profile. These are however very constrained to the exact width and length of the anomaly itself. Yet it is these anomalies that divide up space within a field, and the division of spaces, as can be seen from the pXRF data across the case study field, that can prove more relevant to PF specialists and farmers themselves.

In one area of the magnetic survey, there are large amorphous areas that have a 'magnetically' quiet background in comparison to surrounding areas, and that do not relate specifically to archaeological features (Figure 139). It is possible that they relate to very subtle variations in the amount or size of limestone fragments within the soil profile, or the amount of metal fragments in the soil that affects the soils magnetic contrasts. These, if relating to a change in soil type or area of field applied with a particular fertiliser, could be relevant for PF systems to take account of in soil zoning, sampling or evaluation of other crop or soil imagery. Interestingly, these background magnetic patterns are often not recorded or interpreted in the archaeological geophysical report, since they are perceived as only natural responses and do not relate to any archaeological features. Yet they could have implications for and use within PF systems.

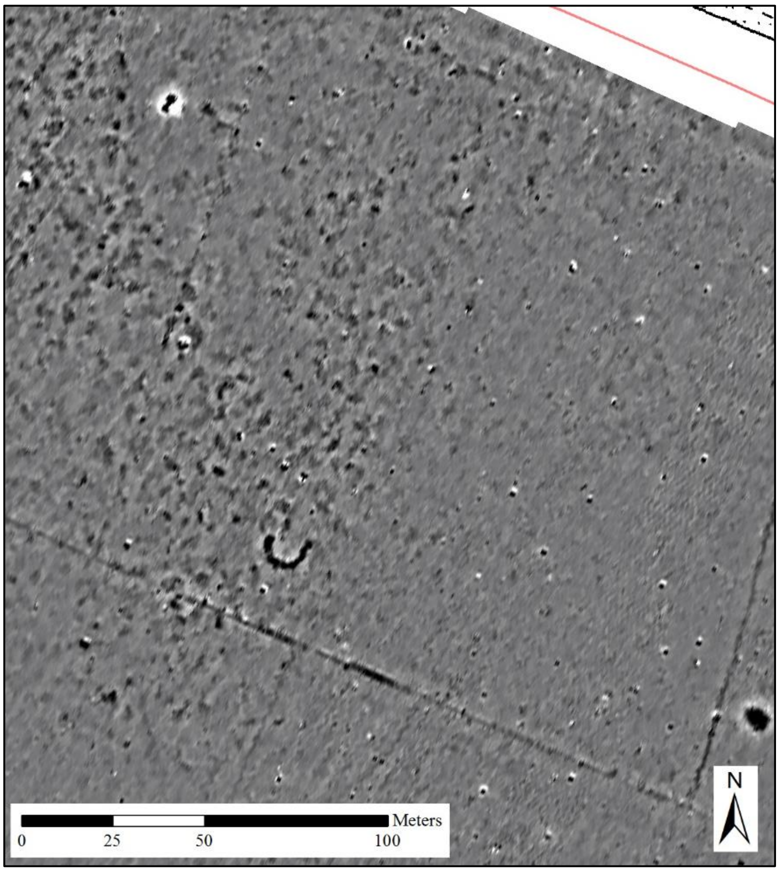


Figure 139: showing a shift in the magnetic background, the eastern half is more consistent with infrequent dipole anomalies, the western half characterised by frequent small positive anomalies (data courtesy of TVAS)

8.6 PF data in Archaeological Investigations

8.6.1 PF Field and Farm Soil Analysis

At Perdiswell there are a number of soil analysis results, both of 100 Acres itself, and of the rest of the farm. The first soil analysis that included analysis of within field variation was from 2003. Although P, K, Mg and pH have all been analysed, only P and K will be compared here for comparison to pXRF data. Figure 140 displays the variation shown across 100 Acres based on a 1ha grid sampling methodology. The map of available P corresponds accurately with the pXRF data shown in Figure 127. Highlighting areas around the villa complex and enclosures, as well as the area in the NE of the field around other late Iron Age and Roman features, and in the NW corner where further ditched enclosures exist.

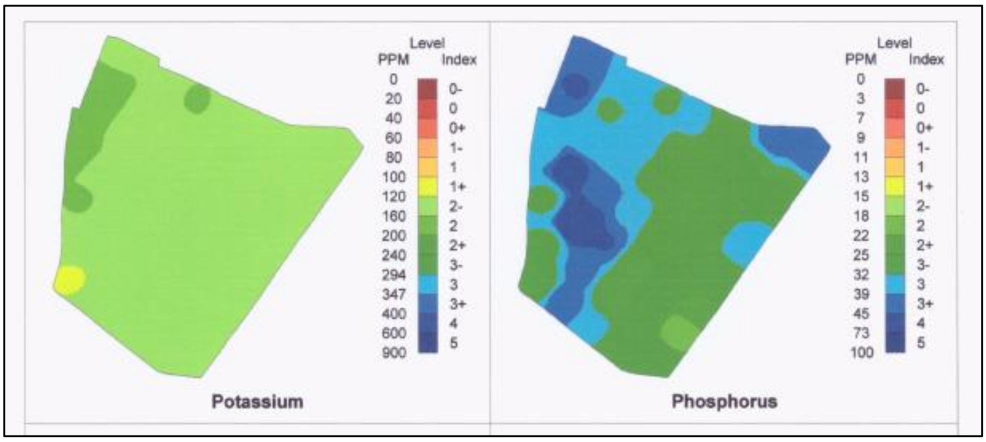


Figure 140: Soil analysis for 100 Acres from 2003 (Potassium left, Phosphorus right)

The following soil tests, by a different company, were sampled in 2013 (Figure 141). The exact locations of each grid sample were not recorded but each data point was placed approximately where the sample was taken. The interpolated maps that have been produced for '100 Acre' field have been georeferenced and overlaid with the geophysical interpretation to give some comparison between the agricultural analysis and the pXRF distribution.

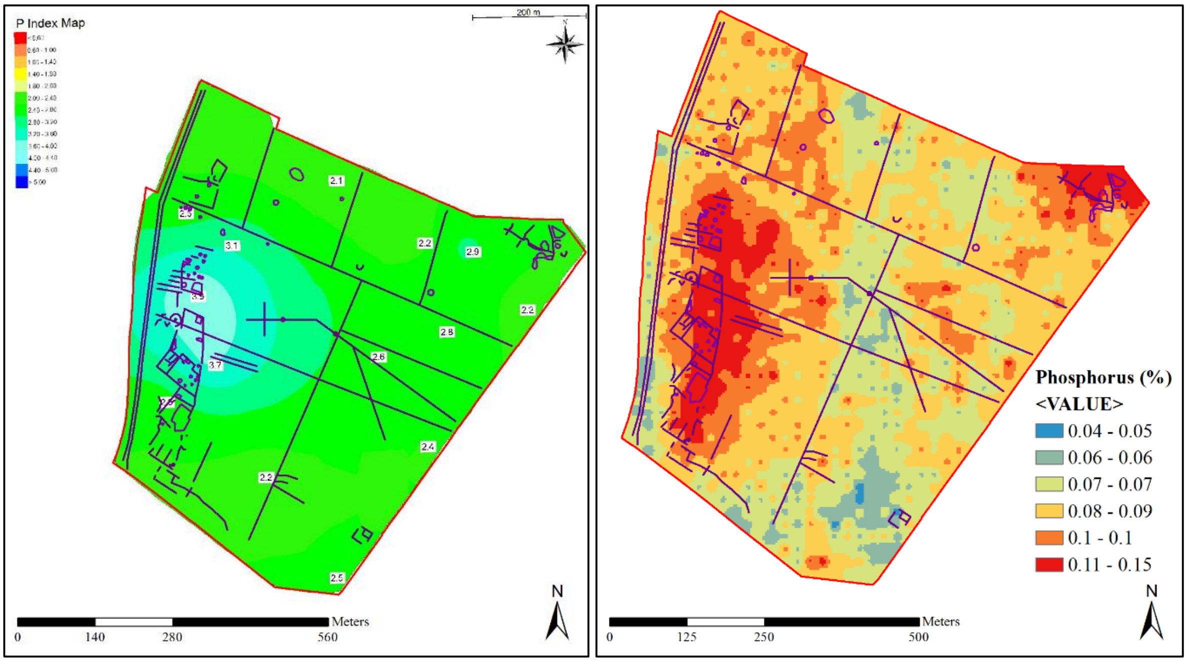


Figure 141: Soil analysis of phosphate from 2013 (left) and total P from pXRF data (right) (data courtesy of TVAS) (© author)

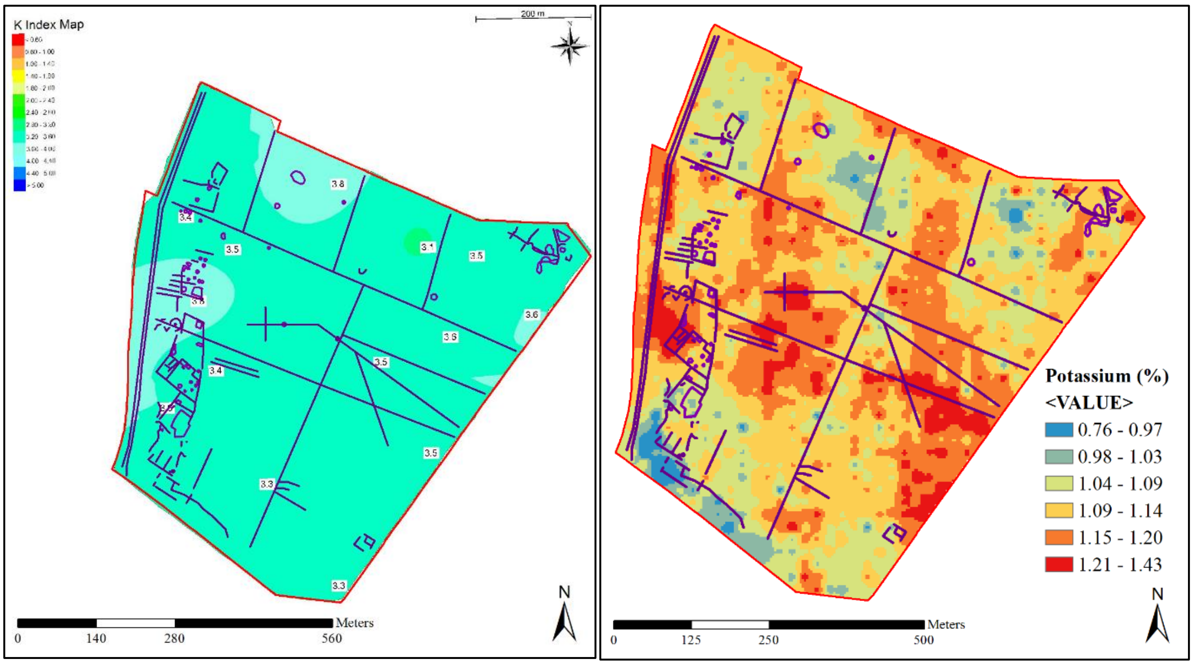


Figure 142: Available K analysis from 2013 (left) and total K from pXRF (bottom right) (data courtesy of TVAS) (© author)

The P results show a similar distribution to the 2003 map and the pXRF data, however only in the area of the villa has high levels of phosphate. The 2013 sampling, either by alternative locations of samples, seems to have missed some high areas of P in the NW and NE of the field. The change cannot be explained by a change in phosphate over the years, since the 2003 survey correlates far better with the pXRF data and P levels do not often change that drastically over that period of time. Equally this reason also means that it cannot be due to a difference between total phosphorus and available phosphate measurements. Therefore the location of samples and distribution of samples is crucial for interpolating maps and interpreting them for either PF analysis or archaeological analysis.

The concentrations of P over the villa is also similar in percentage terms between the pXRF survey and the Olsen P analysis, with the P Index at 3.9, and the average areas at P Index of 2.1. The distribution is therefore similar to the elemental P values with approximately twice the level of P over the villa area in comparison to the average areas of the field.

The maps of K relate much less in comparison, with the 20x20m grid sampled pXRF data showing much more variation than the available K maps from 2003 or 2013, both quantitatively and spatially (Figures 140 and 142). The distributions on the three maps have little spatial correlation linked to any archaeological activity, which is not surprising as K is less often linked with archaeological features.

Additional analysis that is not often tested for on farms, but is important and likely to be more tested in the future, is the level of OM in the soil. The expensive and lengthy procedure of the loss-on-ignition test to determine OM levels in soils means the number of samples is usually one per field, if that. The OM level of 100 Acres is 8.4% which is significantly higher than most of the other fields on the farm. With a lack of more detailed soil sampling for OM it is hard to determine any spatial variation across the field, although one might expect to find quite a significant variability and possible relationships to archaeological features (Aston *et al.*, 1998).

8.6.2 High Resolution Agricultural Drone Imagery

As part of the data collection for this case study site, three drone flights were completed during the growing seasons of 2017 (spring barley) and 2018 (oilseed rape). Two flights in 2017 were captured using the MicaSense Red Edge camera, and one in 2018 with a standard RGB camera. The results from all three drone flights did not yield any significant new crop marks to add to the existing knowledge of the site, which is perhaps surprising considering the archaeological remains known to be present, the shallow soils, and that the 2018 flight in July was during part of the summer drought.

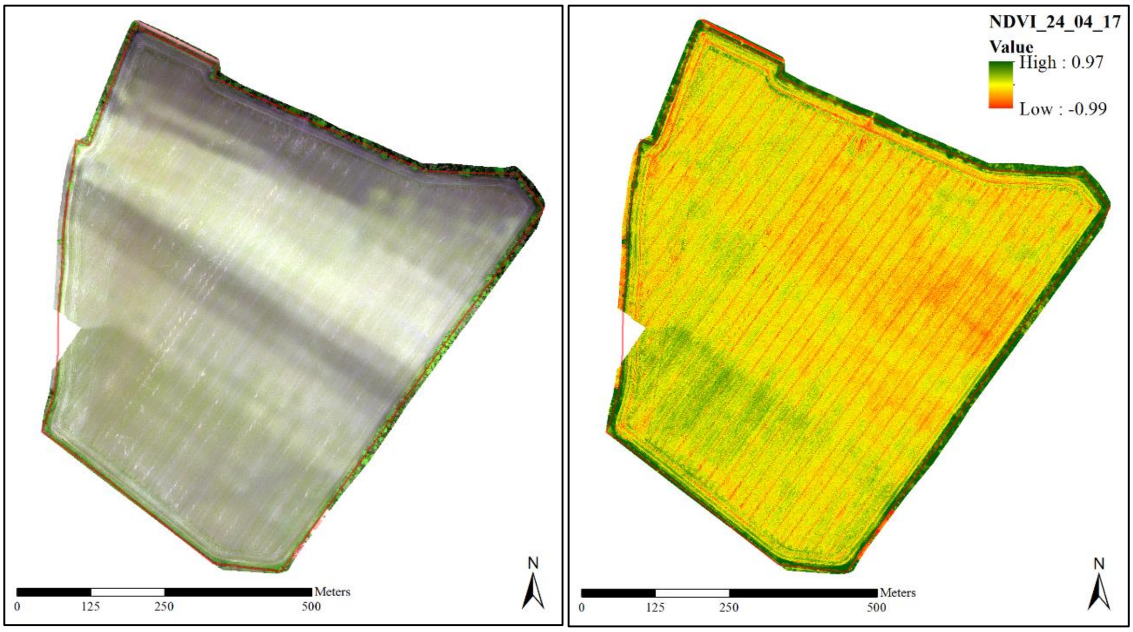


Figure 143: RGB done image from 24 April 2017 with striping caused by irregular light (left), NDVI Index from the same drone flight (right) (© author)

The flights on the 24th of April, and the 13th of May 2017 were both affected by variable light conditions (Figure 143 and 144) which was noted as a problem with using a small quadcopter drone on such large sites. The time taken to complete the planned flight across the field at the correct resolution meant multiple battery changes and around an hour of flying time, and therefore weather conditions had to be clear for longer to achieve more consistent light conditions. The NDVI and NDRE data from 24th April do not show any noticeable anomalies, other than agricultural tracks used in the previous year to cross the field, and some recent cultivation lines.

The NDRE index from the 13th of May 2017 (Figure 144) shows two additional anomalies. The darker patch of soil (in Figure 135) is clearly shown in this drone image by a defined area of healthier crop with high NDRE values. This reinforces the interpretation that this area of variation is far more apparent in the factors that are affecting crop growth directly, in comparison to soil elemental values, since it does not appear in the pXRF data. Another anomaly which can be noticed in the NE corner of this image, is the horse-shoe shaped positive anomaly. This was caused by the storage of fertiliser, in particular organic biosolids that were spread on the field in 2016. The compaction and leaching of nutrients, can have medium term effects on the soil and crops in this immediate area for a number of years.

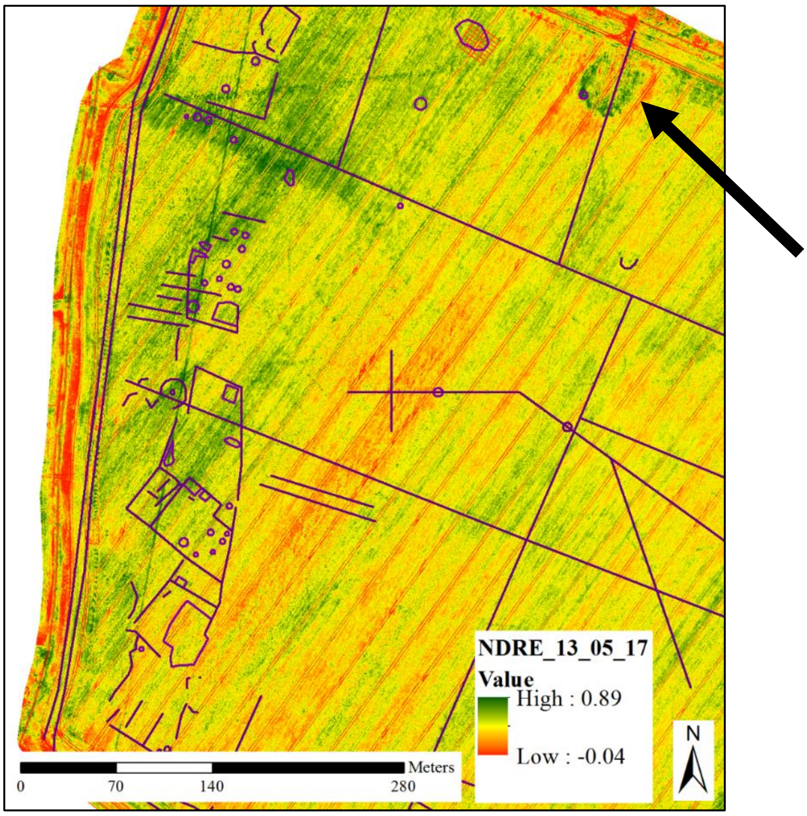


Figure 144: Drone NDRE image from May 2017 in a crop of spring barley, arrow marking previous storage of fertiliser (data courtesy of TVAS) (© author)

The oilseed rape crop in 2018 was captured only with a standard RGB camera (Figure 145). Despite it being the end of a long drought, there were few cropmarks visible through the large and interconnected canopy. Although results at Myncen showed good cropmarks from an oilseed rape crop, timings are important since at the end of the growing season the canopy of each plant spreads to around 2m^2 meaning a loss of resolution if particular plants were growing differently. The trial plots can be seen relatively clearly.

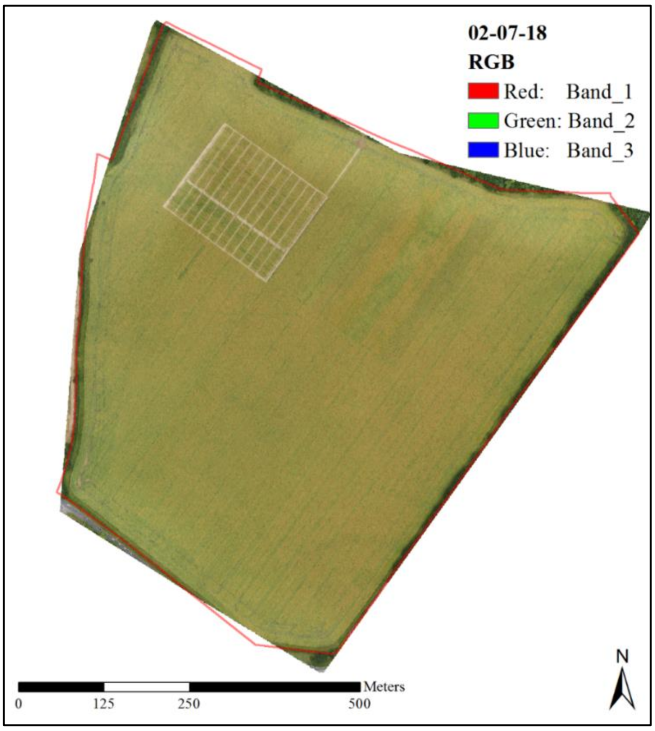


Figure 145: Drone RGB image from July 2018 in an oilseed rape crop (© author)

8.6.3 N-Sensor Imagery

Perdiswell Farm has used an N-Sensor for mapping the biomass of a crop and varying N applications for a number of years. This methodology negates the need for satellite imagery at exactly the right time, and the need for time to analyse the data, because the N-Sensor can automatically vary the rate of fertiliser being applied while actively sensing the crop in front of the tractor. This provides advantages to the farmer, but also allows maps to be recorded of all the data captured.

A selection of these maps from Perdiswell are shown in Figure 146. The data produced is based on tramline widths, therefore the resolution is around 5m/pixel, and then interpolated. The greener the colour in the image, the larger the relative crop biomass. The overall resolution of these images provides good visibility of variability over the whole field, but is limited if looking for anomalies smaller than 20x20m. For example, the rectangular dark patch of soil in Figure 135 is visible in the image from 5 January 2003 in Figure 14. Yet for use in archaeological investigations, as has been the case with much PF data, the N-Sensor data presented here is too low in resolution to be of use on its own. This will depend on the situation however, since if a site has no or little existing data, but does have multiple years of N-Sensor data and other low resolution PF data, these data could help to identify certain zones for further investigation.

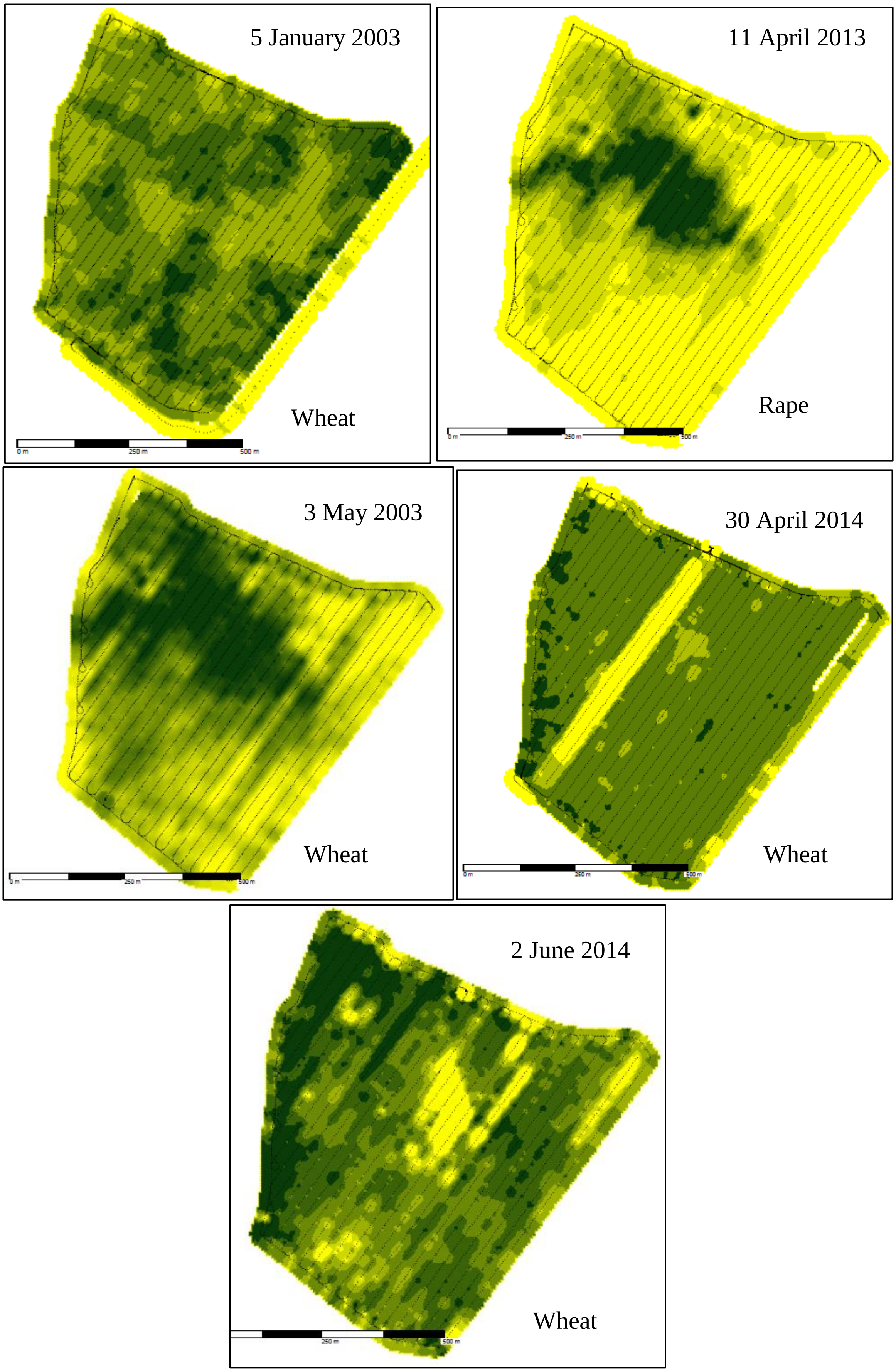


Figure 146: Five N-Sensor biomass maps from a range of years since 2003, dark green = high yield (© author)

8.6.4 Yield Maps

At Perdiswell there are six yield maps available for the field 100 Acres, from 2009 to 2015 (missing 2011). These sixmaps are shown in Figure 147 for a range of crops across these years. Undoubtedly, small or localised variations in crop yield could be for many reasons and, especially regarding yield maps, could be caused by data collection errors. Yet on a larger scale soils with consistently different properties will have influence on the ultimate yields of crops depending on the conditions throughout the year. Thus by taking a multi-year approach to yield maps, and comparing similar areas over time, useful information surrounding archaeological sites might be drawn out.

With three wheat crops, two OSR crops and one bean crop, the first observation between the six maps is the notable variation between crop types. The OSR crops both show a fairly even yield across the field (agreeing with the even NDVI values in Figure 145) with the general trend that the central and northern areas of the field yield highest. This is in contrast to the wheat yields where, if one disregards the striping in the data from data collection, the yield across the field is more variable and with a general trend to the W of the field. This highlights the issue that different crops respond to different sorts of stresses during their growing season. Certain crops might be more dependent or responsive to certain soil characteristics, whether those be related to structure, water content or nutrient content.

In relation to specific archaeological features there is a similar yield distribution to some of the pXRF element maps such as P and Zn. This relates specifically to the elongated area of Roman activity associated with the villa. It is shown particularly well in the bean yields from 2015, but more subtly in every yield map other than the 2013 OSR map. The highest yielding area of the field on average is the dividing area between the northerly set of geophysical features and the enclosures to the S that connect with the villa itself. This area has a number of geophysical features that reflect pits and lies alongside the historic field boundary running E/W, as well as the soil colour changes in a rectangular area of soil as discussed previously.

Although yield maps can be complicated to interpret, from a data quality perspective as well as because of the many factors underlying variance in yield, they can add to the overall analysis of particular anomalies. This is especially true when combined with satellite or drone imagery.

