An interdisciplinary approach to mapping soil carbon

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Abstract – An interdisciplinary approach to mapping soil carbon

Beth Frances Theresa Brockett BSc (Hons), MSc. December 2015. This thesis is submitted in fulfilment of the requirements for the degree of Doctor of Philosophy.

At the global scale, soils are the primary terrestrial reservoir of carbon and therefore have a major influence on the concentration of carbon dioxide in the atmosphere. Soil organic carbon stocks are estimated to have decreased by an average of fifty two percent in temperate regions since 1850. Land use change and management practices are the primary drivers of this decrease. Temperate upland regions have been identified as important for climate regulation, both in terms of current stocks of soil carbon and future sequestration potential. Therefore, appropriate on-farm management of soil carbon stocks in these regions has the potential to contribute to climate change mitigation goals.

This thesis is a contribution to ongoing efforts to improve on–farm soil carbon management. It does so through the development of mapping practices that incorporate both ecological and social data. The ecological aspect of the research identified a role for existing farm survey data in accurately predicting soil carbon distribution without the need for time and labour-intensive field work. The engagement with social science methods acknowledges a societal bias towards scientific ways of representing soil carbon and the marginalisation of alternative, often experiential, knowledge. The research demonstrated a way for different knowledges to be incorporated into soil carbon mapping practices and identified a role for under-utilised scientific and non-scientific knowledge of soil carbon for improving spatially-explicit management plans.

The mapping methods were developed around three case study farms in the Lake District National Park in Cumbria. This region is an upland landscape which has been identified as an important space for carbon management in the UK.

The research offers a distinct and timely approach to assessing the potential of interdisciplinary mapping to improve the management of soil carbon at the farm scale and has wider implications for the management of ecological systems.

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List of Acronyms

AES – agri-environment schemes

BAP – Biodiversity Action Plan

C – carbon

CAP – Common Agricultural Policy

COP21 – Conference of Parties (21)

CWF – community weighted functional (traits)

ES – ecosystem services

GIS – geographical information systems

GV – grounded visualisation

IDR – inter-disciplined researcher

INDC – Intended Nationally Determined Contributions

LDNP – Lake District National Park

MMM – mixed methods mapping

N – nitrogen

NRM – natural resource management

NVC – National Vegetation Classification (system)

PGIS – participatory geographical information systems

QualGIS – qualitative geographical information systems

SOC – soil organic carbon

STS – Science and Technology Studies

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1 Introductory Chapter

1.1 Context

In May of this year, carbon dioxide (CO_2) levels in the Earth's atmosphere surpassed 400 parts per million for the first time on record[1]. Approximately 2,293 petagrams (billion tonnes) of carbon is stored in soil globally[2], which is three times as much as is stored in the atmosphere (Batjes 2014). Moreover, emissions from land use and land cover change are, after emissions from fossil fuel combustion, the second largest anthropogenic source of carbon into the atmosphere (Smith et al. 2014). Conversely, appropriate land management can assist in the removal of carbon from the atmosphere through long term storage in soils (sequestration), and so contribute to climate change mitigation (Lal 2011). Soil carbon also plays an integral role in the functioning of soil, and therefore in food security and ecosystem health (Goulding et al. 2013).

Soil carbon plays a key role in climate mitigation, and has therefore become a topic of great interest to governments and scientific bodies globally. Soil carbon is made up of inorganic and organic carbon. Soil inorganic carbon (carbonate) is predominantly geologically-derived and its role in the active management of soil carbon stocks is generally considered to be insignificant (Monger 2014). Soil organic carbon (SOC) is biologically-derived and the amount in soil is related to the balance between the amount of organic matter entering soils, from plants and animal wastes, and the amount that is released by decomposition, which is largely performed by soil organisms (Ontl and Schulte 2012). SOC is central to soil health, and the benefits of maintaining SOC include greater water and nutrient retention, and improved soil structure resulting in less erosion and soil degradation (Reeves 1997). Reflecting this important role, 2015 was designated the 'International Year of Soils' and the United Nations Food and Agriculture Organisation released the first 'Status of the World Soil Resources Report' on the 4th of December. The report states that the global loss of SOC pool since 1850 is estimated at about 66 +/- 12 petagrams (corresponding to a 52% decrease in