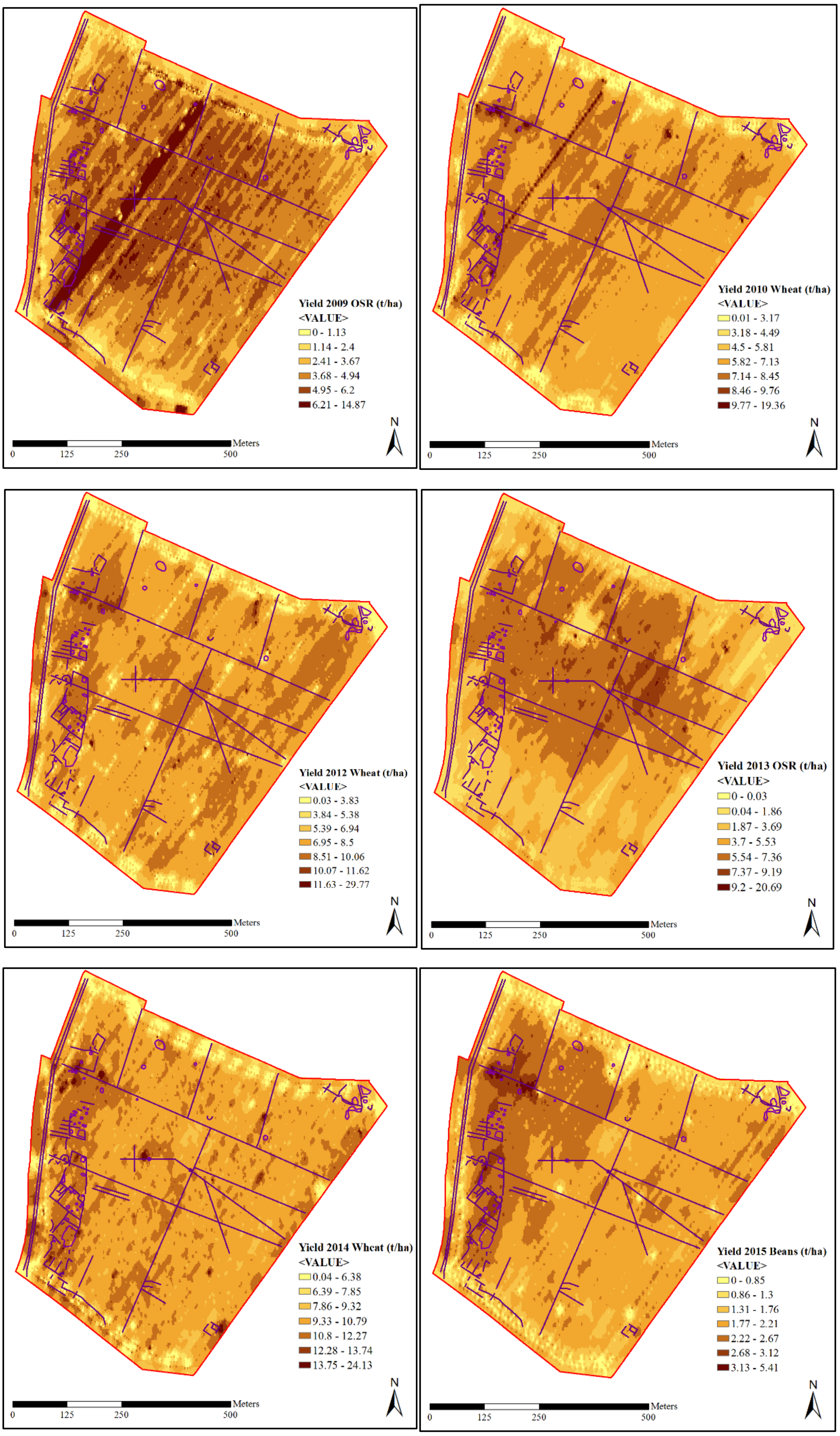


Figure 147: Six yield maps from 2009-2015 showing a range of crop types, with the magnetic anomalies on top (data courtesy of TVAS) (© author)

8.7 Summary

The amount and types of data collected at Perdiswell Farm have been quite different to the first two case study sites. The initial soil, topographic and geological information indicated that this field, 100 Acres, was relatively consistent. These results have demonstrated that the geochemical variation, especially of the topsoil, is far more complex than expected, mainly due to anthropogenic impacts on the soil. The spatial distributions of elements in the topsoil have correlated significantly with a number of known archaeological features and added to the interpretation of the archaeological remains in the field, despite it having had geophysical surveys, DBA and hundreds of shallow excavations to investigate it.

The pXRF data has also shown how archaeological remains, whether from the Roman period, or the Second World War, can still alter elemental values in the soil in ways that correlate with modern agricultural nutrient mapping. The existing geophysical data has provided a baseline for interpretation of the geochemical data, as well as various PF datasets and could be easily integrated into PF systems (even farmer orientated systems such as at Perdiswell) to help sample and map soil nutrients more accurately.

The PF data presents limited use for archaeological investigations at the feature level, but could present better value on larger archaeological sites, or in larger landscapes where indications of activity are required before more detailed investigation occurs.

Chapter 9

9. Evaluating Precision Farming and Archaeology

The results from Myncen Farm, Wilsford Manor Farm and Perdiswell Farm have presented a large volume of data collated from existing sources and from the field, analysed together to provide insight into the archaeological interactions with, and implications for, PF. In this Chapter, the results from each case study will be compared together to answer the research questions from Chapter 1. This evaluation will take into account how case study sites display examples of wider issues that draw together background from Chapters 2, 3 and 4 with evidence in the field.

9.1 To What Extent are Archaeological Data Similar or Different to PF Data?

To assess the similarities or differences between archaeological and PF methods, consideration should be given to the common usage of datasets, the spatial resolution and extent of those datasets, and the temporal frequency that characterises those datasets.

9.1.1 Common Usage of Datasets

The variety of datasets gathered from each case study have been listed in Table 13 along with their use at each case study site, and whether they were included in the archaeological approach or the PF approach for assessing soil or crop variability. There are three data types that are ubiquitous across all case study sites, and in both archaeological and PF approaches:

- The pXRF soil analysis, this was a supplementary analysis for linking both the archaeological and PF elements, so can be discounted for this purpose of evaluating standard PF, or archaeological, methods.
- Satellite imagery was used across all case study sites and in both approaches. Freely available imagery such as Google Earth and Bing imagery is widely used by all types of archaeologist and farmer alike, and provides images at a range of spatial resolutions and temporal frequencies. Across the three PF approaches, two of them made use of frequent lower resolution multispectral satellite imagery that was commercially

purchased. The third case study (Perdiswell) did not pay for any satellite service to provide multispectral imagery, only using freely available data.

- Low altitude imagery (including drone and light-aircraft imaging and historic aerial photography) similarly had use across both approaches and in each case study site. Additional drone-based images were collected on all case study sites, especially where none had previously been gathered on Myncen and Wilsford Manor Farms, but had at Perdiswell Farm.

	Has this data been used in assessing soil variability?					
Type of data gathered	**Myncen Farm**		**Wilsford Manor Farm**		**Perdiswell Farm**	
	Arch	**PF**	**Arch**	**PF**	**Arch**	**PF**
Historic maps	Y	N	Y	N	Y	N
Geological maps	Y	Y	Y	Y	Y	N
Soil maps	Y	Y	Y	Y	N	N
Topographical data	Y	N	Y	N	Y	N
Ground-based spectral sensing	N	N	N	N	N	Y
Low altitude imagery	Y	YY	Y	YY	Y	Y
Satellite imagery	Y	Y	Y	Y	Y	Y
Soil coring	YY	Y	YY	Y	N	N
Excavation/test pit	Y	N	Y	N	Y	N
Geophysical data	Y	N	Y	N	Y	N
Soil nutrient analysis	N	Y	N	Y	N	Y
pXRF elemental analysis	YY	YY	YY	YY	YY	YY
Yield maps	N	N	N	Y	N	Y

Table 13: shows whether a particular data type has been used in the assessment of soil variability at each case study site and under the archaeological approach or the PF approach.(Y = yes, N = no, YY = shows primary data gathered for this research and not existing data.) (© author)

A number of commonly used data types (used in two or three of the case study sites) are consistently only archaeological or PF in nature. PF specific data types are soil nutrient analysis (here meaning topsoil plant-available nutrient analysis), ground-based spectral sensing and yield maps. In contrast, types of data specific only to the archaeological approach include geophysical data, excavations/test pits, topographical data and historic maps. To a certain extent these differences were to be expected from the background set out in Chapter 2 and my own experience of the industry. Some elements, such as the geophysical data, and the historic maps, were less expected.

Geophysical data was one of the first links to be recognised between PF and archaeology, due to the similarity and direct overlap between datasets, as well as the potential for methodological overlap (Webber, 2014). In 2014, there were four major PF companies, three of which recommended use of ‘soil scanning’ to produce soil conductivity maps. Over the past five years the PF industry has changed, now many companies concentrate on lower cost services focused around remotely sensed data rather than geophysical measurements of the soil itself (https://gtr.ukri.org/projects?ref=NE%2FP008860%2F1 accessed on 13/10/19). This could be partially reflected in the case study data collected here or it may reflect choice by individual farmers.

The common use of historic, geological and soil maps is fairly mixed between the archaeological and PF approaches. With regards to geological and soil maps, use is often included in archaeological and PF assessments for background information about the broader changes in soil types and parent material across a site. The suitability of this data for assessing within-field soil variability can be limited by its spatial nature as well as its accessibility. For a PF company, or an archaeological company or researcher, access of these maps (in paper form, by institutional access, or via online services such as NSRI) may be more embedded into their approach when working at a new site. Whereas for a farmer taking the more independent route, access may be more difficult and the value of these maps might be more limited in comparison to experience of the field itself.

With regards to historic maps, access issues may impede the use of these resources within PF approaches. For any archaeological assessment, map regression is a common technique to gather all maps, from archived paper maps to digital online repositories of OS maps such as that provided through Digimap (to UK higher education institutions). Therefore costs to access this information on a commercial scale, and the time taken to seek out unique paper sources, can limit its use and is why these resources have not been used across any of the three PF approaches. This equally applies to historic aerial photographs.

Topographical data is commonly used in archaeological assessments more explicitly with a view to producing topographic maps, but little to no use of topographic data is evident in the PF datasets. The use of topographic data in PF practices tends to be for providing general trends of where soil types differ, for example large valleys or hill tops from Google Earth data, rather than more detailed field maps. This, however, may be changing as the increase in remote sensing techniques, especially provided by low altitude platforms like drones, and the increasing use of RTK GNSS receivers on agricultural machinery, could provide much higher resolution topographical data as a by-product of other practices such as auto-steer machinery. The cost of collecting and analysing such high resolution data in comparison to its’ value in understanding soil variability is limited from a PF perspective. This is in contrast to the important archaeological value of such topographical data for mapping subtle ground undulations and is hence why the use of LIDAR data to produce high resolution digital terrain models is far more common wherever data is available and accessible. Figure 148 shows a sample of RTK GNSS data (collected by hand) from a transect over the henge at Wilsford. This data demonstrates possibility that evidence of a bank to the S edge of the henge still survives in the micro-topography. This accuracy of data (+/- 2cm) is the same as that required for auto-guidance common on many tractors today (Figure 148 bottom).

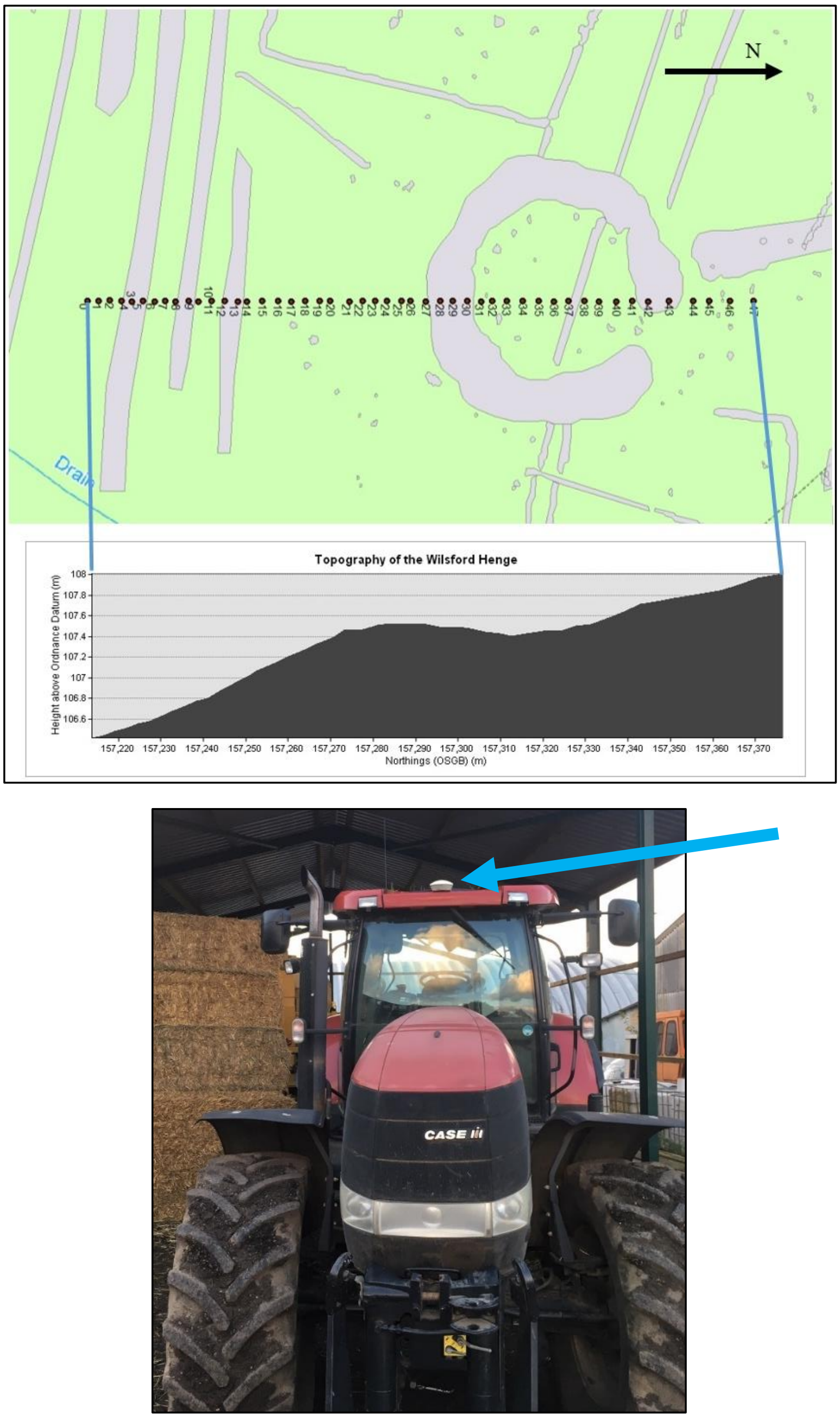


Figure 148: Topographical information from RTK GNSS points over the Wilsford henge (top) and example of tractor fitted with RTK GPS marked with blue arrow (bottom) (© author)

(contains OS data © Crown copyright and database right 2019)

The use of soil analysis, specifically topsoil plant-available analysis, across the three sites again reflects the trends within archaeological methodologies and the driving needs of PF. Soil nutrient levels constantly need to be measured on regular four/five year cycles for PF, even in non-PF agricultural systems, meaning datasets are common. Yet within archaeological approaches, geochemical prospection of topsoils is infrequent. Geochemical analysis, other than the pXRF analysis as part of this research, did take place at Wilsford but because of the wider research excavations rather than for topsoil prospection. This shows the general trend that archaeological investigations tend to focus on DBAs, geophysical surveys and excavations, instead of geochemical analysis of soils, especially as a prospection method rather than a diagnostic tool.

In many cases, the availability and lack of awareness of these datasets is the key inhibitor to multi-dataset collation, and highlighting this is one of the main objectives of this research. For example, the existence of archaeological geophysical datasets across all three of the case study sites could have been utilised in the PF assessment of soil variability, and yet none were included because there was a lack of awareness that these datasets exist, no understanding of how they should be interpreted, as well as the extra time and effort that would be spent to access them.

In other scenarios the accessibility of data might be restricted due to costs or commercial interests. For example historic mapping may not be valued enough by PF companies to enable them to access this data, or multispectral imagery purchased by a PF company is not likely to be available for use on wider scale archaeological assessments, yet might be on smaller scale individual arrangements.

The other major factor contributing to the use of certain common datasets is the farmers' choices. It was highlighted that PF services can vary greatly between different companies (Chapter 2), and farmers can also pick and mix between various companies or take their own, more independent, route for specific services they need. Across the three case study sites, two (Myncen Farm and Wilsford Manor Farm) were both involved in the same subscription service from the same company (showing also the effect of a farmers choice within the same company's services). Whereas the third case study at Perdiswell Farm took the independent route. These sorts of choices can have a significant effect on what types of dataset are available for comparison and how engaged the farmer is in the process itself.

9.1.2 Spatial Nature of Datasets

The spatial variability, resolution and extent of data plays a large role in both PF and archaeology. Broad comparison of the spatial similarities and differences between archaeological and PF approaches is that archaeological datasets tend to be of higher resolution but of a limited spatial extent, whereas PF datasets tend to be of lower resolution but covering larger spatial extents. This in agreement with existing expectations from the Chapters 2 and 3, and the reasons behind this are that agricultural data needs to be time and cost-effective over large areas, requiring a relatively low resolution to match the ability of the farmer (or farmers equipment) to manage variability. Instead, with archaeological investigations the time and cost effectiveness usually means smaller more targeted areas are focused on, with higher resolution data to match the resolution of the archaeological site being recorded.

Within this context, it is worth pointing out how a particular dataset's resolution and extent can impact the interpretation of other datasets when combined together. Geophysical data gathered on each case study site has provided the main starting point for evaluating the archaeological potential of a site. Both Wilsford and Perdiswell sites have full coverage of the entire study field with magnetic data. These datasets have provided the most complete and consistent dataset for showing the below ground archaeological remains at both sites, being used to compare the responses of geochemical mapping, aerial imaging, soil coring and other datasets together. This has led not only to confirmation of existing archaeological features but also new archaeological features such as at Wilsford (Figures 109 and 90).

In comparison, Myncen Farm shows the limitations of having a geophysical dataset that does not extend to cover the whole field (Figure 149). This geophysical survey was targeted to assess the two known archaeological features at the site, the large hill top enclosure and the smaller Iron Age enclosure, but left out more peripheral parts of the field. These peripheral parts, however, contain variations in a drone-based NDRE image that are not explainable from other datasets or agricultural anomalies in the crop, and has elevated elemental concentrations of Cu. This limits the usefulness of the geophysical survey when trying to compare it with PF datasets that are generally always at the field scale and could potentially aid further archaeological interpretation of the site.

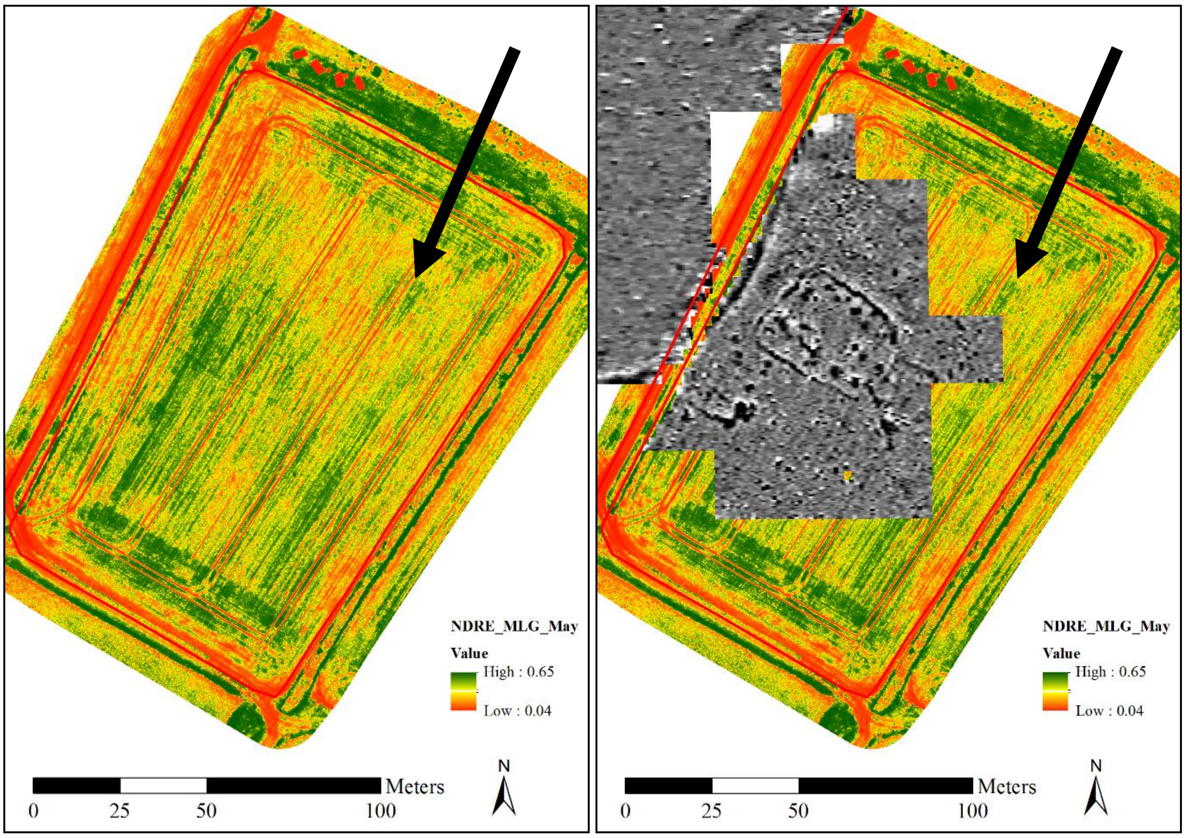


Figure 149: NDRE drone image of Myncen field MLG Top (left) and the same image with magnetic survey overlaid, showing the limited extent of geophysical survey in relation to an anomaly (arrow) in the NDRE data (data courtesy of Bournemouth University) (© author)

Aerial imagery, whether by drone, light aircraft, or by satellite, tends not to have the same extent issues when looking at the field scale. If case study areas were much larger, such as a landscape, then limitations of drone surveys may occur due to the physical limitations of surveying such large areas. Instead it is the spatial resolution of the multiple different types of drone, aircraft or satellite-based imagery that is important at the within-field scale.

Figure 150 shows the large changes in results between the different resolutions over the same areas. The most drastic change is between the 5m resolution satellite image and the 0.08m resolution drone images. For assessing archaeological crop marks and delineating anomalies between tramlines, the level of accuracy provided by a drone, or a higher resolution satellite image is necessary. For assessing areas more relevant to PF, where different management zones can be created, or different rates of nitrogen fertiliser could be applied, the 20m resolution image provides a more easily manageable zone. The advantage of a higher resolution is, however, that it can still be simplified easily into broader zones while retaining the initial level of detail for interpretation of the causes of low or high NDVI measurements (for example the Iron Age enclosure at Myncen Farm).

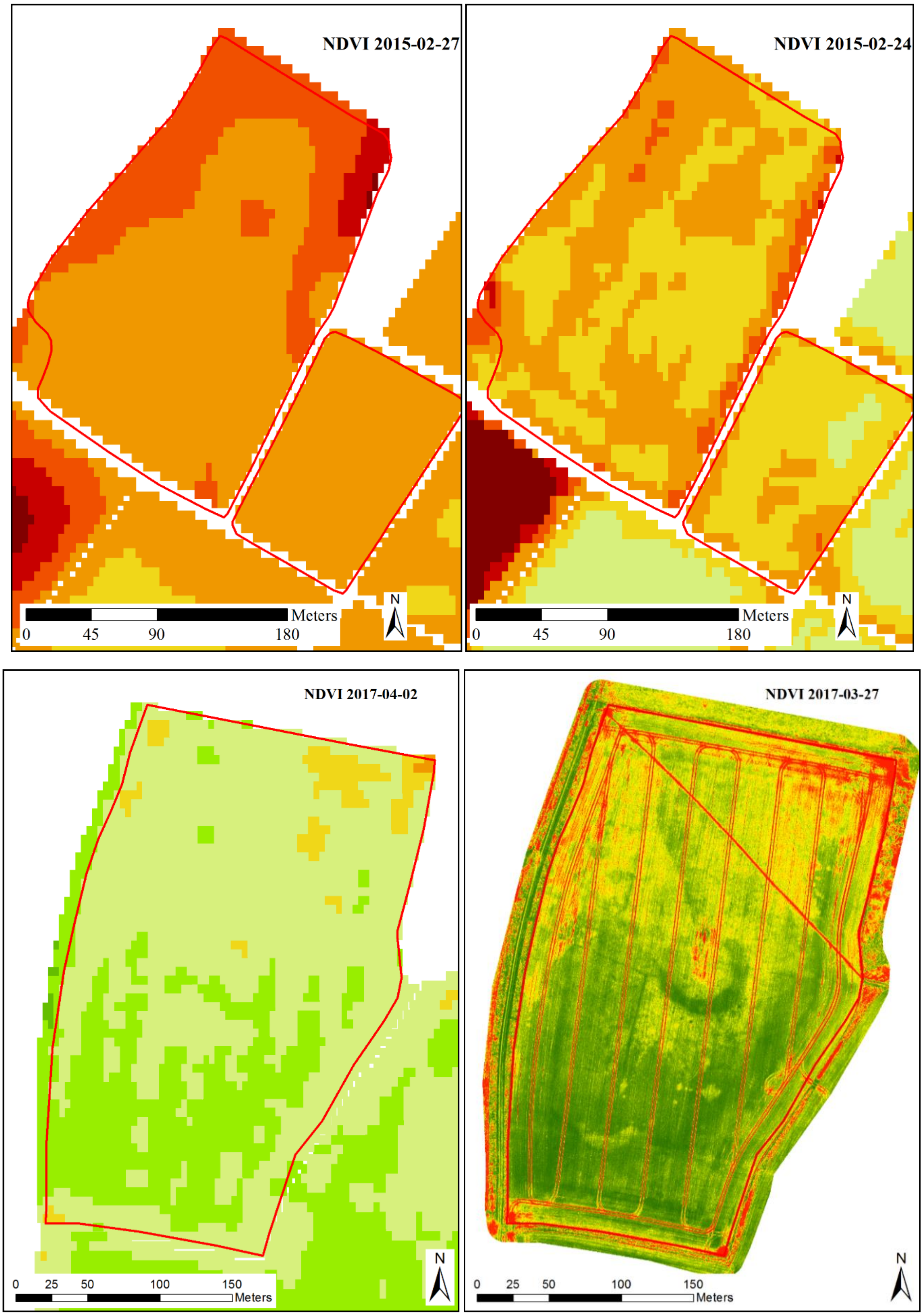


Figure 150: Comparison between 20m resolution (top left) and a 5m resolution satellite image (top right) at Wilsford from a similar time, and between a 5m resolution satellite image (bottom left) and a 0.08m resolution drone image (bottom right) (data courtesy of IPF UK) (© author)

The relative ease of collecting satellite or drone-based imagery over a large area means that a high data point density can be achieved without much cost. This is not the case with actual soil measurements through analysis of soil samples. Instead soil analysis, from the collection of samples to the time and the cost for the laboratory analysis, can take far longer and cost more. This means the density of soil analysis tends to be much lower, leading to sampling locations being targeted through some sort of sampling design. Variations in sampling designs can impact quite significantly on the ultimate maps produced of soil nutrients. Across the case study sites there are three different sampling designs used; systematic grid sampling (Perdiswell), zone-based sampling (Myncen and Wilsford) and targeted sampling (Perdiswell). Figure 151 shows how the spatial variability changes with the increase in sampling frequency (although note that these maps do analyse different fractions of P, at different times, so results are likely to vary slightly between images inherently).

The most significant difference is at Perdiswell Farm, where there have been two different types of sampling tested on the same field by different companies (and using different laboratories for analysis). The correlation between the two systematic surveys is far greater, despite their resolution differing by a factor of five, showing very similar distributions of P and available P in the topsoil, apart from a higher area in the NW of the field. The targeted sampling, with samples taken at each data label location, shows a very different distribution missing some key areas. This highlights the need for consistency in the sampling design over time, but also shows that *in situ*ations where variability is less well understood, a systematic approach is the more appropriate sampling method.

Myncen Farm | **Wilsford Manor Farm** | **Perdiswell Farm**

Zone sampled Olsen P

Dark Blue = high P

Zone sampled Olsen P

Dark Blue = high P

100m grid sampled Olsen P

Targeted sampling Olsen P

20m grid sampled Total P (blue = low P)

Figure 151: Display of multiple soil sampling designs at Myncen, Wilsford and Perdiswell in comparison to the systematic 20m grid for various forms of P (© author)

Existing soil and geological maps can be used in both PF approaches and archaeological approaches if available. Their spatial resolution can vary somewhat according to the level of detail of the original observations. At Wilsford for example, the resolution of the soil survey map was not high enough to pick up smaller within field variations that could be shown by further coring, topsoil geochemistry, and even by aerial imagery. It is recognised in the PF industry that existing soil and geological maps do not provide enough resolution to enable accurate within-field variability to be mapped, and therefore other methods for providing this have been developed (https://www.rhizadigital.co.uk/contour/ accessed on 04/11/19).

HER data can consistently provide data over large areas (being outputs from either county-wide or national datasets) so is not limited by extent issues as some other datasets are. Instead it is the variability in the quality of that data, and its spatial resolution, that can be its limiting factors. Both Myncen and Perdiswell have HER datasets that are limited to single points that contain information about either artefacts or sites that are known within an area (Figures 51 and 138). Whereas Wilsford has a far greater resolution of data, recorded from aerial photographs that show individual archaeological features such as ditches and pits (Figure 97). These variations in the spatial detail represented in the data have impacts on how this data can be used.

9.1.3 Temporal Nature of Datasets

In Chapters 2 and 3, it was described how the temporal nature of archaeological approaches and PF approaches are similar, in that they can be a cyclical process of planning, collecting, analysing and reporting data, but also have differences in the frequency of data collection of individual datasets.

At Perdiswell Farm, the investigation of the site by TVAS produced a DBA all previous archaeological and historical background on the site, followed by geophysical survey and trial trenching, and published reports on the results of their work. This provides one example of a cycle of archaeological planning, collating, analysing and reporting. This process occurred over a time period of around two years, relating to the development potential along with the risks to the scheduled Roman villa. Other case study sites, being more research led in direction, have had multiple smaller archaeological cycles occurring over 30 years or more (Myncen Farm). Therefore cycles can be irregular, being driven by a huge variety of reasons, from research interests to development potential, but never the less mean data is collected at different periods of time, with different technologies and techniques.