[1] Recorded at the US National Oceanic and Atmospheric Administration research station in Mauna Loa, Hawaii.
[2] "Total terrestrial soil carbon pools … excluding carbon held in the litter layer and charcoal, amounts to 2157–2293 Pg of C in the upper 100 cm" (Batjes 2014, 10).

temperate regions), largely as a result of land use change and land management practices (FAO and ITPS 2015). This thesis is a contribution to ongoing efforts to improve soil carbon management.

Soil carbon loss results from ecological and from human-ecological interactions, such as land clearance and climate change. For example, in 2015 the uncontrolled burning of massive areas of Indonesia's forested peat soils resulted from land clearance for agriculture. These fires are emitting up to an estimated 15 megatonnes (million tonnes) of carbon per day[3] (as of 24.11.15), surpassing average daily emissions from the entire US economy[4]. Furthermore, the drainage of wetland areas, land disturbance for mining projects, and deforestation are also among the key land management practices that result in large fluxes of carbon to the atmosphere. Soil carbon levels can sometimes be restored through appropriate land management techniques, which can include re-wetting via blockage of drainage systems, afforestation and adding organic matter directly to soils, such as farm yard manure and crop residues (Ostle et al. 2009; Bussell et al. 2010; Powlson et al. 2011). The effectiveness of these restorative practices depends on place-specific environmental conditions; such as soil type, topography, hydrology, grazing, and climate. Effectiveness is also influenced by human factors, such as commitment to restoration practices, knowledge, agency, financial circumstance, cultural practices, and future plans. There is therefore a need to develop participatory decision-making processes which engage with local stakeholders to recognise the varied human influences on the success of soil carbon management schemes, alongside examining ways of optimising the environmental conditions for soil carbon sequestration.

Several reports have highlighted the potential to increase soil carbon stocks on a regional or national scale. For example, in Europe, Haines-Young and Potschin (2009) identified extensively-farmed agricultural landscapes of English upland regions as important assets for the UK in terms of climate regulation, both in terms of current stocks of soil carbon and future sequestration potential. Further,

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[3] Data from the Global Fire Emissions Database http://www.globalfiredata.org (accessed 24.11.15).

[4] http://www.wri.org/blog/2015/10/indonesia%E2%80%99s-fire-outbreaks-producing-more-daily-emissions-entire-us-economy (accessed 24.11.15).

Schulte et al. (2013) outline the potential for Irish agriculture to be 'carbon neutral', whereby national greenhouse gas (GHG) emissions from agriculture are fully offset by carbon sequestration in grassland soils, through afforestation and other land management changes. At the time of writing, an ambitious agreement at the United Nations Convention on Climate Change (UNFCCC) Conference of Parties (COP21) in Paris (December 2015) could also have implications for national land management policies as governments look to achieve challenging national targets to reduce GHG emissions.

This thesis is a direct contribution to research on participatory approaches to soil carbon management. Specifically, the aim of the thesis is to develop an interdisciplinary approach to mapping soil carbon on farms which explicitly considers humans and their interactions with soil carbon as central to the mapping process. In the following section I discuss why and how an interdisciplinary approach was used. I then outline the objectives of the thesis by chapter and end this chapter by describing the study area.