With regards to the PF approaches, the speed of data collection, interpretation and analysis is far quicker due to the commercial nature of services as well as the need for data to be used each growing season. PF cycles can be quite different from each other, depending on the type of PF system a farmer uses. The subscription services (used at Myncen and Wilsford) are quite structured in their planning (the assessment of existing data and soil zoning process), followed by regular automatic collection of data such as satellite imagery, or soil nutrient analysis, and repeated use of that data in aiding farm management every year. The feedback of how well a soil zone is performing, or whether soil zones need revaluating as a result of further data collection, has not been seen, or planned for, at either case study site yet. In comparison, Perdiswell has far less structured data collection with regards to soil zoning and regular data collection. Although datasets such as N-Sensor crop biomass measurements, or yield maps are collected regularly, they are less frequent than satellite images at Myncen or Wilsford.

The pace of the archaeological investigations is limited by the level of detail that goes into producing geophysical survey reports, or DBAs. Where PF companies have developed the software to process satellite imagery in a matter of seconds, archaeological evaluations have to collate datasets from other people, or from other physical locations, and compile the digital report, taking days, weeks or months. PF data such as satellite images, yield maps, and soil nutrient analysis, however, have not been subjected to the level of detailed interpretation that archaeological geophysical data has been (for example the detailed interpretation of the Wilsford magnetics survey).

In addition to the cyclical process of PF and archaeological investigations. Individual datasets can have different temporal frequencies as a result. Excavations of the exact same area can only occur once, due to its destructive nature. Geophysical surveys, from the case study sites, tend to only occur once, although from experience multiple geophysical surveys might occur in particular situations. Aerial imagery, either historic, or from drone-based surveys can occur on average once or twice a year (from an archaeological perspective). Whereas PF collections of multispectral satellite imagery can reach 12 or more per year. Therefore with the uptake of PF on each case study site, the number of pieces of data being recorded for a particular site increase substantially (Figure 152).

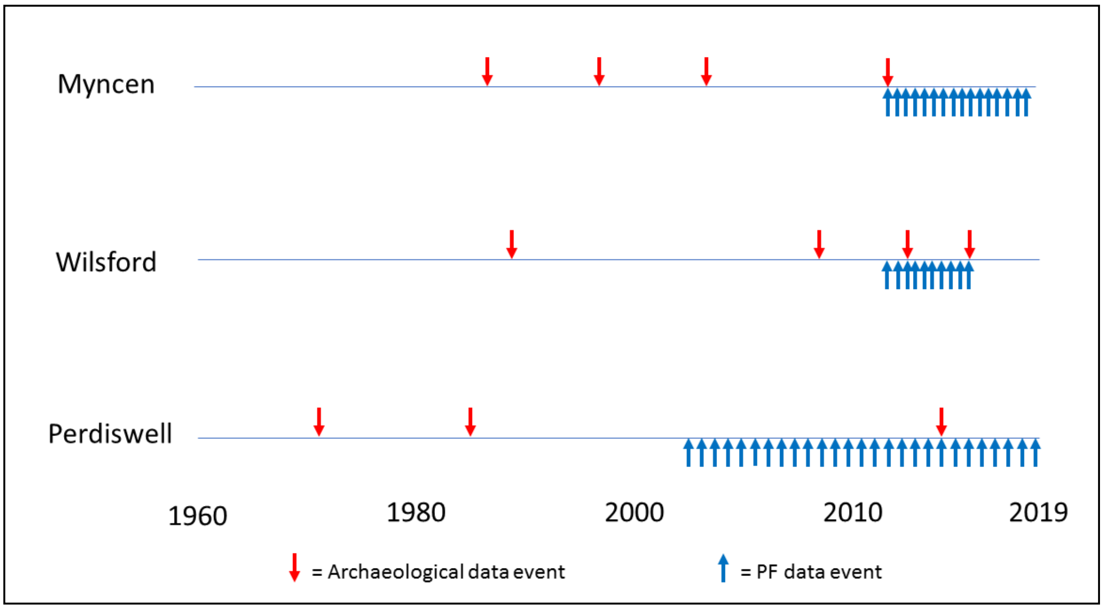


Figure 152: Chronology of digital data events, both archaeological and PF, over time at each case study site (excluding common data such as Google Earth imagery) (© author)

9.1.4 Concluding Remarks

Across three case study sites, over 13 different types of data and hundreds of specific datasets demonstrate the overlap between PF approaches and archaeological approaches. There are similarities in the use of common types of data such as satellite imagery, drone imagery and soil mapping, yet an unexpected lack of geophysical methods (such as conductivity or magnetic gradiometry) in the PF datasets. The use of a particular type of data can be limited due to the varying spatial extents, resolutions and temporal characteristics of that data. Archaeological approaches tend to focus on fewer high resolution datasets with greater interpretation of each, in comparison to the large volume of low resolution data created by PF approaches. Despite this many of the methods displayed in the case study results, whether archaeological or PF in focus, can be spatially and temporally useful in determining crop and soil variability, the core aim of archaeological investigations and PF systems.

9.2 How Have Past Human Actions Impacted Soils and Are Those Impacts Relevant to PF Methods or Data?

Across the three case study sites, there are archaeological features showing human activity from the Neolithic; Iron Age, Roman, post-Medieval and modern use of those fields. Each having its own unique mixture of geological variation, soil development and human management that have created the soils that exist today. Each individual case study site has demonstrated how humans have added to the soil palimpsest, here those results are aggregated together and further linked to the relevance of this data for PF methods and data, wider agronomic influences and impacts on soil management.

9.2.1 Anthropogenic Impacts on Elemental Distribution

The first step in identifying archaeological impacts was to determine the geological distribution of elements across each case study site. The PCA of the pXRF data across all soil samples, from each case study site, was used to find consistent correlations between 21 measured elements. This produced results allowing the segregation of elements according to the major variations in the field. These major variations were likely to represent the changes in the parent material of the soils across the field. The elements that were not correlated with these geological distributions, however, were then investigated for their correlation with evidence of archaeological features.

In general, it is notable that at each site the natural background geological distribution and the natural soil development was more complicated and variable than previously expected. This not only highlights the importance of recognising variability in between one soil profile and wider soil or geological maps, but the affect this may have on the elemental ‘visibility’ of archaeological impacts. The results show how the objective PCA method can identify multiple groupings of elements, some of which may not relate to major soil types or demonstrable archaeological impacts. These ephemeral groupings could relate to archaeological impacts that are not demonstrable through other evidence gathered, or might relate to variations in soil types, or gradients between soil types.

Both Wilsford and Perdiswell have one coherent, but widely spread, group of PCA anomalies whereas Myncen has two groups (noted by brackets in Table 14). This secondary grouping is closely related to the distribution of elements that match the CwF soils but with a noticeable difference. These multiple groupings should not, however, automatically be considered 'archaeological' since they could be representing more subtle soil variations at part of the site caused by the degree of mixing between soil types. This shows how useful the multi-elemental analysis combined with PCA analysis is. Highlighting subtle relationships and elemental patterns in the soil, combined with supplementary datasets, can help to build a better understanding of soil variations, as well as delimit boundaries and mixing between soil types, and the possibility of archaeological impacts. Yet these show that it is difficult to identify the causes behind complex geochemical variations, even with supplementary data as a baseline (such as geophysical surveys).

The elements identified by the PCA analysis (listed in Table 14) all correlate with elements known from other studies to be related to archaeological features (Chapter 3) and this work further demonstrates elements such as P, K, Mn, Cu, Pb, Zn are found in relation to archaeological features. In Table 1 the first row shows the results of the PCA analysis which helps to pin-point geochemical anomalies, the second row shows elements in the topsoil that can be definitively correlated spatially to archaeological features, and the third row similarly shows archaeologically correlated elements from soils below the topsoil, where analysed.

	Myncen Farm	*Wilsford Manor Farm*	*Perdiswell Farm*
PCA anomalies	P, S, Cu, Ba (Pb, As, Mn, Zn)	P, Ba, As, Mn, S, Pb	P, Zn, S, Mn, Pb, Cu
Topsoil archaeological anomalies	P	Zn, As, Pb	P, Zn, Pb, Cu, S
Subsoil archaeological anomalies	P, Ba, Cu, Zn, K, Mn	P, Ca, Pb, Zn	-

Table 14: Elemental anomalies due to PCA (brackets denote two distinct groups), archaeological anomalies in the topsoil and subsoil per case study (© author)

At Myncen Farm, only P was noticeably enhanced within the topsoil in relation to known archaeological features. This P enhancement was not seen in the systematic 20m grid sampling due to the low level of enhancement and the geological variation across the site. The small Iron Age enclosure lay upon the boundary between the calcareous soils and the superficial CwF deposits, making comparison between the archaeological feature and the average background levels of P in those soils more difficult. Hence further sampling was required to test this theory and P levels were enhanced by around 6% on the calcareous soils and 21% on the CwF. The source of this P is likely to be either from deposit on the surface, or the upper fills of the numerous pits that lie within the enclosure. As this land was turned to arable agriculture, cultivation will have mixed these soils and the depth of this mixing will have increased with greater depths of ploughing activity. Due to the number of pits detected within this enclosure it might be more likely that this enhancement has originated from the upper P-rich fills of these pits and mixed into the wider soil. Contrary to this interpretations, however, is the fact that core 27, one of the pits, did not contain high levels of P in its upper fills, only towards the bottom of the pit. Therefore the exact origin cannot be concluded.

The larger enclosure at Myncen did represent a slightly more intriguing archaeological feature that provided little in the way of geophysical anomalies to interpret how it might have been used in the past. It was hoped that by combining a geochemical approach, along with the numerous other imaging techniques, that more evidence could be gathered as to its use. Unfortunately the geochemical data was very similar to the geophysical data, with no significant remains of human impact. A lack of structures suggests no human habitation use, and therefore no pits of concentrated elemental content. The other probable use as a livestock enclosure is still the most likely interpretation, and the geochemical impact of that would only be significant if very intensive stocking took place, or for extensive periods of time.

At Wilsford there is a similar group of elements that the PCA analysis identifies as anomalies to the major soil types. Again, like Myncen, the major soil types are grouped by Ca/Sr-based calcareous soils in comparison to a broader spread of metals and silicon (greensands). The division between these two soil types is slightly more complex, spatially and with depth, than at Myncen, increasing the difficulty of analysing archaeological impacts upon those soils.

From the topsoil perspective there appear to be several elements (Zn, As, Fe, Rb) that correlate specifically with the Neolithic henge monument. None of these elements have large increases other than As (Zn = +28%, As = +100%, Fe = +20%, Rb = +25%), which has the lowest detection consistency and varies between 6ppm and 12ppm with a LOD around 4ppm using the pXRF. The spatial correlation of Zn spreads over the boundary of the ditches to a diameter of around 100m. Both Zn and As do not correlate with either of the background parent materials, while Fe and Rb do correlate with subsurface horizons, especially the heavier textured horizons. This suggests that while mixing has occurred in the topsoil, including elemental signatures from deeper stratigraphic layers, there is also possibility that the Zn and As has been deposited by other processes relating to the shape of the henge.

The second topsoil variation relates to the southern field boundary, where although the soil profile changes from a deeper soil developed over greensand to a shallow calcareous rendzina, there is also a defined geochemical change in the topsoil. This area, delimited by an old track that crossed E-W across the southern portion of the current field, and shown on the First Edition OS map (completed around 1890s), has higher values of a number of elements than the rest of the field. These are all metal elements (Zn, Ba, Bi, Cr, Al, V, Nb, Rb and Ti) that only appear in the upper topsoil layer, and by 30cm deep these distributions disappear making them fully within the modern cultivation layer. Since this spread covers the entire southern portion of the field it is interpreted that these enrichments in metals must have come from different land management practices between these two fields during the past. Some of the elements above were not highlighted by the PCA, but have still been shown to be archaeologically relevant. This is because these elements are mainly associated with the broad group of elements associated with the silica and clay-based soils rather than the calcareous soils, and over all samples taken, this is still true. However it is also true that in the topsoil, these elements have simultaneously had an association with the calcareous soils. Where elements have multiple minor associations the PCA does not include other factors such as horizontal and vertical correlation between soil samples and so cannot be solely relied on for providing accurate assessments of elemental distribution and archaeological causation.

Below the topsoil, the key results from Wilsford show that where archaeological features were excavated or had core samples taken from them, there were impacts on the geochemical content (mainly P, Pb and Zn) at various depths depending on the depositional context of the archaeological feature (Table 15 for comparison of archaeological features and their geochemical impact). In some cases it is not just material added to the soil by past human actions such as middening, but also in redeposited materials such as chalky drift. In one ditch feature a substantially chalky deposit was part of a secondary fill and of course substantially altered the Ca content of the sample. In the ditch and pit features examined across Wilsford and Myncen, the increase in elemental concentration tends to be in the primary and secondary fills (deeper). Later deposits (shallower) tend to, but not always, consist of less nutrient-rich material. This has an impact on the effect of cultivation or bioturbation of those upper layers on the elemental content of topsoils in comparison to a normal soil profile. For example at Wilsford particularly, no real topsoil variations are visible in elements such as P or Pb, despite those elements being enhanced in specific archaeological features.

	Myncen Farm	*Wilsford Manor Farm*	*Perdiswell Farm*
Historic field boundary	-	Zn, Ba, Bi, Cr, Al, V, Nb, Rb, Ti	Zn, Pb, Cu, S
Building/structure	(P)	(Zn, As, Fe, Rb)	(P, Zn, Cu)
Pit	P, Cu, Mn	-	(P, Zn)
Ditch	P, Zn, K, Mn	P, Ca, Pb, Zn	(P, Zn)

Table 15: The archaeological feature types and associated elemental anomalies at each case study site (© author)

100 Acres, at Perdiswell Farm has shown the most impressive geochemical variations from the topsoil. Since cores were not collected over the large and very shallow site, it was questioned how effective the results of solely a topsoil survey would be for assessing geochemical impact of archaeological features on the soil. Yet there are a number of strong elemental concentrations in the topsoil that relate well with geophysical features. Some reasons for this are that the geology is relatively consistent across most of the field, and that the archaeological features are all relatively shallow, with the deepest ditch excavated only 0.6m deep. This means that any archaeological deposits within the top half of this would have already been truncated and mixed into the plough soil horizon. Hence while this is less beneficial for archaeological preservation *in-situ*, the geochemical impact is potentially far more visible from topsoil sampling.

With such a large field, there are many historic field boundaries included within the modern boundary, some mapped previously by the OS, but some not mapped until the geophysical survey in 2014. These field boundaries produced quite significant geochemical variations in Zn, Cu, S, Pb and possibly As, all within one particular historic boundary in the NW corner, but some spreading along the N edge of the field across multiple boundaries. These areas have clearly had different land uses or management in the past, and some of these geochemical variations might also relate to the location of the Isolation Hospital. The levels of magnitude in comparison to the rest of the field are quite strong, with around double the Pb values in this area in comparison to the rest of the field. Across the four elements with high levels in this NW field, it is ultimately Pb, Cu and S that are most enhanced and therefore it is likely that whatever was applied to that field contained large amounts of these elements.

With regard to other archaeological features, the Roman use of parts of this field have provided very clear geochemical signatures of high P and Zn values, again being around double the average values for the field. Unlike the case of the Iron Age enclosure at Myncen Farm, the high levels of P surrounding the villa extends over 125m to the E and creates a large triangular area without any geophysical anomalies visible. This could suggest that the P source has come not just from truncation and mixing of pit or ditch fills, but also from additional material containing P spread over an area of land very close to the villa. There are other areas producing enhanced responses from pits and small ditched enclosures in the NE corner of the field, that again produced enhanced levels of P and smaller enhancements of Zn. Therefore the Roman impacts on this field seem to be mainly correlated with P and Zn, as well as some elevated Cu levels.

9.2.2 Macronutrients

PF soil analysis across the three case study sites, albeit using different sampling strategies, aimed at identifying the plant-available (hence nutrient rather than element) concentration of P, K, Mg. These are the major macronutrient requirements for plants, along with the addition of N, Ca and S. Standard soil testing does not involve analysis of the latter due to the costs, timings and benefits of applying such specific nutrients.

In comparing results from the pXRF analysis of soils with the PF soil analysis, the difference between methods should be noted. The XRF method uses X-Ray level radiation to measure the total elemental content of a sample at an atomic level, disregarding whether an element is tightly bound to soil minerals or within the soil solution. Instead plant-available analysis intends to measure what can be taken up by a plant over a short period of time. Methods use certain strengths of extractants to retrieve certain amounts of nutrient that are thought to be plant-available. For P the most commonly used method is Olsen extraction (Rowell, 1994: p.211), and for K and Mg it is an ammonium nitrate extraction (Rowell, 1994; AHDB, 2017).

Figure 153 shows the relationship between plant-available Olsens P and total P.There is a good correlation, but the relationship is widely spread. This wide spread is likely to be caused by the wide variation of different fractions of P in the soil and variation among different soil types. It does give the indication that the larger the total P, in principal the larger the available Olsens P is likely to be.

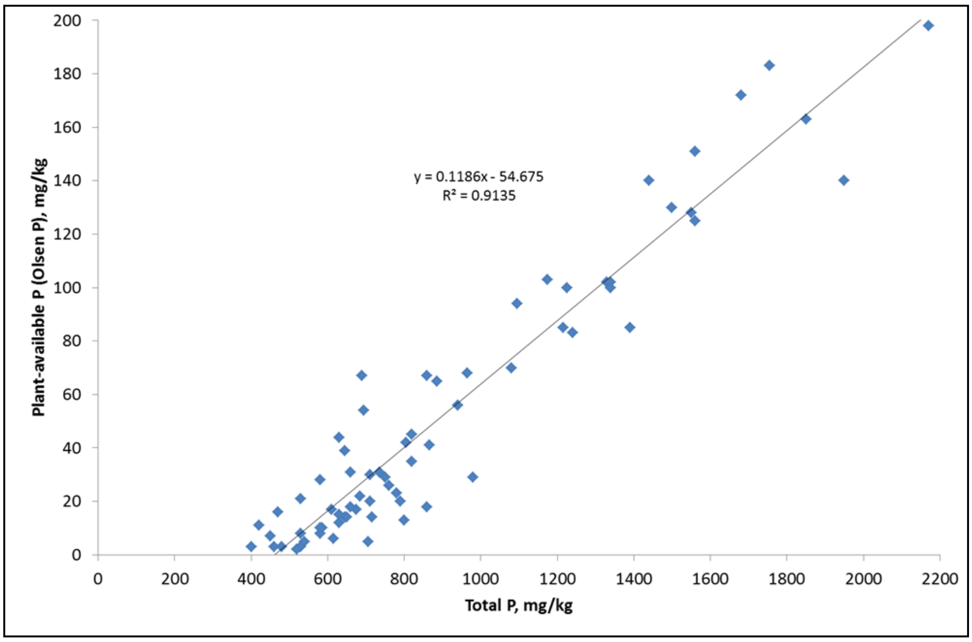


Figure 153: shows the relationship between Olsens P and Total P on the same soil samples from a range of soils at Rothamsted. (courtesy of P. Poulton)

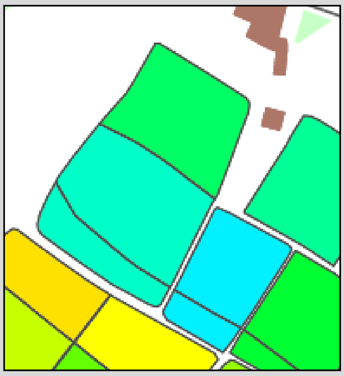
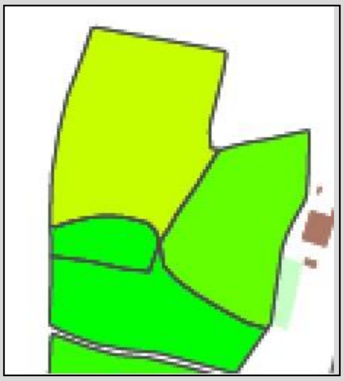
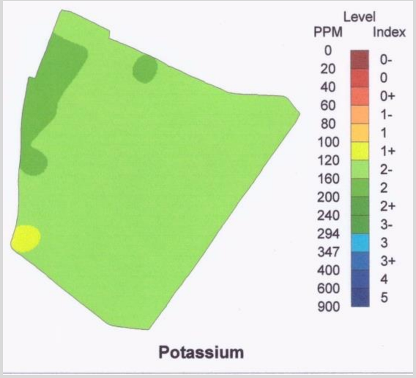
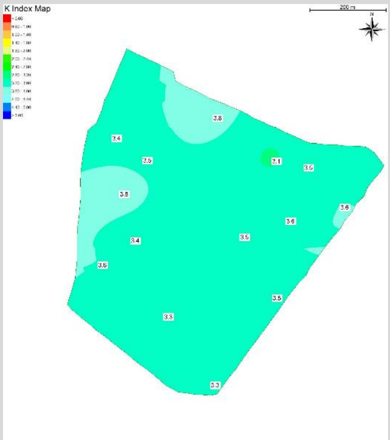
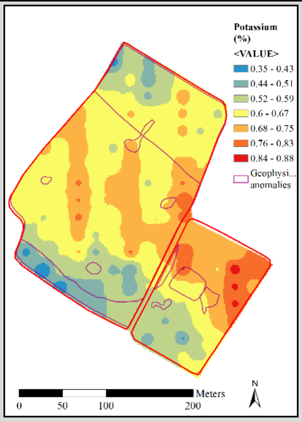
Out of the three agriculturally analysed macronutrients (P, K, Mg), only P has shown variation that is clearly of anthropogenic origin. Within the topsoil, this has occurred at Myncen and Perdiswell, but not at Wilsford. At Myncen, the variation was not significant in comparison to the rest of the field, and there was little agreement between the total P values and Olsens P (demonstrating that much of the P was tightly bound to calcium) (Figure 151). At Perdiswell the variation was significant and covered an area of at least 5 hectares. With an enhancement 87% above the field average. In this case there is a positive agreement between the variation in Olsen P and total P (with Olsen P levels being index 2 on average, but index 4 surrounding the Roman villa). These results show that archaeological areas can be large enough to be considered within PF systems, and have a significant impact on agriculturally relevant soil analysis. This could have implications for altering P fertiliser application rates and reducing the amount of P fertiliser necessary for this field.

The situation for K is not as clear, with less well evidenced relationships between various extractions of K from soils and total K (Rowell, 1994). Similar to P fractions, there are four different fractions of K in the soil (soil solution, exchangeable, fixed, mineral/lattice). Again similarly to P, the majority of the total elemental concentration lies within the mineral and fixed fractions of the soil (mineral K accounts for approximately 95% of the total K). Through various processes K can be cycled at various speeds between certain fractions in the soil, however, the breakdown of mineral structures to release K is very slow and only really contribute to long term K supply, not at a crop relevant timing.

Across the three case study sites K variability is low, and all sites are around the target index 2 for exchangeable K. Comparing the exchangeable K with the distribution of total K there are some considerable differences (Figure 154). At Myncen Farm the two maps agree on higher levels of K in MLG Top, but the total K values suggest only the northern half of this field is high in K. Whereas, the exchangeable K is the same across both zones of the field. Due to many factors, especially previous field management, affecting the K status of soils it is unlikely that any real interpretations can be made about the K distribution in relation to total vs exchangeable K. All that can be said from the total K distributions are that they do relate to broader soil changes, and are thus mainly relating to the mineral and fixed proportions of K that is tightly bound up and not available to plants.

The soil Mg values measured PF soil analysis was not within the detection limits of the pXRF and so no comments can be made on the total vs available Mg.

S is becoming much more widely recognised as deficient in many crop types, so is now regularly applied in conjunction with N fertilisers (AHDB 2017). Currently soil tests for S are not regularly completed because S, like N, can be easily leached when in the soil solution. S is usually held in OM and is released as OM is broken down. Plants have quite a large requirement for S, and so typically a sulphate fertiliser, or elemental S, is applied to fields. The same concerns arise with the comparison between plant- available and total levels of S, but putting these to one side, the elemental distribution of total S across sites such as Perdiswell show how variable S can be (Figure 129). The S distribution is linked to a historic field boundary that has elevated levels of other metals as well, showing historic land use can have an effect on total S concentrations. This could be in relation to higher levels of OM from repeated application of manures or sludges, or from a specific material applied to the soil such as a type of slag high in S. This therefore could be relevant for PF systems, as it may be beneficial to reduce application of S-based fertilisers in areas with significantly higher total S.

<table>
<tr><th>Myncen Farm</th><th>Wilsford Manor Farm</th><th>Perdiswell Farm</th></tr>
<tr>
<td rowspan="2">Zone sampled Exch K

Dark green/Blue = high K</td>
<td rowspan="2">Zone sampled Exch K

Dark Green = high K</td>
<td>100m grid sampled Exch K

 </td>
</tr>
<tr>
<td>Targeted sampling Exch K

 </td>
</tr>
<tr><td colspan="3">20m grid sampled Total K (blue = low K)</td></tr>
<tr>
<td>
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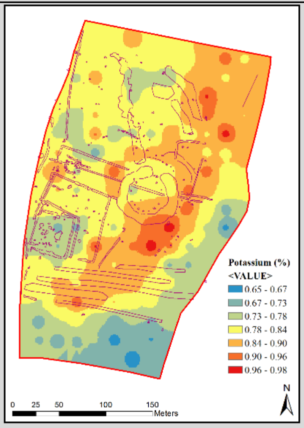
<td>
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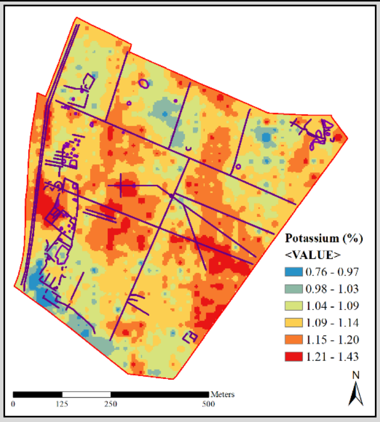
<td>
 </td>
</tr>
</table>

Figure 154: Display of multiple soil sampling designs at each case study site in comparison to the systematic 20m grid for various forms of K (© author)

The last macronutrient is Ca, which is again a major nutrient for plants, but is very unlikely to be deficient across soils in the UK. Only Wilsford has shown variability in Ca levels in relation to archaeological features, a Roman ditch and the henge ditch. The Ca enhancement in the Roman ditch relating to the soil stratigraphy being disturbed and more calcium-rich material deposited in a particular layer. The henge ditch instead being elevated in Ca because of late Bronze Age midden material likely to contain bone and ash, high in Ca. Due to the quantities of Ca in the soils across the three case study sites, which are all essentially calcium carbonate-based parent materials other than the greensand areas at Wilsford, any archaeological elevations would be small in comparison to wider variability and therefore not be visible in bulk analysis of topsoils. Despite this, and also because of the concentrations generally in soils, Ca is also not an important nutrient for fertiliser application and not something that farmers would manage regularly apart from in the case of the effect on pH and the need for liming to maintain the correct soil pH for crops.

9.2.3 Micronutrients

Micronutrients (Fe, Cu, Mn, Na, Zn, B, Mo, Cl, Se) are just as important agronomically as macronutrients are, since any nutrient below necessary levels can become the limiting nutrient in the system (Roques *et al.*, 2013; AHDB, 2017). Micronutrients are needed in lower quantities than macronutrients, but there are also lower quantities in the soil, and the variability of them can differ greatly depending on previous land uses and soil type. Many farmers now take a tailored approach to crop nutrition, named ‘prescription nutrition’, buying fertilisers that are precisely matched to soil/crop requirements, and that may contain multiple macro- and micronutrients (P. Scott, pers. comm.). Micronutrients that have shown variability in relation to archaeological features across the three case study sites include Zn, Fe, Cu and Mn.

Out of these, Zn is the most common, with enhancement at each case study site, in topsoils or within subsoil archaeological deposits. The average values at Myncen (144ppm) and Perdiswell (105ppm) are within normal ranges of total Zn in soils (10-300ppm) (Roques *et al.*, 2013). While Wilsford is low in Zn, with a mean of 38ppm total Zn. In general limestone and siliceous parent materials tend to be low in Zn, which confirms the Zn status at Perdiswell and Wilsford (at Perdiswell the average is positively skewed by high P values surrounding the archaeological site, whereas background levels are actually *c.*50-70ppm). At Myncen it is the CwF soils that have higher Zn levels. Zn deficiencies for plant growth are generally rare in the UK, although a considerable issue internationally (Alloway, 2009), with deficiency relating mainly to Zn ions in the soil solution rather than total Zn contents including Zn tightly bound to minerals (Roques *et al.*, 2013: p.28). Therefore agronomic analysis of Zn would usually focus on plant tissue analysis or soil extraction methods rather than total elemental concentrations (AHDB, 2013a). The total Zn content can be relevant for plant-available Zn, however, in combination with factors such as pH, OM, microbial activity, redox conditions, calcium carbonate content and P status, where in certain circumstances (such as acidic environments) much more tightly bound Zn becomes plant-available (Alloway, 2009; Kabata-Pendias, 2011). It is unlikely archaeological enhancements of Zn within the case study sites contribute to plant-available Zn, or relate to any deficiencies in Zn either.

Cu deficiencies are not widespread but are known to occur mainly on sands and shallow soils over chalk (Roques *et al.*, 2013; AHDB, 2017). Across the case study sites, Cu levels average around 14-32ppm with Wilsford being the lowest (with only three detections out of 169 topsoil samples). This could be partly caused by a lack of recent manuring or addition of organic materials that would contain Cu as well as the parent material considerations (unlike Myncen where manuring has been regular practice and Perdiswell where sewage sludge and digestate has been frequently applied). As was the case for Zn, total Cu is not the best indicator of any deficiency in plant-available Cu, yet low Cu contents of soils can relate to plant deficiencies in conjunction with other geochemical factors that affect its availability. Figure 155 shows signs of Cu deficiency in the crop at Wilsford with so-called ‘withered leaf tips’ and rolling or spiralling leaves. Once symptomatic there is not much that can be done. Management is is usually by earlier Cu chelate-based sprays, copper sulphate fertilisers, or organic manures to the soil. Although no anthropogenic enhancements of Cu exist at Wilsford, at Perdiswell there are enhanced levels of Cu in certain areas relating to the Roman villa complex, and within a historic field boundary. The possibility for human activities to contribute to higher levels of Cu over deficient soils could have an impact on crop health and reduce micronutrient deficiencies, or the need to correct them by applying additional nutrients.

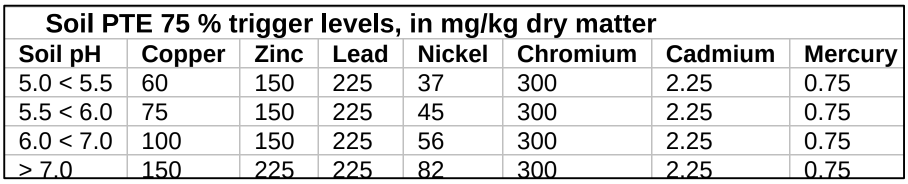
Figure 155: Photograph of winter barley crop at Wilsford in 2017, showing signs of copper deficiencies (© author)

Fe and Mn are both similar elements that are essential for plant growth and occur abundantly within soils in many forms. Deficiencies in Fe are infrequent, whereas Mn deficiencies are one of the most common micronutrient deficiencies for UK crops (Roques *et al.*, 2013). The availability of forms of these elements are crucially dependent on pH, rather than total soil content, and therefore archaeological enhancements in these elements is not likely to affect plant-availability or uptake of Fe and Mn in situations of deficiency.

Other micronutrients, such as B, Cl, Mo, Na, Se are all essential for certain plant or animal functions, however, some have not been detectable in such low concentrations within soils and so cannot be compared. It is worth noting that these are agronomically important in certain situations and therefore could be of relevance if also found relating to anthropogenic activities.

9.2.4 Potentially Toxic Elements (PTEs)

While micronutrients are essential for plant growth in certain amounts, some can be potentially toxic to plants above specific levels (Zn, Cu, Mo, Se). In other cases heavy metals (Cd, Pb, As, Cr, Hg) can also be present in soils and added by processes relating to human activity, also producing potentially toxic effects on plants and implications for human health. On agricultural land known inputs of various materials have been assessed for their contribution to build up of these PTEs (Nicholson and Chambers, 2008).In addition, legislation has set rules around the application of sewage sludge (which although it doesn't cover composts, digestates, and other fertilisers, has similar implications) that can, if not treated properly or if over applied, lead to build ups of PTEs in soils to 'trigger levels' (Table 16) and maximum permissible levels (Table 17).



Soil PTE 75 % trigger levels, in mg/kg dry matter

Soil pH	Copper	Zinc	Lead	Nickel	Chromium	Cadmium	Mercury
5.0 < 5.5	60	150	225	37	300	2.25	0.75
5.5 < 6.0	75	150	225	45	300	2.25	0.75
6.0 < 7.0	100	150	225	56	300	2.25	0.75
> 7.0	150	225	225	82	300	2.25	0.75

Table 16: The 75% trigger levels for PTEs in soil before application of composts, digestates or sludges (taken from https://www.gov.uk/government/publications/sewage-sludge-in-agriculture-code-of-practice/sewage-sludge-in-agriculture-code-of-practice-for-england-wales-and-northern-ireland accessed 02/02/19)

To compare these values with the values across the three case study sites, Table 17 shows the mean and maximum values of the various PTEs listed in the recommended limit tables. It should be mentioned that the analysis methodology set out in the legislation is a strong acid digestion followed by atomic absorption spectrometry rather than X-Ray Fluorescence, however the difference between these two methods should not change the overall values significantly for the major metal PTEs, but will mean some PTEs have been below LOD of the pXRF. From the comparison of values it is clear that there are three instances where the maximum permissible concentrations are already exceeded. There is also one level, the Pb maximum at Perdiswell Farm, that is above the 75% trigger level. All the field mean figures are below the maximum permissible concentrations although at Perdiswell Farm the average concentration of As is only 2mg/kg below the maximum of 50mg/kg.

Potentially toxic elements (PTE)	***Maximum permissible concentration of PTE in soil (mg/kg dry solids)***				***Maximum permissible average annual rate of PTE addition over 10 years (kg/ha)***
	pH 5<5.5	pH 5.5<6.0	pH 6.0-7.0	pH >7.0	
Zinc	200	200	200	300	15
Copper	80	100	135	200	7.5
Nickel	50	60	75	110	3
Cadmium	3				0.15
Lead	300				15
Mercury	1				0.1
Chromium	400				15
Molybdenum	4				0.2
Selenium	3				0.15
Arsenic	50				0.7
Fluoride	500				20

Topsoil PTE levels across the three case study sites (mg/kg)

PTE	**Myncen Farm**			**Wilsford Manor Farm**			**Perdiswell Farm**		
	pH = 7.5-8			**pH = 7-7.5**			**pH = 8**		
	Mean	**Max**	**n**	**Mean**	**Max**	**n**	**Mean**	**Max**	**n**
Zn	144.73	346.53	186	38.46	67.03	169	105.76	176.16	1087
Cu	21.48	39.15	132	14.17	16.54	3	32.07	84.42	499
Ni	< LOD	< LOD	-	< LOD	< LOD	-	< LOD	< LOD	-
Cd	< LOD	<LOD	-	<LOD	<LOD	-	<LOD	<LOD	-
Pb	47.77	194.30	186	19.55	46.41	169	59.26	290.14	1087
Hg	-	-	-	-	-	-	-	-	-
Cr	85.60	133	185	62.43	113.21	169	121.48	594.56	1087
Mo	< LOD	< LOD	-	< LOD	< LOD	-	< LOD	< LOD	-
Se	-	-	-	-	-	-	-	-	-
As	10.75	25	175	2.87	912.19	78	48.87	73.22	1087

Table 17: Maximum permissible levels of PTEs in soils (top)) and the pXRF analysis of PTEs at each case study site (bottom), red = exceeded value, orange = above trigger value (© author) (values taken from https://www.gov.uk/government/publications/sewage-sludge-in-agriculture-code-of-practice/sewage-sludge-in-agriculture-code-of-practice-for-england-wales-and-northern-ireland accessed 02/02/19)

The spatial distribution of As is spread fairly evenly across the majority of the field (Figure 130) but is high near the entrance to the field, which relates to the storage area for any organic materials being applied to the field over the past decade. Therefore it is quite likely that the elevated average levels of As are from more recent applications of sewage sludge and digestates to the whole field boundary. The other PTEs (Pb and Cr) have exceeded maximums in the NW corner of the field aligning with the historic field boundary.

Part of the requirements before sludge can be applied to a field are to have a soil test to check PTE levels. The results from this single bulked sample from 2002 are in Table 12, and allow a comparison between the spatially detailed analysis from the pXRF data and this single historic sample. From the extreme variability across the field it is clear that one bulked sample is not representative of the field and that the methodology set out in legislation is not accurate enough to protect areas of soil from reaching levels above maximum thresholds for PTEs. A number of PTEs are over double the value they were in 2002 (Cr and Zn), while others (Pb) were half the 2002 level. This evidence is critical for informing future fertiliser choices on the farm. If the farmer continued to apply sewage sludge to that field until the mean values reached the maximum, the areas of the field already very high in As, Cr and Pb would be far higher and likely reach plant toxic levels and possibly require remediation.

9.2.5 Anthropogenic Impacts on Soil Depth and Stratigraphy

Across the three sites a number of archaeological features exist; ranging from ditches, to pits, to more subtle areas of previous land use. Not only can these have geochemical impacts on the soils elemental concentrations, but also on the soils depth, structure and stratigraphy. At each site existing data was collected that might indirectly, or directly, provide evidence to how the soil's physical structure changes across the field and how human activity has interacted with this. This was then connected with more systematic evidence at Myncen and Wilsford by core transects that helped identify further how these changes relate to background soils. Broadly the ways that past human activities have impacted soil depths and stratigraphy can be broken down into defined and diffuse effects.

Defined effects can be seen in clearly identified alterations of the soil profile. For example across all three sites there are occurrences of ditch and pit features that in many cases abruptly change the soil profile in both depth and composition. These effects are even further pronounced in soil types that differ significantly from the surrounding soils or parent materials that they are in contrast with. At Wilsford, across many of the aerial images it is possible to see cropmarks of the henge ditch due to the size and depth of this ditch, and the significant changes in OM, texture, nutrients, and most importantly soil water content. In comparison to the soils just inside and outside of the henge ditch which are shallow above a chalky deposit lying on top of greensand, the henge ditch represents a soil profile with a far greater soil water holding capacity than the surroundings. Yet these contrasts are not always as visible, as can be seen with some of the Roman ditch features that are visible when running through the shallower, chalky soils, but are lost in aerial imagery when the ditches continue into the deeper, heavier textured soils with a greater soil water content themselves. The defined effects from a feature, such as a ditch that has been subsequently filled, can also change depending on how material was deposited back into the ditch after its use, or multiple uses, ended. Some ditch features had been backfilled with very similar material to the surrounding soils, see Figure 156 for demonstration of this at Wilsford, making the impact of that feature on the soil less significant from the surrounding soils. The effect of defined features are spatially limited. Most ditch or pit features are only a few metres across and although maybe quite long, cover very limited areas of land.

Figure 156: A defined archaeological ditch feature at the Romano-British site at Wilsford showing a similar chalky fill to the surrounding soil (© author)

Instead the other type of effect from human activity can be described as being more diffuse. Diffuse effects are in relation to activities that impact the soil over a wider horizontal or vertical area and are perhaps less clearly identified in comparison to defined effects. The theory behind these diffuse effects comes from the potential of different land uses, such as soils that have had different types of fertiliser applied to them, or areas of land with buried walls or foundations that might affect the soils composition over a larger areas than the actual building itself. They can be more complex, with unclear boundaries between different types of soil, or complicated by geological variability.

An example from Wilsford (Figure 157), highlights where a number of cores have shown a relatively deeply mixed soil profile, containing ceramic building material, elevated levels of P and Pb, and a decrease in Ca at 39-55cm below the surface. These changes are not spatially defined to any geophysical anomaly that could help interpret their cause, however, the changes do appear to cover a wider area outside of the Roman enclosures and so plausibly relate to a different area of land use in the past.

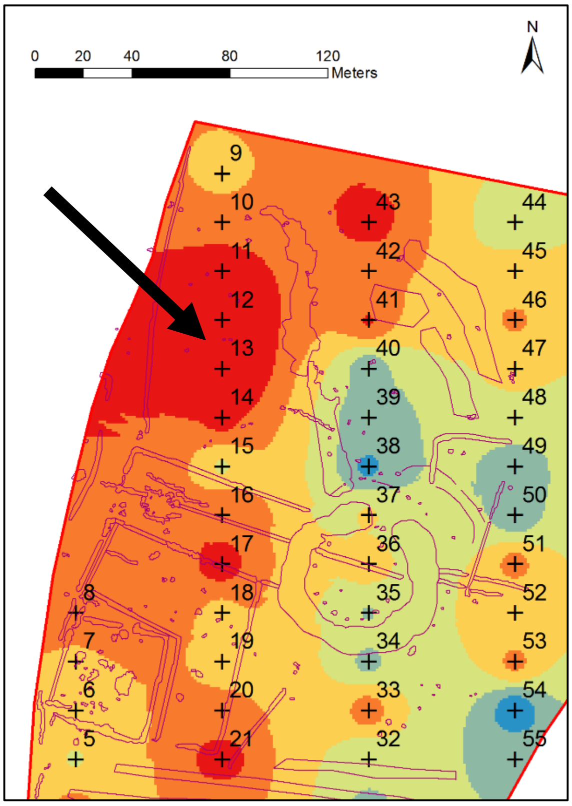


Figure 157: P variation at Wilsford in the 30-50cm layer (high P =red) showing diffuse area of activity (interpretation courtesy of Historic England) (© author)

For PF approaches, these physical impacts on the soil have less relevance than the geochemical variations, primarily because the variability caused by the effects of ditches and pits are so small in area, and spread out in space. It would be impossible to manage areas below 20x20m with the sorts of technology and farm machinery currently available today. This is despite the fact that these archaeological features can have quite significant impacts on plant growth at the individual plant scale. In the future, if analysis and management was possible at the plant scale through the development of robotics, then the impact of archaeological sites on soil physical structure may become more relevant. What is clear is that diffuse effects, with a wider spatial footprint, are of more relevance within PF approaches.

9.2.6 Anthropogenic Impacts on Crop Growth

Traditionally, most cropmarks are recorded during early or late summer, when droughts are most likely and cropmarks most visible. The imaging of crops can, however, produce cropmarks at many times of the year depending the local soil conditions, the crop type and growth stage and the archaeological feature. At Myncen, Figure 158 shows the Iron Age enclosure and its effect on crop growth of oilseed rape. This image is from February, a time when cropmarks are not usually expected, and aerial reconnaissance not usually possible due to weather conditions. This cropmark disappears from satellite imagery later on in the growing season, due to the vigorous growth of the oilseed rape crop, flowering of the crop, and early ripening. Here a number of points are demonstrated; cropmarks can be seen very early on in the growth of a crop (both cereals and brassicas), this contrast can change (either continuing to be visible, or homogenising) throughout the year due to crop type and soil conditions, meaning that some archaeological cropmarks might only be visible in the earlier stages of a crop, and not in later stages as would traditionally be considered.

Continuing the same example, another point can be made regarding why it is important to understand where anthropogenic impacts effect crop growth. Without the aid of the archaeological data and interpretation, this area could have been interpreted in multiple ways by a farmer/PF specialist; it could be an area of weeds in the crop that cause a higher NDVI over winter in comparison to the oilseed rape, or an area that has survived heavy over-winter grazing from pests such as pigeons and therefore retained more leaf than other areas of the field, or it could be a more fertile area of soil. This anomaly could only be explained by the higher resolution archaeological data (geophysical data and drone imagery) and archaeological interpretation of the site. This area of high NDVI was created due to archaeological pits and ditches causing positive crop marks, the close grouping of these pits and ditches not being definable in the resolution of the satellite image, hence multiple smaller anomalies became one larger anomaly in the PF data. Being able to identify this would help a farmer/PF specialist rule out other less likely scenarios such as pests or weeds.

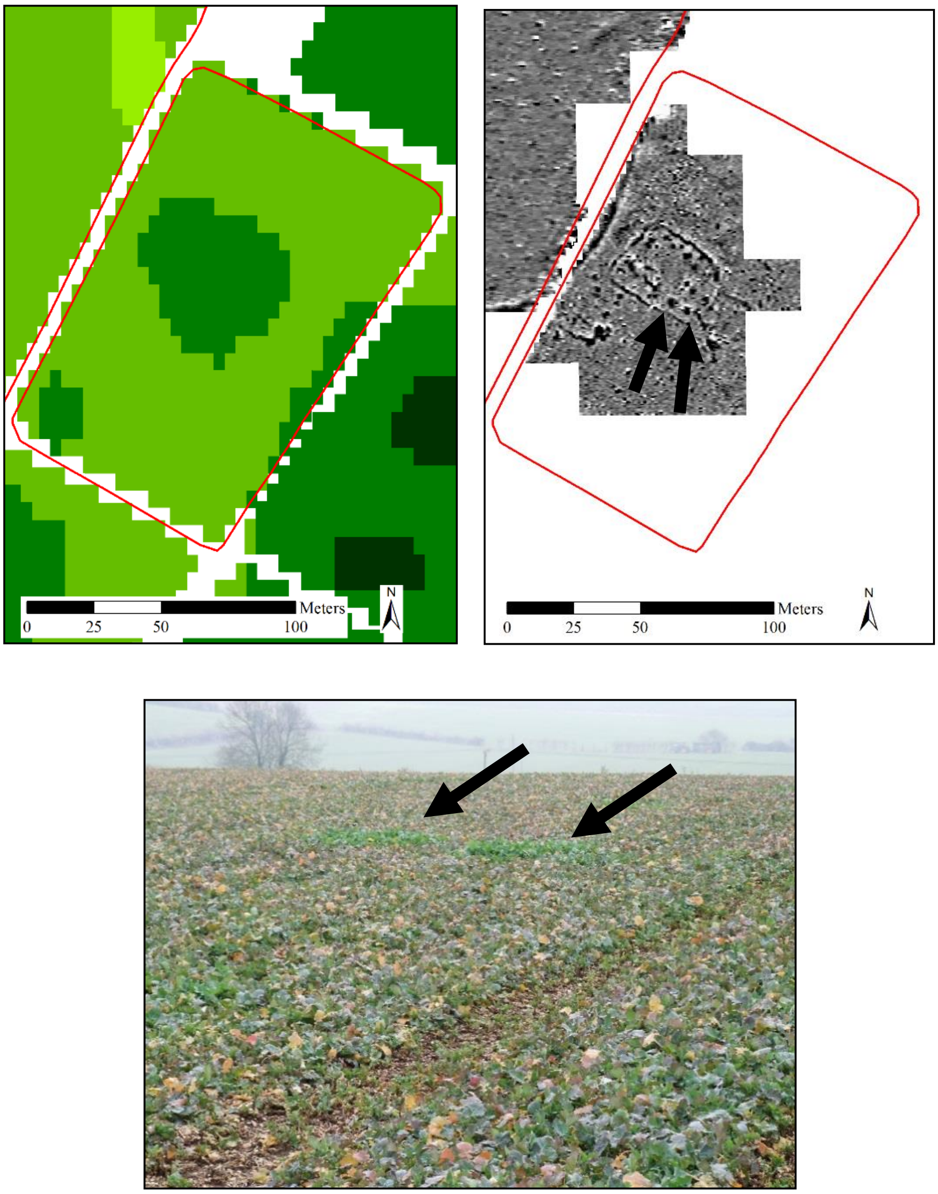


Figure 158: Myncen: NDVI image from a satellite (top left), magnetic data (top right), and photograph of the field, with arrows marking archaeological pits (data courtesy of IPF UK, Bournemouth University) (© author)

Following crop growth stages, the final part of a crop recorded is the yield. Yield maps were only present at two of the case study sites, however both of them show that anthropogenic impacts can cause variable yields in relation to other parts of the field. Broadly yield changes are positive, and this is because of the numerous ditch features at both sites (Wilsford and Perdiswell) as well as nutrient variations (Perdiswell). Yield variability is important for nutrient management because higher yielding crops take away more nutrients than lower yielding crops. In nutrient management guidance this can be seen by recommendations to increase fertiliser applications on fields that yield higher than average (AHDB, 2017). Therefore anthropogenic impacts on crop growth can affect the yield of those crops, both positively and negatively (for example stone walls), and the necessary nutrients necessary the following year to replace those taken away with the crop.

9.2.7 Concluding Remarks

Elements most commonly linked to anthropogenic activity across the three case study sites were P, Pb, Zn. These elemental associations were mostly positive enhancements, showing that in the majority of cases anthropogenic activity increases the elemental content of soils via various processes. In some cases anthropogenic activity does not directly relate to the elements enhanced or depleted, but are indirect effects of activity such as the natural filling in of a ditch. The wide variety of archaeological features that have contributed to the geochemical anomalies in the soils is demonstrated, from a Neolithic henge to a 20th century trackway. This shows how the soil is a repository for evidence of human actions whether those actions were thousands of years ago, or 50 years ago.

By studying the cases study fields as a whole, elemental distributions (whether they do or don’t correlate with plant-available nutrients) contribute relevant information to PF methods for soil sampling, for fertiliser application and for fertiliser choice. They also more widely apply to soil management in general with regards to the future contamination of soils. This field-based approach allows archaeological sites to be situated better within their geographical context, as well as provide possibilities to discover unknown, or extensions of, archaeological sites through crop and soil analysis.

9.3 Which Archaeological Data Have Most Potential to be Integrated Within a PF System and *Vice Versa*?

Having brought together the evidence on the similarities and differences between archaeological and PF approaches, along with how archaeological sites themselves impact soils and crops from the case study results, where is there scope for better integration between these approaches and datasets? To do this account must be taken of the various factors that may affect a method’s ‘potential’, including current skills, accessibility of data, commercial value of such data, spatial availability of the data and the level of detailed interpretation necessary. These can all impact the ‘potential’ for cross-over but the aim is to help suggest where the most likely synergies lie between archaeology and PF.

9.3.1 Integrating Archaeological Data into the PF System

The key piece of data that underpins archaeological approaches at each of the three case study sites is geophysical data. There are a wide number of geophysical techniques used in archaeological applications (Section 3.1.5) but the most common, as shown in this research, is magnetic gradiometry (both fluxgate and caesium vapour-based gradiometers).

The potential for integration within in a PF context is quite high. Surveys are often large scale, at the agricultural field scale, and are increasingly becoming motorized in cart systems to improve data collection speeds (B. Urmston, pers. comm.). Magnetic gradiomatery, used by archaeologists for decades and is well known to provide spatial data for understanding archaeological sites, could provide another layer of data within the PF system, especially for the soil zoning process, or for enhancing the accuracy of crop mark interpretations. Interestingly the difference in the sensitivity of the caesium vapour-based system used at Wilsford (compared to the fluxgate sensors used at Myncen and Perdiswell) allowed not only archaeological anomalies to be identified, but also soil changes affecting the magnetic background of the survey. Hence this allowed far more detailed comparison of where soil types changed in comparison with other data. The two fluxgate surveys did not show broader soil type changes across the fields (other than very subtle and hardly identifiable variations at Perdiswell), mainly highlighting the archaeological anomalies.

This type of data is common across the UK, with thousands of hectares already collected, analysed and interpreted, making it relevant on a PF scale. Yet while much magnetic data exists, it is hindered by the absence of ‘national mapping programme’ for geophysical data as there is within aerial mapping programmes (http://nsgg.org.uk/meetings/old/nsgg2012/abstracts_2012.pdf accessed on 05/05/19), making it difficult to utilise these existing data. Due to no central repository, the publication of a survey report can be difficult to find or get hold of, and the actual physical data can be even harder to get hold of. For example at Myncen the survey data was not available from the researchers who did the survey and instead only an image of it was available, which for the purposes of this research was less accurate and flexible for data analysis than the actual data, although not unworkable.

PF specialists and farmers, having not experienced these datasets as much as archaeologists, do not have the same level of skill to interpret these datasets. Therefore a key blocker to use of geophysical data by PF is the expert analysis and interpretation (whether that is magnetic or any type of geophysical technique not normally used in PF) required. To achieve better use of geophysical datasets across archaeology and PF, joint approaches would be needed between disciplines, and even commercial companies, to access, share and interpret the data accurately.

At each case study site, the usefulness of HER data was tested amongst other datasets collated at each site. The results show that their usefulness ultimately depends on the level of detail that they contain. At Myncen for example the usefulness at an individual field level is limited due it comprising of point-based information with little spatial definition. Yet at Wilsford, with polygonised datasets including interpretations from aerial photography (and in the future combined with geophysical interpretations), HER data could help improve soil zoning processes by allowing PF specialists and farmers to assess those areas separately. Perdiswell sits in between both extremes, with only point-based information limiting use at the field scale, but when taken at the farm scale, can help locate areas of archaeological activity.

These datasets are easily interoperable with PF systems (especially commercially-based systems rather than individual farmers) because of their digital format and ability to be input into GIS systems for overlaying and analysing along with other data. They are interpreted to a certain level of accuracy by historic environment specialists, removing the need for farmers or PF specialists to gain new skills like those needed in interpreting geophysical data, although there may still be a skills gap in the ability to turn HER data into an interpretation of what types of HER data might impact on PF processes. Despite this, as an initial look at the archaeological activity in an area, they represent a very valuable resource that should be researched further. They are also the hub for information about the historic environment that is used in the processing applications for agri-environment schemes across England as part of the Common Agricultural Policy within the EU. Hence for certain stewardship agreements, farms would need to have a Farm Environment Map with known historic features on their land, and if chosen, features that could have management options applied to them under the scheme in return for funding. The Selected Heritage Inventory (SHINE) database already has assessed archaeological sites and monuments in agricultural areas that could benefit from better agricultural management and this represents a nationally comprehensive dataset that could form the basis of future research in this area in connection with PF.

Historic OS mapping could have potential within PF systems. It is a nationally consistent dataset providing information from the 1880s across England. It is not usually included in HER datasets, which is possibly because OS surveys run up until the present and are considered less important from a historic environment perspective. Regardless, historic mapping has been shown in two out of the three case study sites to be valuable for identifying archaeological features relating to the past century and a half and at that have caused significant geochemical variation in the topsoils, especially at Perdiswell. As with other datasets they are already centrally accessible, and in the correct digital format, the interoperability within PF systems could be simple to achieve and help to correlate soil zoning accurately to previous field boundaries within the time range of the OS maps (with geophysical survey or aerial techniques necessary for older boundaries).

The other archaeological methods for surveying buried archaeological sites comprise of excavations, soil coring and geochemical surveying. All of which are seen as less likely to have potential for integration with PF. Although on an individual field basis, if these datasets existed, they could be helpful in assessing the depth of soils across a field for example, or for looking at the spatial and vertical variation in soil nutrients perhaps, often these datasets are more limited in the spatial extent and resolution, and are also less common practice in archaeological investigations.

The more data that can be gathered about an archaeological site, the better, and therefore the above methods are not the only ones to have value for assessing the archaeology within a field or area. If for example a DBA is available for a site then this may package many of these methods into one report. This might make it easier for a PF specialist or farmer to read through, but less able to include within the digital process of mapping soil variations digitally. The above paragraphs, however, represent the most likely to occur, and the most likely on a larger scale to have impacts, relative to the effort and ability to collect the data, on the PF community.

9.3.2 Integrating PF data into Archaeological Investigations

In general the results show that across all sites, the ability for PF approaches to help understand the archaeological landscape is relatively low. The majority of PF data is collected on a scale to be cost-effective for larger areas, this mostly reduces the resolution available and this is key for archaeological investigations, with the ability to define shapes and distributions of anomalies essential for archaeological interpretation.

Yet this is not true of all datasets, and it is also not true in all archaeological investigations and may depend on the level of existing archaeological knowledge that already exists. For example if there was no archaeological data on an area, and it was perhaps a larger area covering multiple fields, then a number of PF datasets could be useful to identify broadly different areas of soils. This could be done by looking at multiple satellite images of crop growth across different years that might highlight consistent patterns of poor or well performing crops. This could even be at a low resolution and still provide indications of variabilities (examples from the case study sites are the Wilsford henge itself and the Iron Age enclosure at Myncen).

In a similar approach farm nutrient maps could also provide valuable information about where nutrients are concentrated across the farm, and in relation to the geology. Then areas of, for example, high available P could be targeted for further investigation as a reasonably consistent indicator of archaeological activity. As seen in Figure 151 the resolution of those nutrient maps depends completely on the sampling design, with zone sampling useful only so far as the zones incorporate archaeological features. On the other hand, nutrient maps such as the grid sampled P map from Perdiswell Farm shows a very good correlation to the much higher resolution sampling for pXRF analysis and can clearly relate to the outline of the Roman villa and the other areas of activity.