1.2 Why and how I used an interdisciplinary research approach

Soil carbon studies have typically been the preserve of scientists – soil chemists, ecologists, agronomists, or those in professions which utilise scientific knowledge of soil carbon – farm environment advisors and policy-makers. However, this thesis demonstrates there are other actors and methods, scientific and non-scientific, who/which also need to be considered in the management of soil carbon stocks. There has been a dominant assumption within society that a scientific way of knowing and managing soil carbon is the best framework for managing soil carbon on-the-ground (Ingram et al. 2014). However, in recent years a lot has been written about interdisciplinary approaches to 'messy' environmental and social problems, issues which do not seem to lend themselves to easy solutions by traditional approaches or methods of analysis (Robinson 2008; Donaldson et al. 2010). Soil carbon management is an excellent example of such a messy problem, as it requires both ecological and human (i.e. cultural, economic, social) factors to be taken into account in seeking to advance knowledge, develop more effective policies and improve land management practice. The conventional academic approach to researching such topics, by dividing them into neat disciplinary questions, is challenged by an interdisciplinary approach, which utilizes collaboration among academic disciplines and often between science overall and civil society.

In this thesis an interdisciplinary, mixed methods (quantitative and qualitative) research approach challenges the standard policy approach to mapping farm environments, which maps quantitative measures of scientifically defined-units, such as biodiversity, GHG emissions and soil carbon, and rarely formally integrates other ways of knowing the farm environment. Farms are socio-ecological systems and farmers hold knowledge about their land and soils, hold opinions about how they are best managed, and are affected by financial, social, cultural and other influences in making decisions about and performing land management practices. Through engaging farmers in the process of mapping soil carbon on their farms and recognising and working with different forms of knowledge about soil carbon, new and better approaches to mapping soil carbon as a socio-ecological entity are developed.

Interdisciplinary research is defined and understood to be research that "analyzes, synthesizes and harmonizes links between disciplines into a coordinated and coherent whole"[5] (Choi and Pak 2006, 351). The adopted approach builds on Donaldson et al's (2010) 'radical interdisciplinarity', which involves the sustained interrogation of, and engagement with, different research approaches and practices to generate new modes of working. My approach to interdisciplinarity in this thesis is as a single 'inter-disciplined researcher' (my term), as distinct from a disciplinary researcher working within an interdisciplinary research environment; the latter is usually conducted with a team of researchers and is the context for most of the literature on interdisciplinary research practice (e.g. Barry et al. 2008; Lowe and Phillipson 2009; Donaldson et al. 2010). Thus, as also experienced by inter-disciplined student researchers Evans and Randalls (2008), this approach has provided novel challenges.

[5] As opposed to multidisciplinary research which "draws on knowledge from different disciplines but stays within their boundaries") (Choi and Pak 2006, 351).

The study draws on the discipline of Science and Technology Studies (STS) to better understand the way in which knowledge is created, and shed new light on how to involve communities with differing, and sometimes competing, knowledge claims. STS understands knowledge not as statements of truth about the world but as something created by a 'knowledge community', using a set of skills, conventions, materials, technologies, assumptions, (the list goes on) (Sismondo 2009). By understanding knowledge as a culturally-created product, rather than as statements of truth viewed from different perspectives, it is possible to understand why it can be difficult to work across disciplinary boundaries. Members of a particular knowledge community (e.g. soil scientists) are likely to approach 'knowledge creation' (i.e. knowledge about soil) and what they consider to be legitimate or 'stable' knowledge (Sismondo 2009) in a different way to a community of famers, for example, who also know a lot about soil but use a different set of skills, conventions, materials (and so on) to create their understandings and knowledge. These different knowledges often do not 'map' directly onto one another. The skill of interdisciplinary research on a particular topic, like soil carbon management, is to draw together diverse knowledge production methods and create new insights despite such foundational differences.

The variation in how knowledge is constructed and considered legitimate (or stable) between different knowledge communities can be the cause of difficulties in multi- or interdisciplinary projects, as can variation in the ontological basis of different knowledge practices. This can manifest as distinct outlooks, beliefs and identities (Lowe and Phillipson 2009). Ontology refers to metaphysical issues concerned with the nature of existence and the structure of reality – what actually exists and what does not – and "the 'logic of ontology' sees interdisciplinary research as driven by the desire to challenge the assumed nature of the objects and practices of research" in an attempt to reconceptualise the basis for research towards producing new types of knowledge (Donaldson et al. 2010, 1524).

In studying soil carbon I wanted to address the topics, the priorities, the concerns and the questions that different knowledge practices insist on; to understand how different knowledge practices know soil carbon, and how this determines how they research it, or otherwise work with it; which in STS terminology is how they 'perform' or 'enact' it (Mol 2014). I did not want to be bound by any one knowledge practice/way of knowing soil carbon, maps and farms but combine knowledge production methods.

Within my research I drew from the disciplines of plant ecology, especially recent work on plant traits and their links with soil processes (Chapter Three); geospatial analysis, recognising the role of mapping in environmental management; and, Critical Cartography and Feminist GIS (described in Chapter Two), which led to my considering an STS/Feminist Technoscience perspective on mapping soil carbon (Chapter Five). Each discipline fed into the on-going mapping process and by 'keeping the toolbox open' I suited the methodological and theoretical tools to emergent understandings and insights within an iterative process. I also drew from my own mixed disciplinary background and non-academic experience working with stakeholders, including my soil science training and management of a project which negotiated the management of a contested ecosystem – an ecosystem within which the focus, type or style of human management is disputed.

This research experience has led me to understand that interdisciplinary research is not just tied to a specific project, but often requires engagement with wider academic processes. Alongside my thesis research, I explored interdisciplinary research and interdisciplinarity outside of my doctoral project. The formation of an interdisciplinary peer-network and engagement with a wider regional and international body of interdisciplinary researchers crucially informed my research practice and opened my mind to consideration of a wider range of knowledge traditions. As well as providing inspiration, these activities and connections gave me courage to try novel and risky avenues in my research.

1.3 Research objectives and thesis outline

Chapter Two asks the broad question: how can we map soil carbon in an interdisciplinary way? As a chapter it has a number of objectives: to provide a broad literature review; outline the overall methodology; and, present my findings regarding the existing role of maps on farms in the study region. The latter because a key part of the initial research process was to develop a better understanding of existing mapping practices and processes and explore how maps are currently used for environmental and resource management on farms in England. The chapter then develops a methodology which explores how mapping as a process can be reimagined as a way of bringing different knowledge communities into the soil management process, rather than viewing maps solely as representations of a scientific truth.

The chapter is written for a multi-disciplinary audience and the choice of narrative style was based on a desire to draw the different disciplines together, whilst exploring how the interdisciplined research evolved. This can be referred to as 'observant participation', which (Kitchin et al. 2013, 6) state is: "a self-reflexive exercise … in which the researcher strives to rigorously examine their own practices … charting the ways in which their research, and the reaction to that research, unfolds". Its inclusion in this chapter was considered important in order to reveal how the interdisciplinary research process, as well as the findings (and connections between the two), led to a more unusual doctoral project process. The first person chronological narrative of Chapter Two allows for the iterative and reflexive nature of the process to be made apparent.

Chapter Three – The project recognises that is important to know, or be able to accurately predict, the spatial distribution of carbon stocks when developing land/soil carbon management plans (FAO and ITPS 2015). Currently the creation of such soil maps requires time and resource-intensive field work and laboratory analysis to generate location-specific coverage of soil carbon values. Alternatively, standardised or proxy carbon storage figures can be used (Jones et al. 2005; Eigenbrod et al. 2010), but these have limitations with regard to how soil carbon storage is differentially affected by variation in local environmental and management conditions (e.g. McSherry and Ritchie 2013). Another way of predicting the amount of carbon stored in different soils is to utilise biogeochemical models, which are used to model the turn-over of carbon in soils (Cerri et al. 2007; Powlson et al. 2008), however the paucity of data at sufficiently high resolution precludes farm-scale predictions. Methods which utilise remotely-sensed vegetation data to predict spatial patterns in soil carbon storage are also being developed, however access to data remains an issue[6], such data analyses can be complex and expensive and the integration of *in situ* data from local ecologists and expert knowledge from remote sensing analysts is limited (Pettorelli et al. 2014). If we wish to engage with farmers and land managers and identify management changes which will promote soil carbon storage, there is a need to develop methods which accurately predict existing spatial soil carbon distributions at the farm scale – the scale at which most agri-environment management schemes are delivered – without resorting to time- and resource-intensive methods.