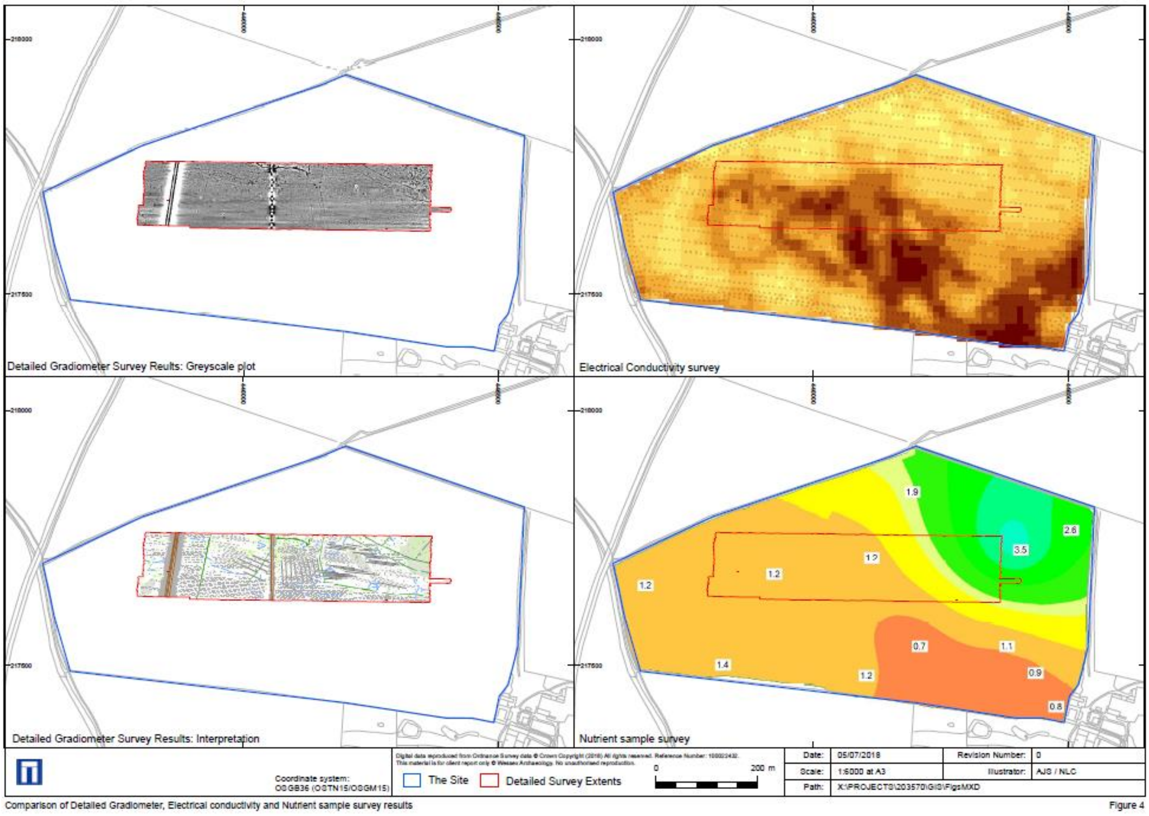


Figure 159: Comparison between magnetic gradiometer data (top left), PF conductivity data (top right), archaeological interpretation (bottom left) and PF plant-available P data (bottom right) at Perdiswell Farm, Prairie Field (© Wessex Archaeology)

The geophysical data collected in PF systems, although not represented in the three main case studies, is demonstrated in Figure 159 which is an example from a second field at Perdiswell Farm produced in collaboration with Wessex Archaeology. From this one example it is possible to see a direct comparison between a conductivity survey by a PF company at a low resolution (20m) and an archaeological resolution fluxgate magnetic gradiometer survey. Not only can the two images show the difference between the two methods and resolutions (which identifies many archaeological anomalies that are of probably Iron Age or Roman in date), but also how this relates to a PF nutrient map of available P, with high P relating to an area enclosed by a double ditch and numerous pit features. This reinforces the ideas that archaeological geophysics can allow identification of defined and diffuse areas which have varying nutrient levels and which can impact the understanding of PF data.

In addition to satellite data and nutrient maps, the other fairly common dataset on farms today who practice PF is yield data. Yield maps at both Wilsford and Perdiswell do exhibit effects of archaeological features, often only the more major archaeological features such as the Neolithic henge. The usefulness of this is limited in an archaeological sense, and does enable some assessment of parts of the field that respond differently to others. However, with knowledge that the henge does exist, the yield data does not add any more detail due to the resolution and accuracy of the yield data. Therefore only serve as indicators along with satellite data and nutrient data, that once combined all together and over multiple years, could provide some useful information on the soil and crop variability across the field.

9.3.3 Dual Use Data

Throughout this research many types of data have been assessed to question how useful these are in answering archaeological or agricultural questions. It is clear that some datasets are not just archaeological in nature, nor PF in nature, but both. When this occurs the same data might have totally different interpretations depending on the context it is being evaluated in.

Aerial imagery of all varieties, whether collected by drone, light aircraft, balloon, or satellite, are captured moments of a landscape. Although a survey might focus on producing one particular interpretation of a field, inherently surveys collect unintended information about other aspects of a landscape useful for different uses to different people. It is this objectivity in a captured image, plus the accessibility and availability of technology to capture the data, that has allowed people from both archaeological and agricultural backgrounds, academic and commercial, and even the general public, to be able to analyse within field variability of soils, crop patterns and landscapes in the same datasets.

The dual nature of these types of dual data show overlaps in various people’s interpretation, depending on what they are looking for from the data. Farmers might only be interested in the management of the crop, a PF specialist might only be interested in within-field variability of the soils, whereas an archaeologist will be looking for characteristic cropmarks or old field boundaries. All three use similar skills and draw on experience of pattern recognition and understanding of crop growth and management. Yet there are gaps in these skills and experiences that appear when more complex or ephemeral variations appear. A Roman villa in the middle of a field may be quite apparent to farmers and archaeologists alike, however a spread of Iron Age pits or rounded enclosure might be more difficult to interpret amongst the other crop and soil factors. Similarly what might appear to be an archaeological feature could actually be a feature caused by the effects of agricultural spraying, or fertiliser application overlaps. Figure 160 shows the square enclosure NE of the Wilsford henge that was fully outlined as a result of this research. The agricultural tramlines can be seen clearly, as well as the modern footpath, and some areas of high NDRE values running in-between the tramlines. This is caused by overlap of N fertiliser being spread by a disc spreader and happens to align with the orientation of two sides of the square enclosure, making it only visible by the corners and perpendicular sides.

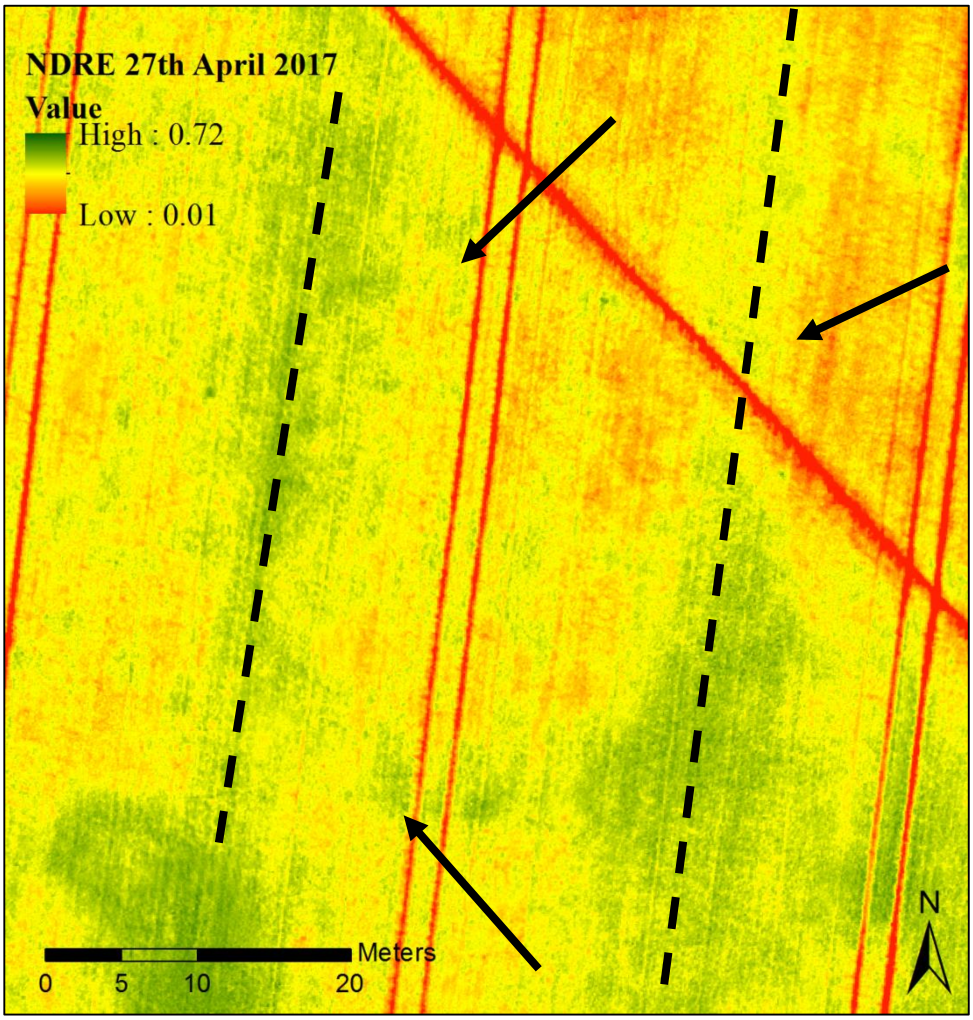


Figure 160: NDRE image of the square enclosure at Wilsford (arrows identifying its extent), compared with agricultural overlap in fertilisers (dashed line) (© author)

Increasingly the interpretation of data is becoming a significant problem due to vast data collection, especially with respect to large amounts of drone or satellite data within PF, and the costly and time consuming human interpretation of that data. In the PF world, companies are now researching the possibilities for AI and machine learning algorithms to automate detection of crop stress, weeds, diseases, or nutrient management decisions (for example Hummingbird Technologies) and integrate this with data from the whole agricultural supply chain (https://www.iof2020.eu/blog/2019/04/artificial-intelligence-for-digital-precision-agriculture accessed on 12/11/19). Similar approaches are also being developed in archaeological situations (I. Kramer, pers. comm.) to speed up the detection of archaeological shapes within large and multi-technique datasets.

It is not only a question of how to interpret these vast datasets, but whether they should be collated and used, or whether they just represent more data for the sake of it. Within archaeological research there has often been concerns over ‘collecting stamps’ rather than understanding and targeting methods that will give the most accurate and economic results (Gaffney 2008). From the case study results it is clear that some of the larger and more frequent datasets collected within PF systems are not as immediately useful for many types of archaeological questioning. Yet they do represent valuable information in certain use cases (finding new sites, confirming existing features effects on the soil/crop). Crucially, in the case of PF and archaeology, this data has already been collected, or will continue to be collected regardless of archaeological questioning or not. As digital approaches have been integrated into many parts of modern life, archaeologists will need to understand and deal with increasingly large, multi-technique and re-interpretable data, working with other disciplines to learn where data can contribute to archaeological questions and where it cannot (Bevan, 2015; Opitz and Limp, 2015).

9.3.4 Concluding Remarks

Depending on the questions being asked, both archaeological data and PF data can be mutually beneficial to archaeological investigations and PF methods. If approaching a farm scale analysis of soils then HER data, historic mapping and even grey literature could be valuable to a PF specialist with the correct advice. Yet on a field scale it might be geophysical data, or drone data that would be of most benefit. For assessing small archaeological sites, high resolution data (such as drone or <5m resolutions satellite imagery) is needed, while larger archaeological sites could benefit from a variety of lower resolution agricultural data. It will be key to ensure that future work builds on utilising existing datasets and being able to integrate them effectively, whether for archaeological or PF processes.

Chapter 10

10 Conclusions

10.1 Future Soil and Heritage Management

Current trends in agricultural soil management are shifting due to better understanding of the impacts of intensive agriculture on soils, and the climate more widely, in the UK and globally. These shifts are towards practices that improve soil health, reduce the use of artificial fertilisers and chemicals, while maintaining productivity (Defra, 2018a). PF is seen as a key tool to meet some of these objectives, from a practical as well as a policy perspective.

Reducing artificial fertiliser use is a core deliverable of PF, by sampling soil nutrients in more detail and providing better long term monitoring of those nutrients over the crop rotation, it allows fertiliser applications to be reduced or targeted to maximise productivity (whether based on yield or environmental targets). This research has demonstrated how archaeological sites impact soil nutrients, especially plant-available nutrients, at scales relevant for farmers to manage with current equipment. With the UK's rich archaeological heritage, this could have a significant impact on farms across the country, saving costs to the farmer as well as benefitting the wider environment, while getting the agricultural community to engage with archaeological heritage itself.

Agricultural trial plots and experiments, whether for new varieties of plants, particular growth traits, or responses to fertilisers, agrochemicals or other management, develop the scientific basis for agricultural improvements. When techniques or recommended practices are applied in the environment, the results can be somewhat more complicated and soil variability is one such complication. At Perdiswell, archaeological features impact on soil variability but have not been taken into account when planning those trials. Depending on the trial, the background soil variability, and the archaeological features, the impact on the trial may vary, yet if no consideration is given to archaeology then no impact could be attributed. How many agricultural trials could be affected by archaeological features? This research has only touched the surface of this issue which could impact upon how agricultural trial sites are placed, how valid historic trials are (see Figure 161 for a further example) and how trials are analysed in the future.

Figure 161: Google Earth image of 'Hoosfield' at Rothamsted Research (UK), a long term field experiment started in 1852, with an arrow pointing to a scheduled Roman mausoleum (© Google)

The decline in soil OM is a significant challenge for intensive agriculture (Kibblewhite *et al.*, 2008; Defra, 2018c). One of the main causes of this is the introduction of artificial N fertilisers coupled with a simultaneous decline in carbon inputs through higher yielding crops and a lack of organically composed fertilisers (Kibblewhite *et al.*, 2008; Mulvaney *et al.*, 2009). To counter this, the simple approach is to increase the amount of organic carbon through widespread use of traditional fertilisers like animal manures, and recycled organic wastes (composts, digestates and sludges) as demonstrated by part of the EU's Circular Economy package (https://ec.europa.eu/commission/presscorner/detail/en/IP_18_6161 accessed on 12/11/19). While improving soil OM, evidence from this research shows how over longer time periods, these approaches can have unintended consequences on other soil factors such as heavy metal content. The historic use of manuring and using organic wastes, for example at Perdsiwell and Myncen Farms, have meant that soil levels of Zn, Pb, Cr and As are approaching, and in some cases exceed, maximum levels already. Therefore while potentially improving OM contents, it could be detrimental to levels of PTEs. Hence archaeological evidence can be used both at a practical level, in understanding the variation that exists within soils due to past management, as well as contribute to future policy development on improving soil health sustainably.

The cultivation impacts on archaeological sites have not been discussed at great length in this work, in part because some of the damaging effects from cultivation as well as other agricultural management has been dealt with in other research (Darvill and Wainwright, 1994; Oxford Archaeology, 2002; Trow *et al.*, 2007; Trow, 2010). Currently arable cultivation, especially inversion cultivations by ploughing, is still the number one threat to the survival or buried archaeological deposits. So what sorts of PF approaches, if any, can contribute towards better management of the archaeological sites?

An example of research in Saxony-Anhalt, Germany, displays how PF technology has been used to variably control the depth of cultivation over historic sites (M. Strobel, pers. comm.). This work input archaeological zones into tractor-based computer software so that when the farmer cultivates the field, the tractor lifts the implement above a certain depth over a certain archaeological zone. The project, which began in 2017, was successful in integrating archaeological zones into PF software and hardware. The difficulty in applying this more widely was in distributing knowledge and making it easy for farmers to carry out as part of their normal operations.

The benefits of this are clear in theory, however in practice there are a number of issues foreseen in application in the UK. Firstly this approach relies on farmers having this type of modified equipment (with only one current commercial provider in the UK - https://www.soyl.com/services/variable-depth-cultivation accessed 12/11/19) and for that type of equipment to be used across the whole farm. In practice many different types of cultivating equipment are used depending on the conditions and the need for cultivation, from ploughs to subsoilers, to tined disks and direct drills with subsoiler legs. Thus depth control is not always as simple, and fitting the equipment is likely to take time if across different cultivators. Yet in the future, with the economic drivers to reduce fuel usage and save costs, the technique may become more popular. The second issue is that it still leads to the cultivation of sensitive archaeological sites, which may not be the most advised approach for that particular site as a result of any advice (COSMIC risk assessment for example).

While PF systems do not lead to a change in the types of crop grown, or the cultivations used (which are part of wider farm management) there are other possibilities for PF to contribute to heritage management. The identification of unknown sites, or unknown features adding to existing knowledge about sites, has been shown within the case studies (albeit relating to only a few types of high resolution data). It promotes the idea that with the massive temporal increase in data (Figure 152), some being high resolution and some low, PF could aid the prospection of archaeological sites. The contribution of mapping unknown sites in general has not been widely recognised within heritage policy, especially policy interconnected with the CAP. Yet in the future, it could be a requirement that farmers who receive subsidies, whether for managing land or for achieving certain environmental objectives, should share PF data for enhancing the archaeological record – a cultural and environmental ‘public good’ (The Heritage Alliance, 2017).

The other benefit of integrating PF and archaeology is in providing another pathway for engaging farmers, land managers, specialists and even governments, on managing the historic environment. Shifting the focus from the restriction of farming activities over archaeological sites, towards the better understanding of that archaeological site and how it interacts with what farmers do on a daily basis – grow crops and manage soils. This approach feeds back into the accuracy and development of the PF system, where an archaeological site is discovered, it can add to the archaeological record, but also aid target soil nutrients more accurately to reduce fertiliser use.

This research should be placed within a growing context of ‘applied archaeology’ (Isendahl and Stump, 2019b). Across a number of different sub-disciplines over the past few decades, researchers have looked at how archaeological evidence can be used to help learn from past events or situations and inform future decisions surrounding land management. While this research furthers some of these ideas, it is also different in approach. It follows a wider methodological approach for utilising archaeological evidence of many varieties, of different time periods, and in different places, rather than narrower situational comparisons such as the re-evaluation of traditional agricultural and water management systems (Caponetti, 2019; Isendahl and Stump, 2019a). It is inherently more spatial, and relies on the distribution of archaeological sites throughout the landscape, it is equally more applicable to a far wider area of land, both ‘traditionally’ managed as well as managed via more westernised developed systems of PF itself, the same principles still apply. Although this research has a UK focus, with the development of PF internationally arguments focusing on the anthropogenic impacts on soils, and their influence on crops and agricultural management, apply globally.

10.2 Critique of the Study

This research, while demonstrating many interesting points surrounding human impacts on soils in relation to modern digital agriculture using a wide range of evidence from multiple datasets, was not without its challenges.

The availability and raw format of data was a particular issue throughout this research. This was caused by the aim to, as far as possible, make use of existing data. In many cases the original data was not available, through deletion of raw files, inaccessible repositories due to cancelled subscriptions to PF services, or people being uncontactable to ask for original data. This then meant that data had to be used in whatever format it was available in, relying sometimes on poorly georeferenced geophysical data (Myncen Farm) or low resolution scanned images of paper soil nutrient maps (Perdiswell). These problems can limit the further analysis of some of these data sets in comparison to other higher quality data and is a factor for future consideration in any larger scale work.

Although the case study selection aimed at a mixture of archaeological and PF methods as well as a mixture of archaeological site types, geologies and farm background, there is a limit to what can be covered in one thesis. The chosen sites represented generally a single type of calcium carbonate-rich geology. While in some respects this is useful for comparing like geologies together, there is argument that none of the sites would be directly comparable due to varying farm and archaeological backgrounds. Therefore a broader mix of geologies might lead to a broader understanding of whether PF data collection strategies have greater impact on deeper soils or on clay geologies for example. In these landscapes aerial photography can have more variable results and this leads into questioning whether multispectral and hyperspectral imaging techniques might benefit archaeological site detection in those landscapes or not.

The sampling and analysis completed as part of the fieldwork have focused on the chemical and physical content of the soils in some depth (especially elemental concentration). Yet the biological variability of soils has not been considered in as much detail. Although mentioned in a few places in relation to the OM content of soils, no fieldwork analysis has been done to assess how this varies over the various soil types in each case study site and in relation to archaeological features. This could be important due to the impacts human activities can have on the build-up of OM (as is demonstrated visually in the Wilsford henge ditch, and spatially at Perdiswell from RGB satellite imagery).

The pXRF analysis of soils has been used as a fundamental dataset for comparing both agricultural analysis of soils, and the chemical remains of anthropogenic activity soils. This analysis has provided a number of benefits. The multi-element aspect makes comparison of concentrations between different elements easy, allows PCA to identify major elemental groups objectively, needs little sample preparation time, requires no other laboratory materials (for example digestion agents), is fast and can be done in the field. As to its limitations, this research has identified that pXRF analysis is affected greatly by moisture content of the soils being analysed. With a 60% reduction in concentration of some elements due to samples being at field level soil moisture, it is less useful for using in the field. Especially if analysis is done during winter (when soil moisture is high) and if looking for elements of a lighter atomic mass such as P in comparison to heavy metals.

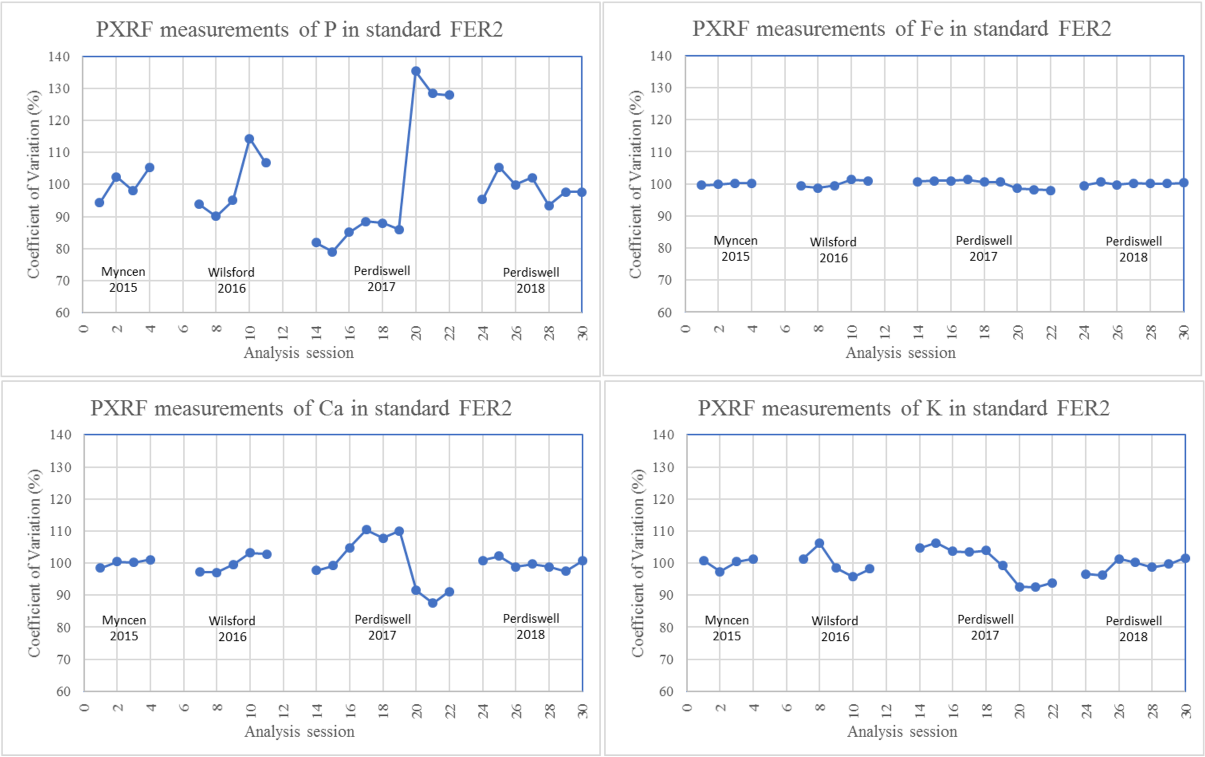


Figure 162 Set of graphs displaying the stability of the PXRF in measuring 4 different elements from the same reference standard over multiple analysis sessions (© author)

The other important factor is the stability of the instrument over time. In Chapter 5, it was mentioned that the stability of the pXRF should be checked regularly through the analysis of reference standards to ensure consistency across the datasets collected. Figure 162 shows the results of this testing for 25 analysis sessions over four years. During the analysis of the Perdiswell samples in 2017, something changed which drastically increased the P values, but decreased other values in Ca, K and Fe. This was noticed and rectified by sending the pXRF for recalibration, and re-testing all the Perdiswell samples to provide a consistent dataset across that field. For this research consistency within each field was critical, whereas quantitative differences between fields would vary anyway and comparisons were not being made on that basis. This highlights the importance of checking reference standards regularly, and that if consistency is necessary over long periods of time, then other methods might be more appropriate.

The other key analysis within my methodology was the PCA of the large multi-elemental dataset produced by the pXRF. While PCA is often used to achieve a dimension reduction in multi-factorial datasets, the limitations described in Section 5.5.1 have to be considered. It's use in this research has therefore been focused on identifying major groupings, and really only considering those components that explain the largest amount of variance in the dataset. It has, however, been demonstrated as a very useful technique, especially in connection with the pXRF data, for identifying major soil boundaries both vertically and horizontally.

Both of the above analyses are totally dependent on the quality and consistency of the sampling design. The effectiveness of the systematic and semi-systematic approaches have proved successful. The spatial mapping of elemental distributions has shown archaeological variations of a number of different sizes, as well as displaying how relevant these are for PF methods. The flexibility to take samples in certain locations, or from certain soil horizons, was essential to provide key information about archaeological deposits.

10.3 Impact of this Research

At the outset of this research, a core objective was to promote mutual understanding and dialogue between various archaeological and agricultural communities. As part of this, it was intended that the case studies should provide powerful ways to communicate these ideas to those various communities.

By presenting initial research results at the 2016 conference of the International Society for Precision Agriculture in the US, I was contacted by the co-founder of MicaSense who became so interested in my work that a Red Edge camera was leant to me for use in this research. This collaboration resulted in a blog article being published which drew international interest about the use of multispectral imagery for archaeological applications (https://blog.micasense.com/archaeological-surveys-with-drone-mapping-563ac0329208 accessed on 04/11/19).

In 2017, the acceptance of a paper, ‘Precision farming and archaeology’, in the *Journal of Archaeological and Anthropological Sciences* (Webber *et al*., 2019) presented an introduction to this research topic and some of these case study sites.

As a result of working with a PF company, remote sensing specialists, farmers, agronomists, soil specialists, archaeologists and heritage managers, this research has been influenced both on a practical level, as well as on a scientific level. This diverse approach has meant I have presented to groups of heritage mangers (Heritage At Risk Team within Historic England), policy teams (the European Association of Archaeologists Working Group on Farming, Forestry and Rural Land Management), farmers and agronomists (Agri-Tech East 2019, International Fertiliser Society Conference 2019).

Academically, this research has already promoted interest in PF within other research projects, focusing around data sharing and integration of archaeology with agricultural communities (R. Opitz pers. comm.), integrated multispectral, hyperspectral and soil analysis for archaeological sites (N. Crabb, pers. comm.), integrating geophysical, geochemical and remote sensing data in archaeological surveys (H. McCreary, pers. comm.).

10.4 Future Research

This research is the first attempt at taking a holistic site-based approach towards integrating multiple types of archaeological and PF data together. It has therefore covered a wide variety of technologies and methodological techniques but as is usually the case, has not been able to fully answer all of the questions raised. Nor tackle some of the wider implications in more detail. Some suggestions for further research are:

- the use of PF-based conductivity scans for archaeological investigations.
- analysis of existing topographic and soil sensing data from tractor mounted implements (TopSoil Mapper, RTK GNSS data from agricultural vehicles) for archaeological investigations.
- the value of using pXRF analysis of soils more widely within agronomy and PF approaches.

- studying nutrient pathways, including cycling of archaeologically derived elements in the soil, from the soil through into the crop and food produced over archaeological sites.

This study has focused on three case study fields to provide an in-depth analysis of all of the datasets available and further work to correlate them together with systematic soil sampling and coring. Yet many of the PF datasets are low resolution and results in this research indicate that they may be of more value archaeologically if applied on a larger scale. Further research should consider taking this approach, or working with specific datasets (for example HER data or farm nutrient maps) to explore farm or larger regional scales of analysis. This may include testing over different geologies, since a limitation of this research has been the variation in geological parent material, as well as different farm types and archaeological site types.

It is clear from the results of this thesis, that data ownership, data access and data sharing aspects are a key consideration in any future use or work involving both archaeological and PF data. The mixed commercial nature of many datasets, the need for protection over certain types of data (such as sensitive archaeological sites) and the choices of individual landowners or farmers could make wider application of large agricultural or archaeological datasets problematic if not considered early on in any proposed work. This stands for both large organised projects as well as small individual community led investigations that might be aware of PF data.

This research has only briefly touched on the full impact of PF on the management of the historic environment. The focus within this thesis has been on the prospection of archaeological sites and the overarching framework of PF data in relation to archaeological sites. There has, however, been work in other countries (Germany) relating to the use of PF systems to implement better ways to protect and conserve the historic environment by automatically varying the depth of cultivation. While this is not common in the UK, may become so in the future and it would be beneficial for awareness to be raised and evidence gathered, to determine whether this was feasible and effective within the UK. In addition, PF systems could represent other ways of managing the historic environment through PF software, future agri-environment schemes and provision of data for monitoring archaeological sites.

10.5 Concluding Comments

The study of Precision Farming and archaeology, a contribution to the future as well as an understanding of the past, offers a number of new perspectives on heritage management and the future of agricultural soils. This research has drawn together a vast array of different types of evidence that demonstrate how interconnected the two are.

It has not only identified practical benefits that might help farmers manage soils and crops in the future, but importantly situates the study of archaeology within future agricultural and environmental policy (Figure 163). Rarely does archaeology have the ability to contribute to debates surrounding agricultural productivity, crop nutrition (field to fork approach), soil health, soil contamination, and digital agronomy. At a time when heritage management can be dwarfed by the multitude of other policy areas involved in the ecosystem services approach, it is vital for archaeology to demonstrate its value for society and the environment.

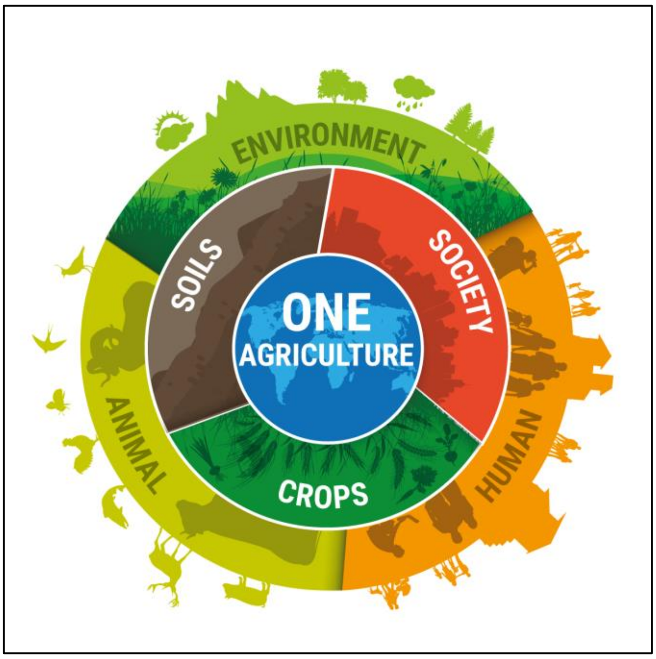


Figure 163: Diagram of 'One Agriculture', the theme of the 2019 Agri-Tech East conference, striving to find integrated solutions to challenges that face agriculture (© Agri-Tech East)

It is important to recognise the value of discovery in both policy and practice surrounding archaeology and Precision Farming. This thesis proposes new ways to engage farmers by discovering unknown archaeological sites and understanding how those archaeological sites impact their crops and soils through Precision Farming data. This is not about whether an impact is positive or negative, it is about managing resources (natural and cultural) intelligently using technology to make it easier. The inevitable increase of agricultural automation, artificial intelligence and computing power will open up opportunities to manage archaeological sites in new ways in the future.

From a policy perspective, current government schemes and agricultural subsidies do not recognise the value of discovering archaeological sites on agricultural land, nor that this may aid other government objectives relating to agriculture and the environment. In the future, there is opportunity to develop better understanding of archaeological heritage while contributing to sustainable land management.

It is hoped that this thesis has provided the first step towards integrating archaeology with Precision Farming, and the future challenges facing agriculture, the environment and society more broadly.

11 Bibliography

Adão, T., Hruška, J., Pádua, L., Bessa, J., Peres, E., Morais, R. and Sousa, J. J. (2017). 'Hyperspectral imaging: A review on UAV-based sensors, data processing and applications for agriculture and forestry'. *Remote Sensing*, 9(11). doi: 10.3390/rs9111110.

ADAS (2018). Guide To Farmers' Crop Trials [online]. Available from https://www.adas.uk/News/guide-to-farmers-crop-trials-released [accessed on 15 July 2019].

Addicott, J. (2016). '*The Computerisation of Agriculture : Social Power , Technology and Control'*. Unpublished PhD thesis. University of Cambridge.

AHDB (2013a). Micronutrients for cereals and oilseed rape [online], Information Sheet, 25. Available from https://cereals.ahdb.org.uk/media/246401/is25micronutrients_autumn_2013.pdf [accessed on 02 February 2019].

AHDB (2013b). Precision Farming – Does it pay ? [online]. Available from https://horticulture.ahdb.org.uk/publication/precision-farming-%E2%80%93-does-it-pay-workbook [accessed on 27 January 2015]

AHDB (2017). 'Nutrient Management Guide RB209' [online]. Available at: https://ahdb.org.uk/projects/RB209.aspx [accessed 5 January 2019].

Aqdus, S. A., Hanson, W. S., and Drummond, J. (2012). 'The potential of hyperspectral and multi-spectral imagery to enhance archaeological cropmark detection: a comparative study'. *Journal of Archaeological Science*. 39 (1915-1924). doi:10.1016/j.jas.2012.01.034

Albani, D., Ijsselmuiden, J., Haken, R. and Trianni, V. (2017). 'Monitoring and mapping with robot swarms for agricultural applications'. In 14th Institute of Electrical and Electronics Engineers International Conference on Advanced Video and Signal Based Surveillance 2017 in Lecce, Italy. doi: 10.1109/AVSS.2017.8078478.

Allen, J. R. L. and Kaye: p. (1973). 'Sedimentary facies of the Forest Marble (Bathonian), Shipton-on-Cherwell Quarry, Oxfordshire'. *Geological Magazine*, 110 (2): 153-163. doi: 10.1017/S0016756800047890.

Alloway, B. J. (2009). 'Soil factors associated with zinc deficiency in crops and humans'. *Environmental Geochemistry and Health*, 31(5): 537-548. doi: 10.1007/s10653-009-9255-4.

Allred, B. J., Daniels, J. J. and Ehsani, M. R. (2008). *Handbook of Agricultural Geophysics*. London: CRC Press, Taylor and Francis Group.

Arranz-Otaegui, A., Gonzalez Carretero, L., Ramsey, M. N., Fuller, D. Q. and Richter, T. (2018). 'Archaeobotanical evidence reveals the origins of bread 14,400 years ago in northeastern Jordan'. *Proceedings of the National Academy of Sciences*, 115(31): 7925–7930. doi: 10.1073/pnas.1801071115.

Arroyo-Kalin, M. (2010). 'The Amazonian formative: Crop domestication and anthropogenic soils'. *Diversity*, 2(4): 473–504. doi: 10.3390/d2040473.

Aston, M. A. and Rowley, T. (1974). *Landscape Archaeology: An Introduction to Fieldwork Techniques on Post-Roman Landscapes*. Newton Abbot: David and Charles.

Aston, M. A., Martin, M. H. and Jackson, A. W. (1998). 'The potential for heavy metal soil analysis on low status archaeological sites at Shapwick , Somerset'. *Antiquity*, 72: 838–847.

Avery, B. W. (1990). *Soils of the British Isles*. Wallingford: C.A. B International.

Awan, S. (2016). 'A review of the past , present and future of precision agriculture in the UK' [online]. AHDB Research Review 87. Available from https://cereals.ahdb.org.uk/publications/2016/september/14/a-review-of-the-past,-present-and-future-of-precision-agriculture-in-the-uk.aspx [accessed on 4 February 2019].

Bakels, G. C. (1997). 'The beginnings of manuring in western Europe'. *Antiquity*, 71: 442–445. doi: 10.1017/S0003598X00085057.

Balafoutis, A., Beck, B., Fountas, S., Vangeyte, J., Van Der Wal, T., Soto, I., Gómez-Barbero, M., Barnes, A. and Eory, V. (2017). 'Precision agriculture technologies positively contributing to ghg emissions mitigation, farm productivity and economics'. *Sustainability*, 9(8): 1–28. doi: 10.3390/su9081339.

Banerjea, R. Y., Bell, M., Matthews, W. and Brown, A. (2015). 'Applications of micromorphology to understanding activity areas and site formation processes in experimental hut floors'. *Archaeological and Anthropological Sciences*, 7(1): 89–112. doi: 10.1007/s12520-013-0160-5.

Barker: p. (1993). *Techniques of archaeological excavation*. 3rd ed. London: Routledge.

Barnes, A. P., Soto, I., Eory, V., Beck, B., Balafoutis, A., Sánchez, B., Vangeyte, J., Fountas, S., van der Wal, T. and Gómez-Barbero, M. (2019). 'Exploring the adoption of precision agricultural technologies: A cross regional study of EU farmers'. *Land Use Policy,* 80: 163–174. doi: 10.1016/j.landusepol.2018.10.004.

Barrett, J. C., Bradley, R. and Hall, M. (1991). *Papers on the Prehistoric Archaeology of Cranborne Chase,* Oxbow Monograph 11. Oxford: Oxbow Books.

Bateman, I. J. and Balmford, B. (2018). 'Public funding for public goods: A post-Brexit perspective on principles for agricultural policy'. *Land Use Policy,* 79: 293–300. doi: 10.1016/j.landusepol.2018.08.022.

Bevan, A. (2015). 'The data deluge'. *Antiquity,* 89: 1473–1484. doi: 10.15184/aqy.2015.102.

Bewley, R. H. (2003). 'Aerial survey for archaeology'. *Photogrammetric Record,* 18: 273–292.

Bhogal, A., Chanbers, B. J., Whitmore, A. P. and Young, I. (2011). 'Organic manure and crop organic carbon returns – effects on soil quality : SOIL-QC'. Final report for Defra Project SP0530. Published online: Defra.

Blackmore, S. (2003). *The role of yield maps in Precision Farming*. Unpublished PhD thesis. Cranfield University.

Bogaard, A., Fraser, R., Heaton, T. H. E., Wallace, M., Vaiglova: p., Charles, M., Jones, G., Evershed, R. P., Styring, A. K., Andersen, N. H., Arbogast, R.-M., Bartosiewicz, L., Gardeisen, A., Kanstrup, M., Maier, U., Marinova, E., Ninov, L., Schafer, M. and Stephan, E. (2013). 'Crop manuring and intensive land management by Europe's first farmers'. *Proceedings of the National Academy of Sciences,* 110: 12589–12594. doi: 10.1073/pnas.1305918110.

Boismier, W. A. (1997). *Modelling the Effects of Tillage Processes on Artefact Distributions in the Ploughzone: A simulation study of tillage-induced pattern formation*. BAR British Series. Oxford: Archaeopress.

Bowden, M. (eds.) (1999). *Unravelling the landscape - an inquisitive approach to archaeology*. Stroud: Tempus Publishing.

Bray, D. and Taylor, A. (2014). Archaeological Evaluation of Land at Shipton Road, Woodstock, Oxfordshire. Reading: Thames Valley Archaeological Services.

Bricka, M. R., Williford, C. W. and Jones, L. W. (1994). ‘Heavy Metal Soil Contamination at U.S. Army Installations: Proposed Research and Strategy for Technology Development’ [online]. Available online https://pdfs.semanticscholar.org/c3e8/e6af6b2e447907680c938d8 997e4920f3c87.pdf [accessed on 25 February 2019].

Bull, I. D., Simpson, I. A. and Evershed, R. P. (1999). ‘Muck ’ n ’ molecules : organic geochemical methods for detecting ancient manuring’. *Antiquity,* 73: 86–96.

Campana, S. (2017). ‘Drones in Archaeology. State-of-the-art and Future Perspectives’. *Archaeological Prospection*, 24(4): 275-296. doi: 10.1002/arp.1569.

Canti, M. (2005). ‘Wondering about Worms: Stones, Soil and Stratigraphy’. In Smith, D. N., Brickley, M. B., and Smith, W. (eds) *Fertile Ground: Papers in Honour of Susan Limbrey*. Oxford: Oxbow Books: 30–42.

Canti, M. and Huisman, D. J. (2015). ‘Scientific advances in geoarchaeology during the last twenty years’. *Journal of Archaeological Science*, 56: 96–108. doi: 10.1016/j.jas.2015.02.024.

Caponetti, L. (2019). ‘The Invisible Landscape: The Etruscan Cuniculi of Tuscania as a Determinant of Present-Day Landscape and a Valuable Tool for Sustainable Water Management’. In Isendahl, C. and Stump, D. (eds) *The Oxford Handbook of Historical Ecology and Applied Archaeology*. First ed. Oxford: Oxford University Press. doi: 10.1093/oxfordhb/9780199672691.013.23.

Carey, C. and Juleff, G. (2013). ‘Geochemical survey and metalworking: a case study from Exmoor, southwest Britain’. In J Humphris & T Rehren (eds), *The world of iron.* Archetype Publications, London: 383-392.

Carpenter, E. and Winton, H. (2011). *Marden Henge and Environs, Vale of Pewsey, Wiltshire: National Mapping Programme Report*. Research Report number 76/2011, Historic England.

Carter, S. P. and Davidson, D. A. (1998). ‘An Evaluation of the Contribution of Soil Micromorphology to the Study of Ancient Arable Agriculture’. *Geoarchaeology: An International Journal*, 13: 535–547.

Chapman, J. (1994). ‘Destruction of a common heritage: the archaeology of war in Croatia, Bosnia and Hercegovina’. *Antiquity*, 68: 120–126.

Chernysheva, E., Korobov, D. and Borisov, A. (2017). ‘Thermophilic microorganisms in arable land around medieval archaeological sites in Northern Caucasus, Russia: Novel evidence of past manuring practices’. *Geoarchaeology,* 32: 494–501. doi: 10.1002/gea.21613.

Chippindale, C. (1983). ‘The making of the first ancient monuments act, 1882, and its administration under general A. Pitt-rivers’. *Journal of the British Archaeological Association*, 136: 1–55. doi: 10.1179/jba.1983.136.1.1.

CIfA (2014a) Standard and guidance: for archaeological excavation. Reading: CIfA. doi: 10.1093/jhmas/jrr055.

CIfA (2014b) Standard and guidance for historic environment desk-based assessment. Reading: CIfA

CIfA (2014c) Standard and guidance for the creation, compilation, transfer and deposition of archaeological archives. Reading: CIfA. doi: 10.1049/ep.1974.0517.

Clark, A. (1990). *Seeing Beneath the Soil*. London: Batsford.

Conley, R. and Lavrakas, J. W. (2000). ‘Global implications on the removal of selective availability’. In *Institute of Electrical and Electronics Engineers*: 506–513. doi: 10.1109/PLANS.2000.838346.

Connolly, D. (2008). Field Survey, Field Walking and Detecting Survey [online]. Available at: http://www.bajr.org/BAJRGuides/15. Field Survey - Land Survey, Fieldwalking and Metal Detecting/ShortGuidetoFieldSurvey.pdf [accessed on 09 September 2019].

Conyers, L. B. (2016). *Interpreting Ground-Penetrating Radar for Archaeology*. Oxford: Altamira Press.

Cook, S. R., Clarke, A. S. and Fulford, M. G. (2005). ‘Soil geochemistry and detection of early Roman precious metal and copper alloy working at the Roman town of Calleva Atrebatum (Silchester, Hampshire, UK)’. *Journal of Archaeological Science*, 32: 805–812. doi: 10.1016/j.jas.2005.01.006.

Corwin, D. L. and Lesch, S. M. (2005). ‘Characterizing soil spatial variability with apparent soil electrical conductivity: Part II. Case study’. *Computers and Electronics in Agriculture,* 46(1-3): 135–152. doi: 10.1016/j.compag.2004.11.003.

Council of Europe (1992). ‘European Convention on the Protection of the Archaeological Heritage (Revised)’. European Treaty Series - No. 143. doi: 10.1007/s12180-009-0001-7.

Cowley, D. C., Moriarty, C., Geddes, G., Brown, G. L., Wade, T. and Nichol, C. J. (2018). ‘UAVs in Context : Archaeological Airborne Recording in a National Body of Survey and Record’. *Drones*, 2(1): 1–16. doi: 10.3390/drones2010002.

Cranfield University (2019) The Soils Guide [online]. Available at: www.landis.org.uk [Accessed: 1 November 2019].

Crawford, O. G. S. and Keiller, A. (1928). *Wessex From The Air*. Oxford: The Clarendon Press.

Cuenca-García, C. (2012). *The Interface of Geophysical & Geochemical Survey in Archaeological Prospection*. Unpublished PhD thesis. University of Glasgow.

Dabas, M. (2009). ‘Theory and practice of the new fast electrical imaging system ARC’. In Campana, S. and Piro, S. (eds) *Seeing the Unseen: Geophysics and Landscape Archaeology*. London: Taylor & Francis: 105–129.

Dalan, R. A. (2008). ‘A Review of the Role of Magnetic Susceptibility in Archaeogeophysical Studies in the USA: Recent Developments and Prospects’. *Archaeological Prospection*, 15: 1–31. doi: 10.1002/arp.

Darvill, T. and Fulton, A. (1998). MARS: The Monuments at Risk Survey of England, 1995 Main Report. Bournemouth: University of Bournemouth.

Darvill, T. and Wainwright, G. (1994). ‘The Monuments At Risk Survey: An introduction’. *Antiquity*, 68: 820–824. doi: 10.1017/S0003598X00047517.

Darvill, T., Russell, B., Bell, C., Hunt, A., May, K., Milner, E., Mitchell, L., Connor, B. O., Spencer, J., Stocks, A. and Talbot, G. (2002). ‘Archaeology after PPG16 : archaeological investigations in England 1990-1999’, Research Report 10. University of Bournemouth: School of Conservation Sciences.

Davidson, D. A. and Carter, S. P. (1998). ‘Micromorphological evidence of past agricultural practices in cultivated soils: the impact of a traditional agricultural system on soils in Papa Stour, Shetland’. *Journal of Archaeological Science*, 25(9): 827–838. doi: 10.1006/jasc.1997.0225.

Davidson, D. A., Dercon, G., Stewart, M. and Watson, F. (2006). 'The legacy of past urban waste disposal on local soils'. *Journal of Archaeological Science*, 33: 778–783. doi: 10.1016/j.jas.2005.10.017.

Dawson, T. and Bray, D. (2014) Geophysical Survey (Magnetic) of Land at Shipton Road, Woodstock, Oxfordshire. Reading: Thames Valley Archaeological Services.

DCMS (2017). 'The Heritage Statement 2017' [online]. Available at: https://www.gov.uk/government/publications/the-heritage-statement-2017 [accessed on 3 January 2019].

De Smedt: p., Saey, T., Lehouck, A., Stichelbaut, B., Meerschman, E., Islam, M. M., Van De Vijver, E. and Van Meirvenne, M. (2013). 'Exploring the potential of multi-receiver EMI survey for geoarchaeological prospection: A 90ha dataset'. *Geoderma*, 199: 30–36. doi: 10.1016/j.geoderma.2012.07.019.

Defra (2013a) 'Farm Practices Survey Autumn 2012 – England' [online]. Available from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/181719/defra-stats-foodfarm-environ-fps-statsrelease-autumn2012edition-130328.pdf [accessed on 12 March 2019].

Defra (2013b). SHINE: How can the baseline for monitoring and evaluating the impacts of Environmental Stewardship on the historic environment be improved? Project Ref. LM0426. Published online: Defra.

Defra (2018a). '25-Year-Environment-Plan' [online]. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/693158/25-year-environment-plan.pdf [accessed on 9 February 2019].

Defra (2018b). 'Agriculture in the United Kingdom' [online]. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/741062/AUK-2017-18sep18.pdf [accessed on 15 February 2019].

Defra (2018c). 'Health and Harmony: the future for food, farming and the environment in a Green Brexit' [online]. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/684003/future-farming-environment-consult-document.pdf [accessed on 18 February 2019].

Demšar, U., Harris: p., Brunsdon, C., Fotheringham, A. S. and McLoone, S. (2013). ‘Principal Component Analysis on Spatial Data: An Overview’. *Annals of the Association of American Geographers*, 103(1): 106–128. doi: 10.1080/00045608.2012.689236.

Drennan, R. D. (2009). *Statistics for Archaeologists. A common sense approach*. Dordrecht: Springer.

Duckett, T., Pearson, S., Blackmore, S., Grieve, B., Chen, W.-H., Cielniak, G., Cleaversmith, J., Dai, J., Davis, S., Fox, C., From: p., Georgilas, I., Gill, R., Gould, I., Hanheide, M., Hunter, A., Iida, F., Mihalyova, L., Nefti-Meziani, S., Neumann, G., Paoletti: p., Pridmore, T., Ross, D., Smith, M., Stoelen, M., Swainson, M., Wane, S., Wilson: p., Wright, I. and Yang, G.-Z. (2018). ‘Agricultural Robotics: The Future of Robotic Agriculture’. White Paper. doi: arXiv:1806.06762v2.

Dungworth, D. B., Comeau, B. and Lowerre, A. (2013). St Algar’s farm, Selwood, Somerset: Geochemical Survey. Research Report Series 28-2013. Historic England.

Dyer, J. (2016). *The Data Farm: An investigation of the implications of collecting data on farm*. Nuffield Farming Scholarship Trust Report.

Eidt, R. C. (1977) ‘Detection and Examination of Anthrosols by Phosphate Analysis’. *Science*, 197(4311: 1327–1333.

English Heritage (2009). Heritage at Risk Register 2009 [online]. Available from https://historicengland.org.uk/images-books/publications/har-2009-summary/harsummaryacc_2009/ [accessed on 15 December 2018].

English Heritage (2009). Historic farm buildings : Extending the evidence base. English Heritage.

Entwistle, J. A., Abrahams: p. W. and Dodgshon, R. A. (1998). ‘Multi-element analysis of soils from Scottish historical sites. Interpreting land-use history through the physical and geochemical analysis of soil’. *Journal of Archaeological Science*, 25(1): 53–68. doi: 10.1006/jasc.1997.0199.

Entwistle, J. A., Dodgshon, R. A. and Abrahams: p. W. (2000). ‘An investigation of former land-use activity through the physical and chemical analysis of soils from the Isle of Lewis, Outer Hebrides'. *Archaeological Prospection*, 7(3): 171–188. doi: 10.1002/1099-0763(200009)7:3<171::AID-ARP142>3.0.CO;2-G.

Environmental Audit Committee (2016). 'Soil Health: First Report of Session 2016-17' [online]. Available at: http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/soilhealth_home [accessed on 20 February 2019].

Eriksen, J., Murphy, M. D. and Schnug, E. (1998). 'The Soil Sulphur Cycle'. In Schnug E. (eds.) *Sulphur in Agroecosystems. Nutrients in Ecosystems*, vol 2. Springer: Dordrecht. pp. 39–73.

European Commission (2019). 'The Post-2020 Common Agricultural Policy: Environmental Benefits and Simplification' [online]. Available from https://ec.europa.eu/info/sites/info/files/food-farming-fisheries/key_policies/documents/cap-post-2020-environ-benefits-simplification_en.pdf [accessed on 10 March 2019].

European Landscape Convention (2000). 'European Landscape Convention' [online]. Available from http://conventions.coe.int/Treaty/en/Treaties/Html/176.htm [accessed on 15 September 2019].

European Parliamentary Research Service (2016). Precision agriculture and the future of farming in Europe, Scientific Foresight Study [online]. Available from http://conventions.coe.int/Treaty/en/Treaties/Html/176.htm [accessed on 23 March 2019].

Evans, R. and Catt, J. A. (1987). 'Causes of crop patterns in eastern England'. *Journal of Soil Science*, 38(2): 309–324. doi: 10.1111/j.1365-2389.1987.tb02147.x.

Evans, S. (2019). Historic England Aerial Investigation & Mapping (formerly National Mapping Programme) Standards Technical Review [online]. Research Report Series 46-2019. Available from: https://research.historicengland.org.uk/redirect.aspx?id=7714%7C [accessed on 1 October 2019].

Fairclough, G. J., Rippon, S. and Bull, D. (2002). 'Europe's Cultural Landscape : archaeologists and the management of change', EAC occasional paper 2. Belgium: Europae Archaeologiae Consilium.

Fairhead, J. and Leach, M. (2009). ‘Amazonian dark earths in Africa?’. In Teixeira, W. G., Woods, W. I., Steiner, C., Lehmann, J., Rebellato, L., and WinklerPrins, A. (eds) *Amazonian Dark Earths: Wim Sombroek’s Vision*: 265–278.

FAO (2017). The future of food and agriculture: trends and challenges, The future of food and agriculture: trends and challenges [online]. Available at: http://www.fao.org/3/a-i6583e.pdf [accessed on 23 March 2019].

Fassbinder, J. W. E. (2015). ‘Seeing beneath the farmland, steppe and desert soil: magnetic prospecting and soil magnetism’. *Journal of Archaeological Science,* 56: 85–95. doi: 10.1016/j.jas.2015.02.023.

Fletcher, R., Pottier, C., Evans, D. and Kummu, M. (2008). ‘The development of the water management system of Angkor: a provisional model’. *Bulletin of the Indo-Pacific Prehistory Association,* 28(0): 57–66. doi: 10.7152/bippa.v28i0.12016.

Fluck, H. and Holyoak, V. (2017). Ecosystem Services, Natural Capital and the Historic Environment [online]. Research Report Series 19-2017. Available from https://research.historicengland.org.uk/Report.aspx?i=15572&ru=%2FResults.aspx%3Fp%3D371 [accessed 9 September 2018].

Foard, G. (1977). ‘Systematic fieldwalking and the investigation of Saxon settlement in Northamptonshire’. *World Archaeology,* 9(3): 357–374. doi: 10.1080/00438243.1973.9979709.

Fowler: p. J. and Evans, J. G. (1967). ‘Plough-marks, Lynchets and Early Fields’. *Antiquity,* 41(164): 289–301. doi: 10.1017/S0003598X00033524.

Frahm, E. and Doonan, R. C. P. (2013). ‘The technological versus methodological revolution of portable XRF in archaeology’. *Journal of Archaeological Science*, 40(2): 1425–1434. doi: 10.1016/j.jas.2012.10.013.

Fraser, R. A., Bogaard, A., Heaton, T., Charles, M., Jones, G., Christensen, B. T., Halstead: p., Merbach, I., Poulton: p. R., Sparkes, D. and Styring, A. K. (2011). ‘Manuring and stable nitrogen isotope ratios in cereals and pulses: Towards a new archaeobotanical approach to the inference of land use and dietary practices’. *Journal of Archaeological Scienc,* 38(10): 2790–2804. doi: 10.1016/j.jas.2011.06.024.

French, C. (2003). *Geoarchaeology in Action: Studies in Soil Micromorphology and Landscape Evolution*: London: Routledge.

French, C. (2015). *A handbook of geoarchaeological approaches for investigating landscapes and settlement sites*. Digital Ed. Oxford: Oxbow Books.

Gaffney, C. (2008). 'Detecting Trends In The Prediction Of The Buried Past : A Review Of Geophysical Techniques In Archaeology'. *Archaeometry*, 50: 313–336. doi: 10.1111/j.1475-4754.2008.00388.x.

Gaffney, C. and Gater, J. (2003). *Revealing the Buried Past: Geophysics for Archaeologists*. Stroud: Tempus Publishing.

Gaffney, C., Gaffney, V. L., Neubauer, W., Baldwin, E., Chapman, H., Garwood: p., Moulden, H., Sparrow, T., Bates, R., Locker, K., Hinterleitner, A., Trinks, I., Nau, E., Zitz, T., Floery, S., Verhoeven, G. and Doneus, D. (2012). 'The Stonehenge Hidden Landsapes Project'. *Archaeological Prospection*, 19: 147–155. doi: 10.1002/arp.

Gascoyne, A. (2006). 'Conservation Management of the Rural Historic Environment in Essex' [online]. Available from: http://www.academia.edu/download/35375799/planarchfinshed2803.pdf [accessed on 7 February 2018].

Ge, L., Lai, W. and Lin, Y. (2005). 'Influence of and correction for moisture in rocks, soils and sediments on *in situ* XRF analysis'. *X-Ray Spectrometry*, 34(1): 28–34. doi: 10.1002/xrs.782.

Gebbers, R. and Adamchuck, V. I. (2010). 'Precision Agriculture and Food Security', *Science*, 327 (5967): 828-831. doi: 10.1126/science.1183899.

Gerrard, C. and Aston, M. A. (eds.) (2017). *The Shapwick Project, Somerset. A Rural Landscape Explored*. Abingdon: Routledge.

Gerrard, J., Caldwell, L. and Kennedy, A. (2015). 'Green Waste and Archaeological Geophysics'. *Archaeological Prospection*, 22: 139–142. doi: 10.1002/arp.

Gheyle, W., Saey, T., Van Hollebeeke, Y., Verplaetse, S., Note, N., Bourgeois, J., Van Meirvenne, M., Van Eetvelde, V. and Stichelbaut, B. (2016). 'Historical Aerial Photography and Multi- receiver EMI Soil Sensing, Complementing Techniques for the Study of a Great War Conflict Landscape'. *Archaeological Prospection*, 23: 149–164. doi: 10.1002/arp.

Godwin, R. J., Richards, T. E., Wood, G. A., Welsh, J. P. and Knight, S. M. (2003). ‘An economic analysis of the potential for precision farming in UK cereal production’. *Biosystems Engineering,* 84(4): 533–545. doi: 10.1016/S1537-5110(02)00282-9.

Graham, L. (2014). ‘Precision agriculture on the global stage’ [online]. Norton Rose Fulbright: 4–6. Available from: http://www.nortonrosefulbright.com/files/cultivate-issue-5-120824.PDF [accessed 21 March 2015].

Green, M. (2000). *A Landscape Revealed. 10,000 years on a Chalkland Farm*. Stroud: Tempus.

Guttmann, E. B. (2001). *Continuity and Change in Arable Land Management in the Northern Isles : Evidence from anthropogenic soils*. Unpublished PhD thesis. University of Stirling.

Guttmann, E. B., Simpson, I. A. and Davidson, D. A. (2005). ‘Manuring Practices in Antiquity: A Review of the Evidence’. In Smith, D. N., Brickley, M. B., and Smith, W. (eds) *Fertile Ground: Papers in Honour of Susan Limbrey*. Oxford: Oxbow Books: 68–76.

Haldenby, D. and Richards, J. D. (2010). ‘Charting the effects of plough damage using metal-detected assemblages’. *Antiquity,* 84(326): 1151–1162. doi: 10.1017/S0003598X00067144.

Hall, D. (2001). ‘*Turning the Plough. Midland open fields: landscape character and proposals for management.* English Heritage and Northamptonshire County Council.

Hallett, S. H., Sakrabani, R., Keay, C. A. and Hannam, J. A. (2017). ‘Developments in land information systems: examples demonstrating land resource management capabilities and options’. *Soil Use and Management,* 33(4): 514–529. doi: 10.1111/sum.12380.

Halliday, S. (2013). ‘I Walked, I Saw, I Surveyed, but what did I see?... and what did I survey?’. In Opitz, R. and Cowley, D. C. (eds) *Interpreting Archaeological Topography: Airborne Laser Scanning, 3D Data and Ground Observation*. Oxford: Oxbow Books: 63–76.