In Chapter Three this research objective is addressed through testing the utility of easily available and accessible farm vegetation maps, produced for the delivery of existing agri-environment schemes (AES), along with basic information on soil properties for use as proxies for the farm-scale prediction of soil carbon. The format is that of a scientific academic journal article (except for the inclusion of a preface). The article addresses three specific research questions across three case study farms:

i. Is it possible to predict total soil carbon stocks, to depth, at a farm-scale within topographically heterogeneous landscapes by utilising simple measures of vegetation and soils derived from information commonly used within agri-environment schemes?
ii. Is it possible to create accurate maps of soil carbon stocks by utilising these simple measures?
iii. Is there a role for such maps in improving soil carbon management planning?

Chapter Four is also in the format of an academic journal article (except for the inclusion of a preface) – written for the Journal of Applied Ecology and an ecologist audience. The article's objective is to demonstrate how qualitative local knowledge can be valuable for ecological research by asking which socio-ecological considerations improve the design and delivery of an agri-

[6] This project was originally to have used such data but was unable to access it.

environment scheme, where the criterion for success is improved soil carbon storage. In order to achieve this, the article specifically addresses:

i. How farmers and other agricultural professionals understand, experience and currently manage for soil carbon (if at all);
ii. Asks about farmers' experiences of agri-environment schemes (AES) and the role of mapping in planning for and delivery of AES;
iii. Considers whether mapping using mixed methods Geographical Information Systems (GIS) can uncover place-based farmer experiences and understandings of AES and soil carbon; and,
iv. Explores associated policy recommendations to improve the planning, delivery, and so therefore ecological success, of 'carbon farming' schemes – whereby, through management of land, carbon is accumulated over the long-term (approximately one hundred years or more; Stockmann et al. 2013) within soil or vegetative biomass.

Chapter Five is written for an interdisciplinary environmental social science (sociology, human geography) audience. It develops the idea that there are multiple soil carbons; entities performed in different ways by 'soil carbon collectives'. Soil carbon collectives are humans and non-human things brought together around a concept of soil carbon (e.g. scientists, scientific equipment, protocols, sample sites etc.). Conceived as a way to move past contested (disputed) representations of soil carbon on the case study farms, it is a significant departure from usual approaches to the management of soil carbon. The chapter was strongly influenced by the work of researchers at Lancaster University and the Centre for Ecology and Hydrology (CEH) who used an interdisciplinary approach to research a water quality issue at Loweswater, a study site near to my own (Waterton et al. 2006; Tsouvalis and Waterton 2012; Waterton and Tsouvalis 2015).

Chapter Six presents and discusses the research conclusions, explores the implications for the future, and offers recommendations for future research and policy and practice in managing soil carbon.

1.4 Study region

The research centres on three extensive (low-input) upland sheep farms in the Lake District National Park (LDNP) in the northwest of England. The LDNP is an example of an upland landscape which has been identified as an important space for carbon management (Lake District National Park Authority 2015). The area is topographically varied, with a cool and wet climate. Largely deforested from the late Bronze Age onward, it is now a patchwork of low-input 'rough grazing' grasslands, 'improved' and 'semi-improved' more intensely-managed grasslands, heath, wet areas, woodland, and scrub vegetation. The average hill farmer in the LDNP is 56 years old, with 94 hectares (ha) of 'inbye' (improved/semi-improved grassland), 236 ha of rough grazing and 14 ha of woodland, with access to common grazing equivalent to about 25% of the farm's own rough grazing holding (Harvey et al. 2013). The average farm carries 45 suckler cows and 840 breeding ewes (Harvey et al. 2013). There are extensive tracts classed as 'Less Favoured Areas'[7] for farming by the UK Government. Due to the low income-potential of managing land for food production alone (Rockliffe 2009) and because of a strong regional association with 'landscapes of preservation' – landscapes valued because they are stable and unchanging (Tsouvalis et al. 2012) – farmers in the Lake District region have a wealth of experience in managing their farmland to deliver environmental public goods alongside food production. Total Single Payment Scheme[8] and agri-environment payments to farmers in the LDNP are estimated to be in the region of £25-30 million per annum (Harvey et al. 2013).