Harding, A. F. and Lee, G. E. (1987). *Henge monuments and related sites of Great Britain: air photographic evidence and catalogue*. British Archaeological Reports, Volume 175 British Series.

Hartley, T. N., Macdonald, A. J., McGrath, S. P. and Zhao, F. J. (2013). ‘Historical arsenic contamination of soil due to long-term phosphate fertiliser applications’. *Environmental Pollution*. 180: 259–264. doi: 10.1016/j.envpol.2013.05.034.

Harvey, F. (2018). ‘UK farmers to be given first ever targets on soil health’-The Guardian [online]. Available from: https://www.theguardian.com/environment/2018/mar/13/uk-farmers-to-be-given-first-ever-targets-on-soil-health [accessed on 10 July 2019].

Haselgrove, C., Millet, M. (eds.) and Smith, I. (1985). *Archaeology from The Ploughsoil: Studies in the Collection and Interpretation of Field Survey data*. Sheffield: University of Sheffield.

Hayes, K. (2013). ‘Parameters in the use of pXRF for archaeological site prospection: a case study at the Reaume Fort Site, Central Minnesota’. *Journal of Archaeological Science*, 40(8): 3193–3211. doi: 10.1016/j.jas.2013.04.008.

Haygarth: p. M. and Ritz, K. (2009). ‘The future of soils and land use in the UK: Soil systems for the provision of land-based ecosystem services’. *Land Use Policy*, 26: 187–197. doi: 10.1016/j.landusepol.2009.09.016.

Hewitt, I. (1998). Sixpenny Handley: Goldfields Farm 1998, *Proceedings of the Dorset Natural History and Archaeological Society,* 120 :114.

Hewitt, I. and Rumsey, K. (1999). ‘Sixpenny Handley, Goldfields Farm: Interim Statement’, in *Proceedings of the Dorset Natural History and Archaeological Society*, 121: 158–159.

Hill, I., Challis, K., Knight, D., Leech, C., Linford, N., Smith, B. and Wardrop, D. (2008). The FASTRAC Project - Final Report (ALSF Research Project 5366). University of Leicester.

Historic England (2007). Geoarchaeology, Using Earth Sciences to Understand the Archaeological Record [online]. Available from https://historicengland.org.uk/images-books/publications/geoarchaeology-earth-sciences-to-understand-archaeological-record/heag067-geoarchaeology/ [accessed on 5 February 2019].

Historic England (2015a). ‘Heritage At Risk: South West Register 2015’ [online]. Available from https://historicengland.org.uk/images-books/publications/har-2015-registers/sw-har-register2015/ [accessed on 10 January 2019].

Historic England (2015b). Environmental Archaeology: A Guide to the Theory and Practice of Methods, from Sampling and Recovery to Post-excavation [online]. Available from https://historicengland.org.uk/images-books/publications/environmental-archaeology-2nd/environmental_archaeology/ [accessed on 9 February 2019].

Historic England (2017a). Land Contamination and Archaeology, Good Practice Guide [online]. Available from https://historicengland.org.uk/images-books/publications/land-contamination-and-archaeology/heag096-land-contamination-and-archaeology/ [accessed on 15 February 2019].

Historic England (2017b). Photogrammetric Applications for Cultural Heritage [online]. Available from https://historicengland.org.uk/images-books/publications/photogrammetric-applications-for-cultural-heritage/heag066-photogrammetric-applications-cultural-heritage/ [accessed on 17 February 2019].

Historic England (2017c). Understanding the Archaeology of Landscapes [online]. Available from: http://www.english-heritage.org.uk/publications/understanding-archaeology-of-landscapes/ [accessed on 5 May 2018].

Historic England (2018a). Graphical and Plane Table Survey of Archaeological Earthworks: Good Practice Guidance [online]. Available from https://historicengland.org.uk/images-books/publications/graphical-and-plane-table-survey-archaeological-earthworks/heag256-graphical-plane-table-survey-archaeological-earthworks/ [accessed on 6 September 2019].

Historic England (2018b). Heritage at Risk: East of England Register 2018 [online]. Available from https://historicengland.org.uk/images-books/publications/har-2018-registers/ee-har-register2018/ [accessed on 16 September 2019].

Historic England (2018c). Using Airborne Lidar in Archaeological Survey: The Light Fantastic [online]. Available from: https://historicengland.org.uk/images-books/publications/using-airborne-lidar-in-archaeological-survey/ [accessed on 16 September 2019].

HM Government (2013). A UK Strategy for Agricultural Technologies [online]. Available from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/227259/9643-BIS-UK_Agri_Tech_Strategy_Accessible.pdf [accessed on 7 January 2017].

Hodgson, M. J. (1978). *Soil sampling and soil description*. Oxford: Oxford University Press.

Holliday, V. T. and Gartner, W. G. (2007). ‘Methods of soil P analysis in archaeology’. *Journal of Archaeological Science*, 34: 301–333. doi: 10.1016/j.jas.2006.05.004.

Holliday, V. T., Lawrence-Zuniga, D. and Buchli, V. (2010). ‘Prologue to uses of chemical residues to make statements about human activities’. *Journal of Archaeological Method and Theory*, 17(3): 175–182. doi: 10.1007/s10816-010-9089-5.

Holopainen, M., Vastaranta, M. and Hyyppä, J. (2014). ‘Outlook for the Next Generation’s Precision Forestry in Finland’. *Forests*, 5:1682–1694. doi: 10.3390/f5071682.

Hunt, A. M. W. and Speakman, R. J. (2015). ‘Portable XRF analysis of archaeological sediments and ceramics’. *Journal of Archaeological Science*, 53: 626–638. doi: 10.1016/j.jas.2014.11.031.

Ingle, C. and Saunders, H. (2011). *Aerial Archaeology in Essex: the role of the National Mapping Programme in interpreting the landscape*. Chelmsford: Essex County Council

Isendahl, C. and Stump, D. (2019a). ‘Conclusion: Anthropocentric Historical Ecology, Applied Archaeology, and the Future of a Usable Past’. In Isendahl, C. and Stump, D. (eds.) *The Oxford Handbook of Historical Ecology and Applied Archaeology*. First Ed. Oxford: Oxford University Press. doi: 10.1093/oxfordhb/9780199672691.013.37.

Isendahl, C. and Stump, D. (eds.) (2019b). *The Oxford Handbook of Historical Ecology and Applied Archaeology*. First Ed. Oxford: Oxford University Press.

Jackson, R. and Miller, D. (2010). ‘cosmic +: informed protection for rural sites’, *The Archaeologist*, 78: 18-19.

Jarman, M., Vesey, J. and Febvre: p. (2016). ‘Unmanned Aerial Vehicles (UAVs) for UK Agriculture: Creating an Invisible Precision Farming Technology; White Paper’ [online]. Available from https://sa.catapult.org.uk/wp-content/uploads/2016/07/White-paper-UAVs-and-agriculture_Final2.pdf [accessed on 28 July 2017].

Joernsgaard, B. and Halmoe, S. (2003). ‘Intra-field yield variation over crops and years’. *European Journal of Agronomy*, 19(1): 23–33. doi: 10.1016/S1161-0301(02)00016-3.

Joint Research Centre (JRC) (2014). Precision Agriculture: an Opportunity for EU Farmers-Potential Support With The CAP 2014 – 2020 [online]. Available from http://www.europarl.europa.eu/RegData/etudes/note/join/2014/529049/IPOL-AGRI_NT(2014)529049_EN.pdf [accessed on 12 December 2018].

Jolliffe, I. (2014). ‘Principal Component Analysis’ [online]. Available from https://onlinelibrary.wiley.com/doi/full/10.1002/9781118445112.stat06472 [accessed on 2 January 2019]. doi: 10.1002/9781118445112.stat06472.

Jones, D. L., Cross: p., Withers: p. J. A., Deluca, T. H., Robinson, D. A., Quilliam, R. S., Harris, I. M., Chadwick, D. R. and Edwards-Jones, G. (2013). ‘Nutrient stripping: The global disparity between food security and soil nutrient stocks’. *Journal of Applied Ecology,* 50(4): 851–862. doi: 10.1111/1365-2664.12089.

Jones, G., Bogaard, A., Halstead: p., Charles, M. and Smith, H. (1999). ‘Identifying the intensity of crop husbandry practices on the basis of weed floras’. *The Annual of the British School at Athens,* 94: 167–189. doi: 10.1017/S0068245400000563.

Jones, R. (2012). *Manure Matters: Historical, Archaeoogical and Ethnographic Perspectives*. Farnham: Ashgate Publishing Limited.

Kabata-Pendias, A. (2011). *Trace Elements in Soils and Plants*. Fourth Ed. London: CRC Press, Taylor and Francis Group.

Kaminski, J. (1995). T*he Environmental Implications of Romano-British Iron Production in the Weald*. Unpublished PhD thesis. University of Reading.

Kerry, R. and Oliver, M. A. (2003). ‘Variograms of ancillary data to aid sampling for soil surveys’. *Precision Agriculture,* 4(3): 261–278. doi: 10.1023/A:1024952406744.

Kerry, R. and Oliver, M. A. (2011). ‘Soil geomorphology: Identifying relations between the scale of spatial variation and soil processes using the variogram’. *Geomorphology*, 130: 40–54. doi: 10.1016/j.geomorph.2010.10.002.

Khosla, R. (2010). ‘Precision agriculture: challenges and opportunities in a flat world’ [online]. *19th World Congress of Soil Science, Soil Solutions for a Changing World*. Available from https://www.iuss.org/19th%20WCSS/Symposium/pdf/0779.pdf [accessed on 13 January 2019].

Kibblewhite, M. G., Ritz, K. and Swift, M. J. (2008). ‘Soil health in agricultural systems’. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1492): 685–701. doi: 10.1098/rstb.2007.2178.

Knight, S., Miller: p. and Orson, J. (2009). *Up-To-Date Cost/benefit Analysis of Precision Farming* [online]. AHDB Research Review 71. Available from https://cereals.ahdb.org.uk/publications/2009/may/20/an-up-to-date-costbenefit-analysis-of-precision-farming-techniques-to-guide-growers-of-cereals-and-oilseeds.aspx [accessed on 27 January 2019].

Kritikos, M. (2017). Precision agriculture in Europe: Legal,social and ethical considerations [online]. Available from http://www.europarl.europa.eu/thinktank/it/document.html?reference=EPRS_STU%282017%29603207 [accessed on 18 January 2019].

Lamb, D. W. and Brown, R. B. (2001). 'Review Paper: Remote-Sensing and Mapping of Weeds in Crops'. *J. agric. Engng Res*, 78(2): 117–125. doi: 10.1006.

Lambrick, G. (1977). *Archaeology and Agriculture: A survey of modern cultivation methods and the problems of assessing plough damage to archaeological sites*. Leamington: Council For British Archaeology and the Oxfordshire Archaeological Unit.

Lasaponara, R. and Masini, N. (2007). 'Detection of archaeological crop marks by using satellite QuickBird multispectral imagery'. *Journal of Archaeological Science*, 34(2): 214–221. doi: 10.1016/j.jas.2006.04.014.

Leary, J. (2015). 'The Vale of Pewsey Project, Season 1, 2015 Marden henge and Wilsford henge: Archaeological Assessment Report'. Unpublished Report. University of Reading.

Leary, J. (2016). 'The Vale of Pewsey Project, Season 2, 2016 Marden henge and Wilsford henge: Archaeological Assessment Report'. Unpublished Report. University of Reading.

Leary, J. and Field, D. (2012). 'Journeys and Juxtapositions. Marden Henge and the View from the Vale'. In Gibson, A. (ed.) *Enclosing the Neolithic: Recent studies in Britain and Europe*. Oxford: Archaeopress: 55–65.

Limbrey, S. (1975). *Soil Science and Archaeology*. London: Academic Press.

Linford, N. (2006). 'The application of geophysical methods to archaeological prospection'. *Reports on Progress in Physics*, 69: 2205–2257. doi: 10.1088/0034-4885/69/7/R04.

Linford, N., Linford: p. and Payne, A. (2013). Marden Barrows and Wilsford Henge, Wiltshire : Report on Geophysical Survey September 2012 [online]. Available from http://services.english-heritage.org.uk/ResearchReportsPdfs/008_2013WEB.pdf [accessed on 20 November 2015].

Linsley, C. M. and Bauer, F. C. (1929). ‘Test your soil for acidity.’ [online]. Available from https://www.ideals.illinois.edu/bitstream/handle/2142/33105/6541437.pdf?sequence=2&isAllowed=y [accessed on 29 January 2018].

Lubos, C., Dreibrodt, S. and Bahr, A. (2016). ‘Analysing spatio-temporal patterns of archaeological soils and sediments by comparing pXRF and different ICP-OES extraction methods’. *Journal of Archaeological Science,* 9: 44–53. doi: 10.1016/j.jasrep.2016.06.037.

Lund, E. D. (2011). ‘Proximal sensing of soil organic matter using the Veris® OpticMapper^{TM}’, in *The Second Global Workshop on Proximal Soil Sensing – Montreal 2011*.

Macphail, R. I. (1998). ‘A reply to Carter and Davidson’s “An evaluation of the contribution of soil micromorphology to the study of ancient arable agriculture”’. *Geoarchaeology*, 13(6): 549–564. doi: 10.1002/(sici)1520-6548(200006)15:5<499::aid-gea5>3.3.co;2-1.

Macphail, R. I., Galinié, H. and Verhaeghe, F. (2002). ‘A future for Dark Earth?’. *Antiquity,* 77(296): 349-358. doi: 10.1017/S0003598X00092334.

Macphail, R., Courty, M.-A. and Goldberg: p. (1990). ‘Soils and Micromorphology in Archaeology’. *Soil Science*, 150(6): 904. doi: 10.1097/00010694-199012000-00014.

Maddison, D. (2000). ‘A hedonic analysis of agricultural land prices in England and Wales’. *European Review of Agricultural Economics*, 27(4): 519–532. doi: 10.1093/erae/27.4.519.

Maestrini, B. and Basso, B. (2018). ‘Predicting spatial patterns of within-field crop yield variability’. *Field Crops Research*. 219: 106–112. doi: 10.1016/j.fcr.2018.01.028.

MAFF (1988). ‘Ministry of Agriculture , Fisheries and Food Agricultural Land Classification of England and Wales’. Published online: MAFF.

Major, J., Ditommaso, A., Lehmann, J. and Falcão, N. P. S. (2005). ‘Weed dynamics on Amazonian Dark Earth and adjacent soils of Brazil’. *Agriculture Ecosystems and Environment,* 111(1-4): 1–12. doi: 10.1016/j.agee.2005.04.019.

Malenovský, Z., Rott, H., Cihlar, J., Schaepman, M. E., García-Santos, G., Fernandes, R. and Berger, M. (2012). ‘Sentinels for science: Potential of Sentinel-1, -2, and -3 missions for scientific observations of ocean, cryosphere, and land'. *Remote Sensing of Environment*, 120: 91–101. doi: 10.1016/j.rse.2011.09.026.

Matthews, W., French, C., Lawrence, T., Cutler, D. F. and Jones, M. K. (1997). 'Microstratigraphic Traces of Site Formation Processes and Human Activities'. *World Archaeology*, 29(2): 281–308. doi: 10.1080/00438243.1997.9980378.

Maxwell, G. S. (1983). The Impact of Aerial Reconnaissance on Archaeology [online]. Council for British Archaeology Research Report No 49. Available from https://archaeologydataservice.ac.uk/archives/view/cba_rr/rr49.cfm [accessed on 5 February 2019].

McBratney, A., Whelan, B., Thomir, A. and Bouma, J. (2005). 'Future Directions of Precision Agriculture'. *Precision Agriculture*, 6(1): 7–23. doi: https://doi.org/10.1007/s11119-005-0681-8.

McConnell, D. (2017). *Digital Dairy: optimising the value of precision technology in the UK dairy industry*. Nuffield Farming Scholarship Trust Report.

McOmish, D., Field, D. and Brown, G. (2002). *The Field Archaeology of the Salisbury Plain Training Area*. Swindon: English Heritage.

Meharg, A. A., Deacon, C., Edwards, K. J., Donaldson, M., Davidson, D. A., Spring, C., Scrimgeour, C. M., Rg Feldmann, J. and Rabb, A. (2006). 'Ancient manuring practices pollute arable soils at the St Kilda World Heritage Site, Scottish North Atlantic'. *Chemosphere*, 64(11): 1818-1828. doi: 10.1016/j.chemosphere.2006.01.076.

Mertens, F. M., Pätzold, S. and Welp, G. (2008). 'Spatial heterogeneity of soil properties and its mapping with apparent electrical conductivity'. *Journal of Plant Nutrition and Soil Science*, 171(2): 146–154. doi: 10.1002/jpln.200625130.

Metcalfe, H., Milne, A. E., Coleman, K., Murdoch, A. J. and Storkey, J. (2019). 'Modelling the effect of spatially variable soil properties on the distribution of weeds'. *Ecological Modelling*. 396: 1–11. doi: 10.1016/j.ecolmodel.2018.11.002.

Middleton, W. D. and Price, T. D. (1996). 'Identification of Activity Areas by Multi-element Characterization of Sediments from Modern and Archaeological House Floors Using

Inductively Coupled Plasma-atomic Emission Spectroscopy’. *Journal of Archaeological Science*, 23: 673–687.

Minasny, B. and McBratney, A. B. (2016). ‘Digital soil mapping: A brief history and some lessons’. *Geoderma*, 264, Part B: 301–311. doi: 10.1016/j.geoderma.2015.07.017.

Monge, G., Jimenez-Espejo, F. J., García-Alix, A., Martínez-Ruiz, F., Mattielli, N., Finlayson, C., Ohkouchi, N., Sánchez, M. C., De Castro, J. M. B., Blasco, R., Rosell, J., Carrión, J., Rodríguez-Vidal, J. and Finlayson, G. (2015). ‘Earliest evidence of pollution by heavy metals in archaeological sites’. *Scientific Reports*, 5:14252. doi: 10.1038/srep14252.

Moriarty, C., Cowley, D. C., Wade, T. and Nichol, C. J. (2018). ‘Deploying multispectral remote sensing for multi-temporal analysis of archaeological crop stress at Ravenshall, Fife, Scotland’. *Archaeological Prospection*, 26 (1):33-46. doi: 10.1002/arp.1721.

Morris, R. (2003). ‘The Archaeology of Conflict’, Conservation Bulletin 44, English Heritage: 1–64.

Mulla, D. and Khosla, R. (2015). ‘Historical Evolution and Recent Advances in Precision Farming’ [online]. Available from https://www.ispag.org/files/Mulla%20and%20Khosla%202015.pdf [accessed on 15 December 2018].

Mulla, D. J. (2013). ‘Special Issue: Sensing in Agriculture Review Twenty five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps’. *Biosystems Engineering*, 114: 358–371. doi: 10.1016/j.biosystemseng.2012.08.009.

Mulvaney, R. L., Khan, S. A. and Ellsworth, T. R. (2009). ‘Synthetic nitrogen fertilizers deplete soil nitrogen: A global dilemma for sustainable cereal production’. *Journal of Environmental Quality*, 38(6): 2295–2314. doi: 10.2134/jeq2008.0527.

Nash, E., Korduan: p. and Bill, R. (2009). ‘Applications of open geospatial web services in precision agriculture: a review’. *Precision Agriculture*, 10(6): 546–560. doi: 10.1007/s11119-009-9134-0.

National Research Council (1997). *Precision Agriculture in the 21st Century: Geospatial and Information Technologies in Crop Management*. Washington D.C.: National Academy Press.

National Soil Resources Institute (2018a). Soil Site Report Myncen Farm. Available at: http://www.landis.org.uk/arcimsoutput/PDFs/SSRv3_0_Webber_Undergraduate_Student_Report_bf38ddff-a367-4fe5-be1b-2ad152a2bb17.pdf [accessed on 5 February 2018].

National Soil Resources Institute (2018b). Soil Site Report Perdiswell Farm. Available at: http://www.landis.org.uk/arcimsoutput/PDFs/SSRv3_0_Webber_Undergraduate_Student_Report_23725a5c-c19c-4a93-bd58-ed2fc119f8a9.pdf [accessed on 5 February 2018].

National Soil Resources Institute (2018c). Soil Site Report Wilsford Manor Farm. Available at: http://www.landis.org.uk/arcimsoutput/PDFs/SSRv3_0_Webber_Undergraduate_Student_Report_cd9cd75d-60b9-49e2-abe6-cfcaee0d6a47.pdf [accessed on 5 February 2018].

Natural England (2016). The ecological effects of air pollution from road transport: an updated review [online]. Available from http://publications.naturalengland.org.uk/publication/6212190873845760 [accessed on 6 September 2019].

NCC (2019). ‘State of Natural Capital Annual Report 2019’ [online]. Available from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/774218/ncc-annual-report-2019.pdf. [accessed on 5 March 2019].

Nicholson, F. and Chambers, B. J. (2008). ‘Sources and Impacts of Past, Current and Future Contamination of Soil, Appendix 1: Heavy metals’. Project SP0547. Published online: Defra and ADAS.

Nielsen, N. H. and Kristiansen, S. M. (2014). ‘Identifying ancient manuring: Traditional phosphate vs. multi-element analysis of archaeological soil’. *Journal of Archaeological Science*, 42(1): 390–398. doi: 10.1016/j.jas.2013.11.013.

Oliver, M. A, (ed.) (2010). *Geostatistical Applications for Precision Agriculture*. Dordrecht: Springer.

Oliver, M. A. and Frogbrook, Z. L. (1998). ‘Sampling to Estimate Soil Nutrients for Precision Agriculture’. *International Fertiliser Society -Proceedings (Precision Agriculture),* 417.

Oonk, S., Slomp, C. P., Huisman, D. J. and Vriend, S. P. (2009). ‘Geochemical and mineralogical investigation of domestic archaeological soil features at the Tiel-Passewaaij site, The Netherlands'. *Journal of Geochemical Exploration,* 101(2): 155–165. doi: 10.1016/j.gexplo.2008.06.004.

Oonk, Stijn, Slomp, C. P. and Huisman, D. J. (2009). 'Geochemistry as an Aid in Archaeological Prospection and Site Interpretation: Current Issues and Research Directions'. *Archaeological Prospection*, 16: 35–51. doi: 10.1002/arp.

Opitz, R. and Herrmann, J. (2018). 'Recent Trends and Long-standing Problems in Archaeological Remote Sensing'. *Journal of Computer Applications in Archaeology,* 1(1): 19–41. doi: 10.5334/jcaa.11.

Opitz, R. and Limp, W. F. (2015). 'Recent Developments in High-Density Survey and Measurement (Hdsm) for Archaeology: Implications for Practice and Theory'. *Annual Review of Anthropology*, 44: 347–64. doi: 10.1146/annurev-anthro-102214-013845.

Opitz, R. S. and Cowley, D. C. (eds.) (2013). *Interpreting Archaeological Topography: Airborne Laser Scanning, 3D Data and Ground Observation*. Oxford: Oxbow Books. doi: 10.2307/j.ctvh1dqdz.6.

Oxford Archaeology (2002). The Management of Archaeological Sites in Arable Landscapes. Final Project Report BD1701.Published online: Defra.

Oxford Archaeology (2006). Conservation of Scheduled Monuments in Cultivation (COSMIC) for English Heritage and Defra. Final Project Report BD1704. Published online: Defra.

Oxford Archaeology (2014). National Implementation of the Conservation of Scheduled Monuments in Cultivation Assessment (COSMIC 3) [online]. Available from https://research.historicengland.org.uk/Report.aspx?i=15755 [accessed on 16 February 2019].

Parliamentary Office of Science and Technology (2015). Precision Farming [online]. Available from https://researchbriefings.parliament.uk/ResearchBriefing/Summary/POST-PN-0505#fullreport [accessed on 12 April 2016].

Paustian, M. and Theuvsen, L. (2017). 'Adoption of precision agriculture technologies by German crop farmers'. *Precision Agriculture*, 18(5): 701–716. doi: 10.1007/s11119-016-9482-5.

Pérez-Ruiz, M., Carballido, J., Agüera, J. and Gil, J. A. (2011). 'Assessing GNSS correction signals for assisted guidance systems in agricultural vehicles'. *Precision Agriculture*, 12(5):

639–652. doi: 10.1007/s11119-010-9211-4.

Ploska, K. (2009) ‘*Theory and practice of archaeological heritage management – a European perspective*’. Unpublished PhD thesis. University of Cardiff.

Portable Antiquities Scheme (2015). Treasuring Our Past: Portable Antiquities & Treasure Strategy: 2020 [online]. Available from https://finds.org.uk/documents/file/PAS-strategy-2019.pdf [accessed on 28 August 2019].

Powlesland, D., Lyall, J., Hopkinson, G., Donoghue, D., Beck, M., Harte, A. and Stott, D. (2006). ‘Beneath the Sand - Remote Sensing, Archaeology, Aggregates and Sustainability: a Case Study from Heslerton, the Vale of Pickering, North Yorkshire, UK’. *Archaeological Prospection*, 13: 291–299. doi: 10.1002/arp.

Preston, S. (2014). Archaeological Desk-based Assessment of Land at Shipton Road, Woodstock, Oxfordshire. Reading: Thames Valley Archaeological Services.

Price, T. D. and Bar-Yosef, O. (2011). ‘The Origins of Agriculture: New Data, New Ideas’. *Current Anthropology*, 52(4): 161–S162. doi: 10.1086/660154.

Professional Nutrient Management Group (2018) *Update report on nutrient management planning* [online]. Available from http://www.nutrientmanagement.org/tried-and-tested/2018-pnmg-report/ [accessed on 15 March 2019].

Rapp, G. and Hill, C. L. (2006). *Geoarchaeology: The Earth-Science Approach to Archaeological Interpretation*. 2nd Ed. New Haven and London: Yale University Press.

Richards, I. (2004) ‘Micronutrients in Arable and Field Vegetable Crop Production’, in *International Fertiliser Society*, Proceeding 551.

Römkens: p., de Vries, W. and Kros, H. (2017). ‘Dynamic Cadmium balances in arable soils and grassland soils in the EU: impact of revision of fertiliser regulation on accumulation rates and levels of Cd in soils’ [online]. Available from https://cdn2.hubspot.net/hubfs/2828618/downloads/dynamic-cadmium-balances-in-arable-soils-and-grassland-soils-in-the-eu.pdf?t=1509722697959 [accessed on 6 March 2019].

Roques, S., Kendall, S., Smith, K., Newell Price: p. and Berry: p. (2013). A review of the non-NPKS nutrient requirements of UK cereals and oilseed rape [online]. HGCA Research Review

No. 78. Available from https://cereals.ahdb.org.uk/media/679184/rr78.pdf [accessed on 26 September 2019].

Rowell, D. L. (1994). *Soil Science: Methods and Applications*. First Ed. London: Routledge.

Royal Commission on Environmental Pollution (1996). Nineteenth Report on Sustainable Use of Soil [online]. HMSO: London. doi: 10.1016/S0140-6736(79)91519-8. Available from https://webarchive.nationalarchives.gov.uk/20110322143911/http://www.rcep.org.uk/reports/19-soil/documents/1996-19soil.pdf [accessed on 28 February 2019].

Rudolph, S., Marchant, B. P., Weihermüller, L. and Vereecken, H. (2018). 'Assessment of the position accuracy of a single-frequency GPS receiver designed for electromagnetic induction surveys'. *Precision Agriculture*, 20(1): 1–21. doi: 10.1007/s11119-018-9578-1.

Salisbury, R. B. (2013). 'Interpolating geochemical patterning of activity zones at Late Neolithic and Early Copper Age settlements in eastern Hungary'. *Journal of Archaeological Science*, 40(2): 926–934. doi: 10.1016/j.jas.2012.10.009.

Saunders, N. J. (2002). 'Archaeology and the Great War, 1914-2001'. *Antiquity*, 76: 101–108.

Schmidt, A., Linford: p., Linford, N., David, A., Gaffney, C., Sarris, A. and Fassbinder, J. (2015). EAC Guidelines For The Use Of Geophysics In Archaeology. EAC Guidelines 2. Belgium: Europe Archaeologia Consilium (EAC). Available from https://bradscholars.brad.ac.uk/handle/10454/8129 [accessed on 4 September 2016].

Schmidt, M. J., Py-Daniel, A. R., De, C., Moraes: p., Valle, R. B. M., Caromano, C. F., Texeira, W. G., Barbosa, C. A., Fonseca, J. A., Magalhães, M. P., Silva, D., Santos, C., Da Silva E Silva, R., Guapindaia, V. L., Moraes, B., Lima, H. P., Neves, E. G. and Heckenberger, M. J. (2014). 'Dark earths and the human built landscape in Amazonia: a widespread pattern of anthrosol formation'. *Journal of Archaeological Science*, 42: 152–165. doi: 10.1016/j.jas.2013.11.002.

Scurlock, J., Price, T. and Wordsworth, R. (2017). 'Electric tractors by 2020? – a review of advanced vehicle technology in the agricultural sector' [online]. Available at: http://www.nfuonline.com/assets/93644 [accessed on 3 March 2017].

Sharma, R., Kamble, S. S. and Gunasekaran, A. (2018). 'Big GIS analytics framework for agriculture supply chains: A literature review identifying the current trends and future perspectives'. *Computers and Electronics in Agriculture*, 155: 103–120. doi: 10.1016/j.compag.2018.10.001.

Shepherd, M., Bhogal, A., Philipps, L. and Jackson, L. (2002). 'The nutrient content of cattle manures from organic holdings in England'. *Biological Agriculture and Horticulture*, 20(3): 229–242. doi: 10.1080/01448765.2002.9754967.

Shillito, L.-M., Matthews, W., Almond, M. and Bull, I. (2011). 'The microstratigraphy of middens: capturing daily routine in rubbish at Neolithic Çatalhöyük, Turkey'. *Antiquity*, 85(329): 1024–1038. doi: http://dx.doi.org/10.1017/S0003598X00068460.

Six, L. and Smolders, E. (2014). 'Future trends in soil cadmium concentration under current cadmium fluxes to European agricultural soils'. *Science of the Total Environment*. 485–486: 319–328. doi: 10.1016/j.scitotenv.2014.03.109.

Solomon, D., Lehmann, J., Fraser, J. A., Leach, M., Amanor, K., Frausin, V., Kristiansen, S. M., Millimouno, D. and Fairhead, J. (2016). 'Indigenous African soil enrichment as a climate-smart sustainable agriculture alternative'. *Frontiers in Ecology and the Environment*, 14(2): 71–76. doi: 10.1002/fee.1226.

Sparey-Green, C. (1996). 'Myncen Farm, Sixpenny Handley, Dorset - Interim Report'. In *Proceedings of the Dorset Natural History and Archaeological Society*, 118: 155–157.

Sparey-Green, C. (2007). 'Excavations at Myncen Farm, Sixpenny Handley, Dorset: a Summary Report'. In *Proceedings of the Dorset Natural History and Archaeological Society* 122: 153-157.

Stafford, J. V. (2000). 'Implementing precision agriculture in the 21st century'. *Journal of Agricultural and Engineering Research*, 76(3): 267–275. doi: 10.1006/jaer.2000.0577.

Stockdale, E. A., Griffiths, B. S., Hargreaves: p. R., Bhogal, A., Crotty, F. V. and Watson, C. A. (2019). 'Conceptual framework underpinning management of soil health—supporting site-specific delivery of sustainable agro-ecosystems'. *Food and Energy Security*, 8(2): 0–18. doi: 10.1002/fes3.158.

Stockmann, U., Cattle, S. R., Minasny, B. and McBratney, A. B. (2016). 'Utilizing portable X-ray fluorescence spectrometry for in-field investigation of pedogenesis'. *Catena*, 139: 220–231. doi: 10.1016/J.CATENA.2016.01.007.

Stoner, E. R. and Baumgardner, M. F. (1982). *Characteristic Variations in Reflectance of Surface Soils*. West Lafayette, Indiana: UKS.

Sylvester-Bradley, R., Kindred, D. R., Marchant, B., Rudolph, S., Roques, S., Calatayud, A., Clarke, S. and Gillingham, V. (2017). 'Agronōmics: transforming crop science through digital technologies'. *Advances in Animal Biosciences,* 8 (02): 728–733. doi: 10.1017/S2040470017001029.

Sylvester-Bradley, R., Lord, E., Scott, R., Clare, R., Basford, W., Bryson, R., Clark, W., Clarke, J., Dampney: p., Froment, M., Goodlass, G., Orson, J., Parker, W., Pavely, N., Spink, J. and Wiltshire, J. (1997). The Potential Of Precision Farming From An Agronomic Perspective [online]. HGCA Research Review 37. Available from https://cereals.ahdb.org.uk/publications/1997/november/01/the-potential-of-precision-farming-from-an-agronomic-perspective.aspx [accessed on 14 February 2017].

Tamba, R. (2012). 'Testing the Use of Geostatistics to Improve Data Visualization. Case Study on GPR Survey of Tarragona's Cathedral'. *Archaeological Prospection*, 19: 167–178. doi: 10.1002/arp.1425.

Taylor, K. (2009). 'Biological flora of the British Isles: Urtica dioica L.'. *Journal of Ecology*, 97(6): 1436–1458. doi: 10.1111/j.1365-2745.2009.01575.x.

The Heritage Alliance (2017). 'Rural heritage under threat: looking after our landscapes post Brexit' [online]. Available from http://www.theheritagealliance.org.uk/tha-website/wp-content/uploads/2017/10/Looking-after-our-landscapes-post-Brexit.pdf [accessed on 24 January 2019].

Tilley, C. (1989). 'Excavation as theatre'. *Antiquity*, 63(239): 275–280. doi: 10.1017/S0003598X00075992.

Tremblay, N., Wang, Z., Ma, B. L., Belec, C. and Vigneault: p. (2009). 'A comparison of crop data measured by two commercial sensors for variable-rate nitrogen application'. *Precision Agriculture*, 10(2): 145–161. doi: 10.1007/s11119-008-9080-2.

Trinks, I. and Pregesbauer, M. (2016). 'Efficient mapping of agricultural soils using a novel electromagnetic measurement system' [online]. In *Geophysical Research Abstracts*: p. 2622.

Available from http://adsabs.harvard.edu/abs/2016EGUGA..18.2622T [accessed on 15 October 2019].

Trinks, I., Johansson, B., Gustafsson, J., Emilsson, J., Friborg, J., Gustafsson, C., Nissen, J. and Hinterleitner, A. (2010). ‘Efficient,Large-scale Archaeological Prospection using a True Three-dimensional Ground-penetrating Radar Array System’. *Archaeological Prospection*, 17: 175–186. doi: 10.1002/arp.

Trow, S. (2010). ‘Ripping up history, sordid motives or cultivating solutions? Plough damage and archaeology: a perspective from England’. In Trow, S., Byrnes, E. ad Holyoak, V. (eds) *Heritage Management of Farmed and Forested Landscapes in Europe [online]*. EAC Occasional Paper No. 4. Belgium: EAC. Available from http://old.european-archaeological-council.org/files/eac_4_crop.pdf [accessed on 10 January 2019].

Trow, S. (2018). ‘Archaeology and the State We’re In: Defining a Role for Historic England in the Archaeological Practice of the Twenty-First Century’. *Historic Environment: Policy and Practic*e, 9(2): 83–101. doi: 10.1080/17567505.2018.1456718.

Trow, S., Holyoak, V. and Byrnes, E. (2010). *Heritage Management of Farmed and Forested Landscapes in Europe [online]*. EAC Occasional Paper No. 4. Belgium: EAC. Available from http://old.european-archaeological-council.org/files/eac_4_crop.pdf [accessed on 10 January 2019].

Trow, S., Holyoak, V. and Fachtna McAvoy (2007) ‘Understanding plough damage: Research in Field and Lab’. *The Archaeologist*, 63: 32–33.

UK National Ecosystem Assessment (2014). ‘The UKNEA Follow-on: Synthesis of the Key Findings’ [online]. Available from http://uknea.unep-wcmc.org/Resources/tabid/82/Default.aspx [accessed on 5 September 2019]. doi: 10.1177/004057368303900411.

UNESCO (1972) Convention Concerning The Protection Of The World Cultural And Natural Heritage [online]. Available from http://whc.unesco.org/uploads/activities/documents/activity-562-4.pdf [accessed on 27 March 2019].

Vecco, M. (2010). ‘A definition of cultural heritage: From the tangible to the intangible’. *Journal of Cultural Heritage*, 11(3): 321–324. doi: 10.1016/j.culher.2010.01.006.

Verhoeven, G. (2009*). Beyond Conventional Boundaries*. Unpublished PhD thesis. Univeriteit Gent.

Webb, J., Fraser, A., Wiltshire, J., Jephcote, C., Rose, R. and Vincent, K. (2015). *Review of crop requirements for sulphur and the adequacy of current sulphur fertilizer recommendations*. Project SCF0308. Published online: Defra.

Webber, H. (2014). *Archaeological Geophysics and Precision Farming*. Unpublished MPhil dissertation. University of Bristol.

Webber, H., Heyd, V., Horton, M., Bell, M., Matthews, W. and Chadburn, A. (2019). 'Precision farming and archaeology'. *Archaeological and Anthropological Sciences*, 11(2): 727–734. doi: 10.1007/s12520-017-0564-8.

Webley, L., Vander Linden, M., Haselgrove, C. and Bradley, R. (2012). *Development-led archaeology in Northwest Europe*. Oxford: Oxbow Books.

Webster, R. (1994). 'The development of pedometrics'. *Geoderma*, 62(1–3): 1–15. doi: 10.1016/0016-7061(94)90024-8.

Weindorf, D. C., Bakr, N. and Zhu, Y. (2014). 'Advances in Portable X-ray Fluorescence (PXRF) for Environmental, Pedological, and Agronomic Applications'. *Advances in Agronomy:*1-45. doi: 10.1016/B978-0-12-802139-2.00001-9.

Wessex Archaeology (2004). Myncen and Goldfields Farms, Minchington, Dorset [online]. Available from https://www.wessexarch.co.uk/sites/default/files/52568_Minchington.pdf [accessed on 21 September 2015].

Wickstead, H. and Barber, M. (2010). 'A Newly Recorded Hilltop Enclosure at Myncen Farm, Minchington'. *Proceedings of the Dorset Natural History and Archaeological Society*, 131: 103–112.

Wiedner, K., Schneeweiß, J., Dippold, M. A. and Glaser, B. (2015). 'Anthropogenic Dark Earth in Northern Germany — The Nordic Analogue to terra preta de Índio in Amazonia'. *Catena*, 132: 114–125. doi: 10.1016/j.catena.2014.10.024.

Williamson, A. (2014). *Precision agriculture: how to realise the full potential.* Nuffield Farming Scholarship Trust Report.

Wilson, C. a., Davidson, D. a. and Cresser, M. S. (2008). ‘Multi-element soil analysis: an assessment of its potential as an aid to archaeological interpretation’. *Journal of Archaeological Scienc*e, 35(2): 412–424. doi: 10.1016/j.jas.2007.04.006.

Wilson, D. R. (1975). Aerial reconnaissance for archaeology [online]. Council for British Archaeology Research Report No 12. Available from https://archaeologydataservice.ac.uk/archives/view/cba_rr/rr12.cfm [accessed on 3 September 2019].

Wilson, D. R. (1982). *Aerial photograph Interpretation for Archaeologists*. London: Batsford.

Yara International (2018). Yara Fertilizer Industry Handbook [online]. Available at: https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2018/fertilizer-industry-handbook-2018-with-notes.pdf/ [accessed on 5 March 2019].

Yorston, R. M., Gaffney, V. L. and Reynolds: p. J. (1990). ‘Simulation of artefact movement due to cultivation’. *Journal of Archaeological Science,* 17(1): 67–83. doi: 10.1016/0305-4403(90)90015-W.

Zhang, N., Wang, M. and Wang, N. (2002). ‘Precision agriculture—a worldwide overview’. *Computers and Electronics in Agriculture*, 36(2–3): 113–132. doi: 10.1016/S0168-1699(02)00096-0.

Zhao, W., Tian, G., Forte, E., Pipan, M., Wang, Y., Li, X., Shi, Z. and Liu, H. (2015). ‘Advances in GPR data acquisition and analysis for archaeology’. *Geophysical Journal International*, 202(1): 62–71. doi: 10.1093/gji/ggv121.

Websites used:

https://www.claas.co.uk/products/easy-2018/retrofit-gps-steering-systems/correction-signals accessed 02/02/19

https://www.dji.com/uk/products/phantom?site=brandsite&from=nav accessed 13/10/19

https://www.dronedeploy.com/ accessed 13/10/19

https://www.agrii.co.uk/products-services/precision-farming/ accessed on 13/10/19 https://www.fwi.co.uk/arable/land-preparation/soils/how-three-growers-hope-to-improve-soil-health-in-yorkshire accessed 13/10/19

https://www.soyl.com/ accessed on 01/02/19

http://www.precisiondecisions.co.uk/ accessed on 01/02/19

http://www.ipf-uk.com/ accessed on 01/02/19

http://www.ag-space.com/ accessed on 01/02/19

https://droneag.farm/ accessed on 01/02/19

http://www.handsfreehectare.com/ accessed on 02/02/19

https://gtr.ukri.org/projects?ref=NE%2FP008860%2F1 accessed on 13/10/19

https://agrimetrics.co.uk/home accessed on 13/10/19

http://www.kypwest.org.uk/ accessed on 22/10/19

https://historicengland.org.uk/listing/the-list/list-entry/1021367 accessed 03/11/19

https://www.rhizadigital.co.uk/contour/ accessed on 04/11/19

http://nsgg.org.uk/meetings/old/nsgg2012/abstracts_2012.pdf accessed on 05/05/19

https://www.iof2020.eu/blog/2019/04/artificial-intelligence-for-digital-precision-agriculture accessed on 12/11/19

https://ec.europa.eu/commission/presscorner/detail/en/IP_18_6161 accessed on 12/11/19

https://www.soyl.com/services/variable-depth-cultivation accessed 12/11/19

https://blog.micasense.com/archaeological-surveys-with-drone-mapping-563ac0329208 accessed on 04/11/19)

http://www.wrap.org.uk/content/bsi-pas-110-producing-quality-anaerobic-digestate accessed 15/02/19

http://www.wrap.org.uk/sites/files/wrap/PAS%20100_2011.pdf accessed 15/02/19

https://statistics.laerd.com/spss-tutorials/principal-components-analysis-pca-using-spss-statistics.php accessed on 17/04/17 https://www.gov.uk/government/publications/sewage-sludge-in-agriculture-code-of-practice/sewage-sludge-in-agriculture-code-of-practice-for-england-wales-and-northern-ireland accessed 02/02/19

https://ahdb.org.uk/greatsoils accessed 10/07/19

https://www.cranfield.ac.uk/research-projects/soil-mapping accessed on 25/10/19

Websites accessed multiple times:

https://digimap.edina.ac.uk/os

https://environment.data.gov.uk/DefraDataDownload/?Mode=survey

https://digimap.edina.ac.uk/historic

https://www.britainfromabove.org.uk/

https://archaeologydataservice.ac.uk/

https://archaeologydataservice.ac.uk/archives/view/ehgsdb_eh_2011/

https://digimap.edina.ac.uk/geology

http://www.landis.org.uk/

http://www.ukso.org/

http://mapapps2.bgs.ac.uk/geoindex/home.html

https://finds.org.uk/

https://www.bgs.ac.uk/data/boreholescans/home.html

https://www.metoffice.gov.uk/datapoint/product/historical-station-obs

Legislation Referenced:

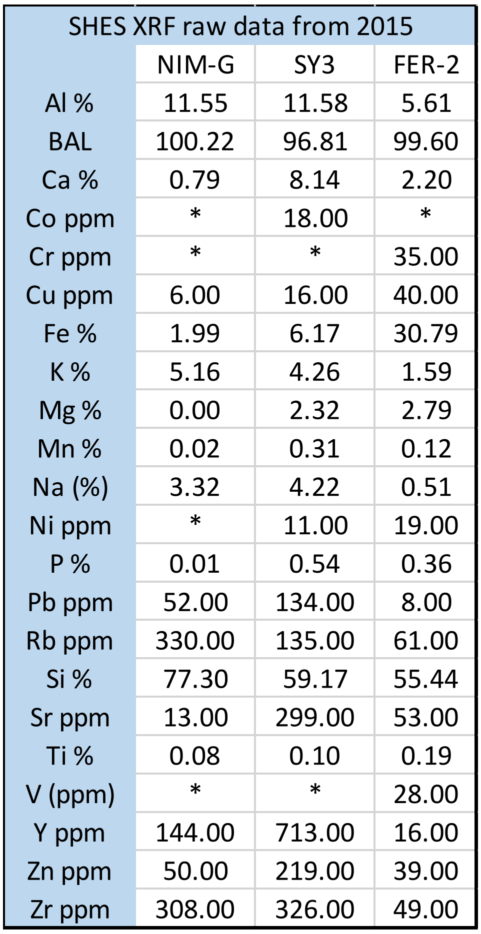
HM Government (1882) ‘Ancient Monuments Protection Act’: p. 12. Available at: http://www.legislation.gov.uk/ukpga/1882/73/pdfs/ukpga_18820073_en.pdf%0Ahttp://www.unesco.org/culture/natlaws/media/pdf/gb/uk_act_1882_orof.pdf [accessed on 28 July 2019]/

Environmental Protection Act (1990). Great Britain. Available at: https://www.legislation.gov.uk/ukpga/1990/43/pdfs/ukpga_19900043_en.pdf [accessed on 28 July 2019].

12 pXRF Methodological Appendix

In addition to the methods set out in Chapter 5 surrounding the use of pXRF in this thesis, the following appendix adds some further evaluations to the usefulness of pXRF in soil studies. While in Chapter 5, and in the critique of the methodology in Section 10.2, the issues of instrument stability, sampling design and sampling preparation have been covered, one crucial issue is that of quantitative accuracy of pXRF over time in comparison to lab-based instruments. A key aspect of much archaeological and geoarchaeological work on pXRF relates to the ability to make meaningful comparisons between archaeological objects or sites, based on the quantity of elements within the sample.

To evaluate this, existing reference standards that show a range of elemental ratios were homogenised and set in resin discs and analysed by lab-based XRF in 2015 by staff at the University of Reading (Table 18).



SHES XRF raw data from 2015			
	NIM-G	SY3	FER-2
Al %	11.55	11.58	5.61
BAL	100.22	96.81	99.60
Ca %	0.79	8.14	2.20
Co ppm	*	18.00	*
Cr ppm	*	*	35.00
Cu ppm	6.00	16.00	40.00
Fe %	1.99	6.17	30.79
K %	5.16	4.26	1.59
Mg %	0.00	2.32	2.79
Mn %	0.02	0.31	0.12
Na (%)	3.32	4.22	0.51
Ni ppm	*	11.00	19.00
P %	0.01	0.54	0.36
Pb ppm	52.00	134.00	8.00
Rb ppm	330.00	135.00	61.00
Si %	77.30	59.17	55.44
Sr ppm	13.00	299.00	53.00
Ti %	0.08	0.10	0.19
V (ppm)	*	*	28.00
Y ppm	144.00	713.00	16.00
Zn ppm	50.00	219.00	39.00
Zr ppm	308.00	326.00	49.00

Table 18: Lab-based XRF data for the three reference standards used to check the stability of the pXRF

From these accurately measured values, it was then possible to compare the pXRF values for each reference standard to the values from the pXRF analysis of each standard over time during this project (2015-2018). The results are shown below in Figures 164-168.

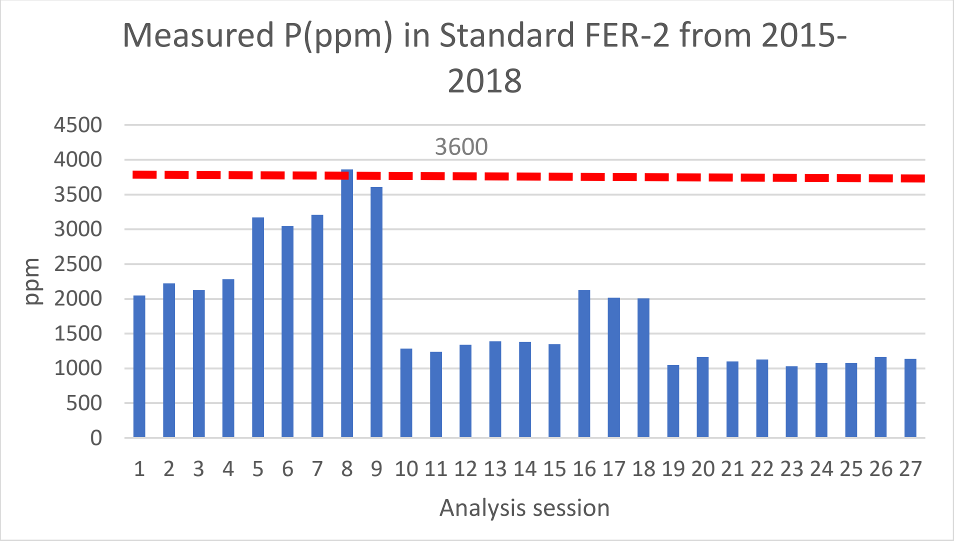


Figure 164: Variability in the pXRF detection of P in standard FER-2 over time compared to lab-based XRF

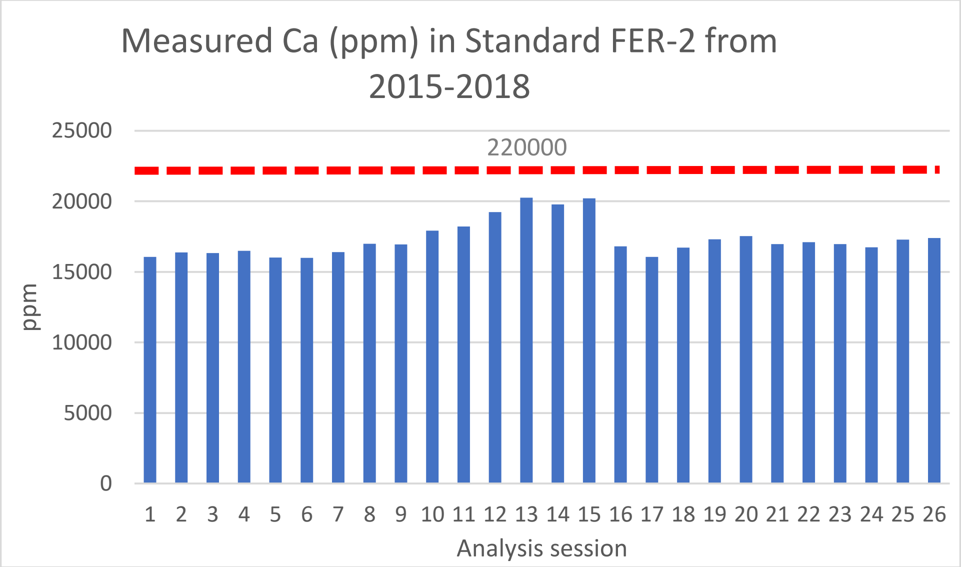


Figure 165: Variability in the pXRF detection of Ca in standard FER-2 over time compared to lab-based XRF

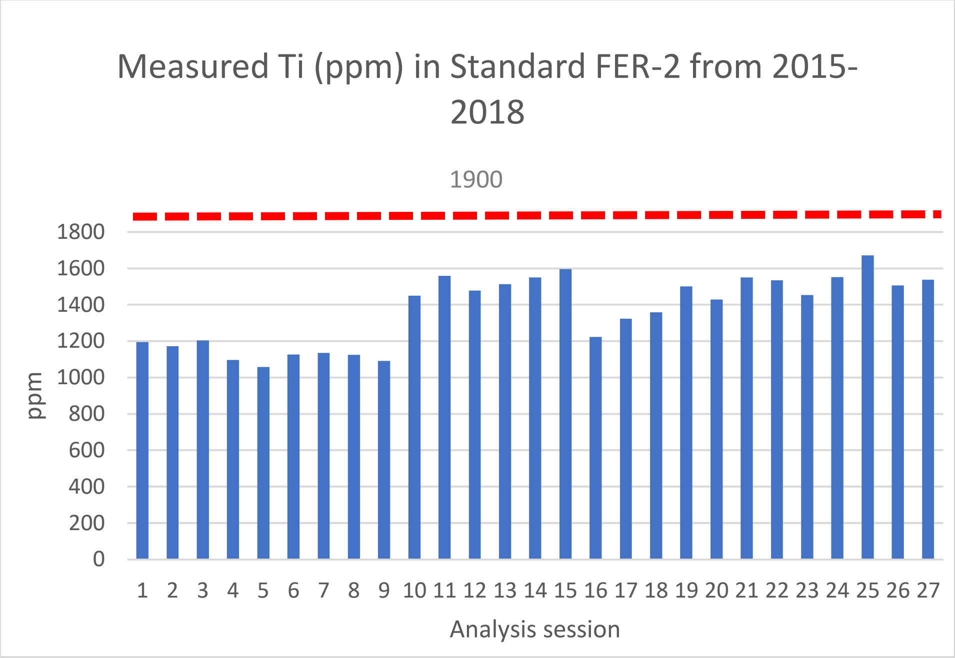


Figure 166: Variability in the pXRF detection of Ti in standard FER-2 over time compared to lab-based XRF

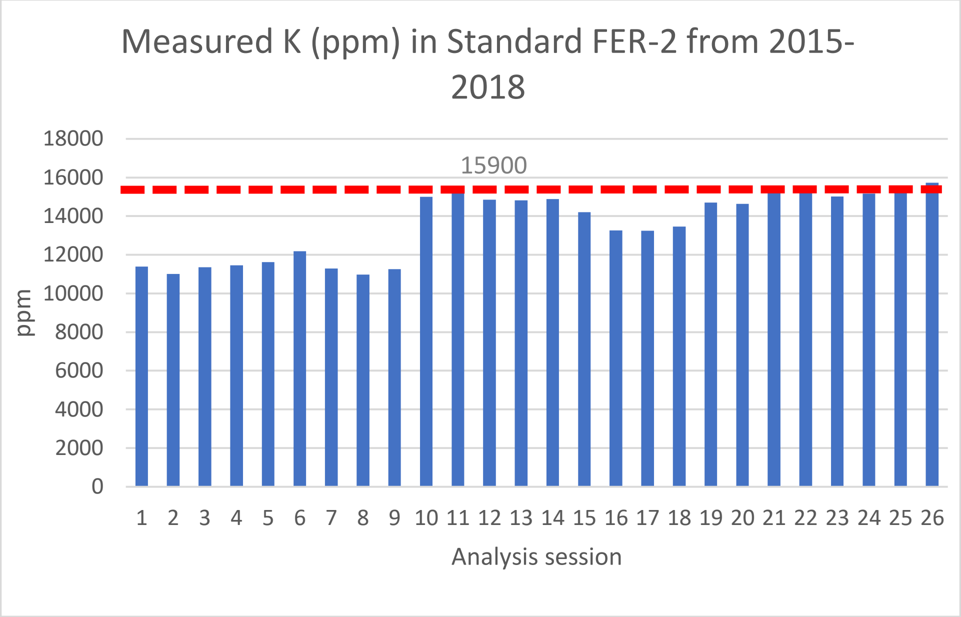


Figure 167: Variability in the pXRF detection of K in standard FER-2 over time compared to lab-based XRF

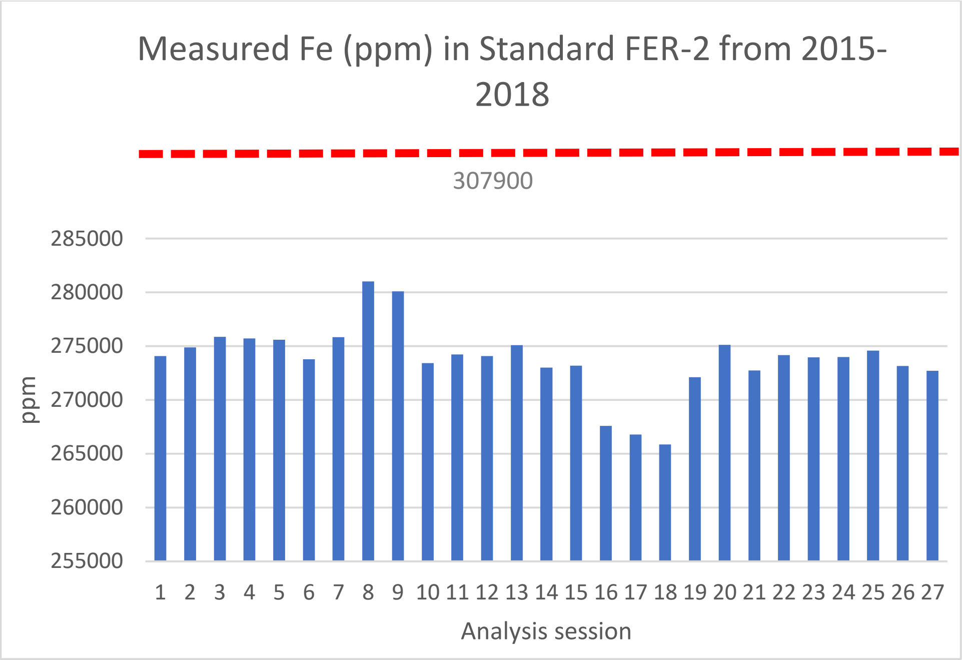


Figure 168: Variability in the pXRF detection of Fe in standard FER-2 over time compared to lab-based XRF

One result is that the pXRF seems to consistently detect lower values than the lab-based XRF in nearly every circumstance. In some cases the values are not far from the lab-based values (K), whereas others (Fe and P) vary by a significant percentage. The variation between elements is to be expected due to the nature of the method, lighter elements take more X-Ray energy to displace electrons in comparison to heavier elements. However the lower detection could be caused by a number of reasons. It could be related to the length of exposure time, the voltage and ampere settings of the two instruments, but could also be degradation of the actual reference standards as over time being used by multiple people, could cause variation in the surface of the standard. The amount of variation in the levels of P, when considering archaeological variations could be only 10s or 100s of ppm, is quite significant and certainly raises queries over the ability to accurately compare quantities over reasonable periods of time, especially without any other stratigraphic or spatial evidence to supplement the interpretation of quantitative data.

Despite this, as with all scientific procedures of analysis, careful methodological planning is necessary to ensure the results are suited to the objectives of the study. For example in this study the absolute quantitative accuracy was not essential in comparison to the spatial relativity of the sampling and analysis to provide results. It is also fundamental to ensure references standards fit target elements, represent the samples for analysis, and are tested regularly across multiple instruments for the best accuracy, a similar procedure to lab-based methods, even with the portability of the pXRF.