Recent agricultural policy interventions in this region have caused tensions. Frictions and political impasse have been documented after policy interventions such as those in reaction to the Chernobyl disaster (Wynne 1989), the bovine spongiform encephalopathy (BSE) crisis in the 1990s, the 2001 foot and mouth

[7] This means land located and included in the list of less favoured areas adopted by Article 2 of European Council Directive No.75/268EEC on mountain and hill farming in less favoured areas. In the UK, there are two distinct classifications - the Severely Disadvantaged Area (SDA) or the Disadvantaged Area (DA). DA and SDA land is generally suitable for extensive livestock production and for the growing of crops for livestock feed, but agricultural production is restricted (and for SDA areas, severely restricted) by soil, relief, aspect or climate conditions (UK Government 2012).

[8] The 'basic' agricultural subsidy scheme for farmers in the European Union.

disease epidemic (Christie et al. 2002; Law and Singleton 2014), and as a result of reductions in livestock stocking densities on Biodiversity Action Plan priority habitats after Common Agricultural Policy reform and as part of AES.

1.4.1 The case study farms

Farm 1 was recruited by invite after being identified as a good fit for the scientific research aims. It is a 34 ha holding with access to approximately 150 hectares of common grazing. It is the only farm which is contained in one continuous land parcel. As with the other two case study farms it has been in the family for numerous generations. It is managed by a husband and wife team who live on the holding. One of their sons hopes to take on the farm on their retirement. Some parts of the farm were in the Higher Level Scheme (an AES) at the time of data collection. They farm sheep mostly but also have a small herd of beef cattle. It is topographically the most variable. As with many hill farms it has limited inbye.

Farm 2 was recruited through the 'snowball technique'. It is a 95 ha tenanted holding with access to a 350 ha common and with an additional 60 ha rented from other land owners. The farm is split across two areas – labelled 'north' and 'south' on maps. It is run by a husband and wife and is soon to be handed-over to a son. The farm was in the Higher Level Scheme (AES) at the time of data collection and has areas designated as Sites of Special Scientific Interest (SSSI) and a County Wildlife Site. They have approximately 700 head of sheep.

Farm 3 was recruited through a professional network and is the largest of the three farms with 80 ha of inbye across two holdings. They also hold 200 ha of owner-occupied rough grazing (or 'fell') with access to 1800-head sheep grazing rights on 2000 ha of 'common' – which is "peat and blanket bog, valley flushes to high montane heath" (Farmer W 2.5.12). For cartography purposes the farm is split across two areas – labelled 'east' and 'west' on maps. It is run by a father and son. The farm was in the Environmentally Sensitive Area (ESA) agri-environment scheme and they were enrolling in the Higher Level Scheme at the time of data collection. They have 2,800 breeding ewes in total in summer with 800 replacement 'hogs' and 60 beef cattle. They farm a 'stratified' sheep system whereby particular breeds occupy specific environments to which they are adapted and are connected by the movement of lambs and older animals from higher, to lower ground[9]. The farm is at a lower elevation than the other two farms and is less topographically varied.

[9] http://www.ukagriculture.com/livestock/sheep_industry.cfm (accessed 24.11.15)

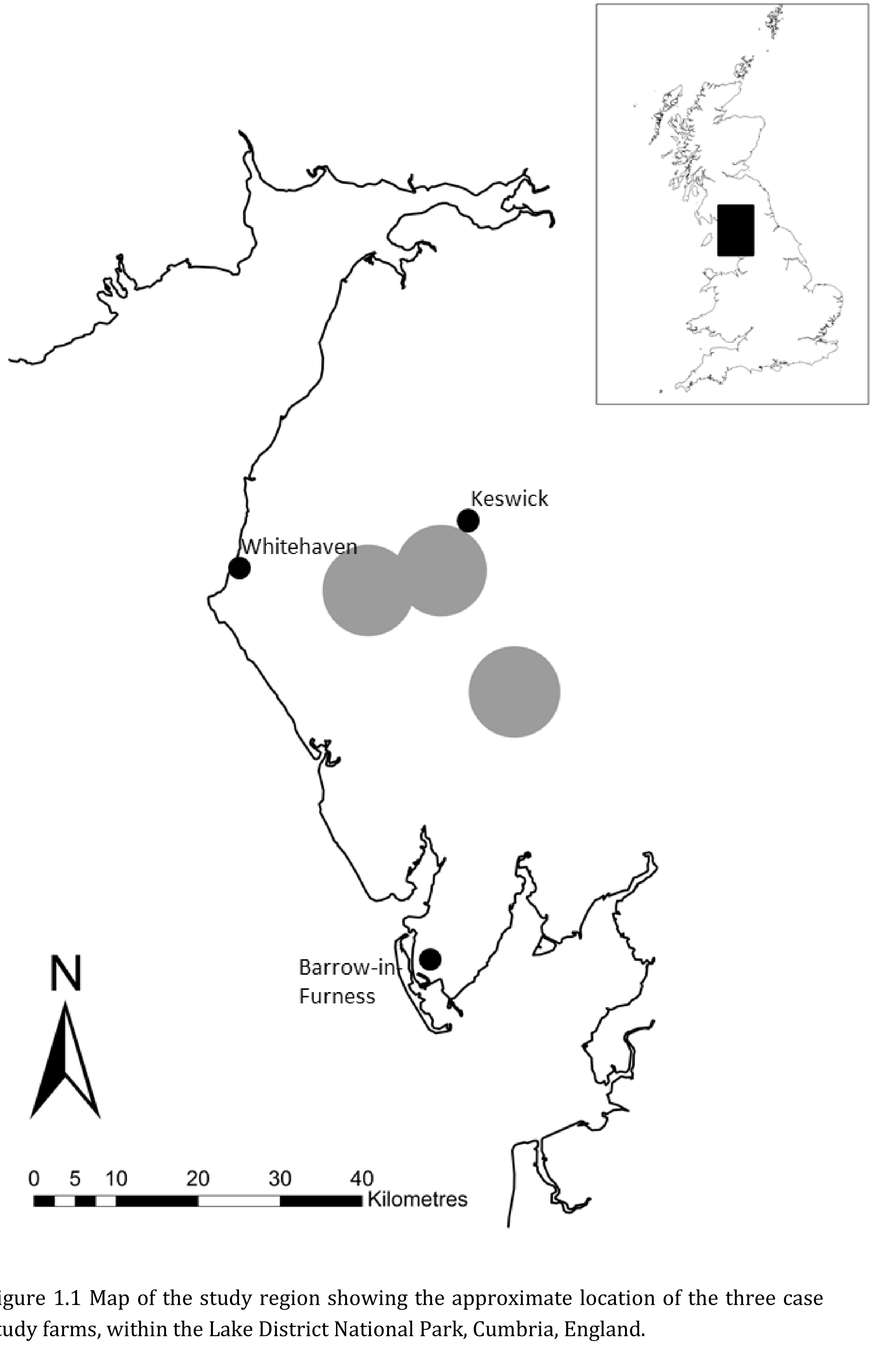

Figure 1.1 Map of the study region showing the approximate location of the three case study farms, within the Lake District National Park, Cumbria, England.

1.5 Acknowledgement of contribution

All of my supervisors have been involved in the research related to the two chapters written in a journal article format (Chapters Three and Four) and therefore they are all included as co-authors. Andy Beanland (Lancaster University Visiting Scholar) provided considerable Geographical Information Systems (GIS) technical support for the research related to these two chapters, so he has also been included as a co-author.

Predicting farm-scale soil carbon stocks using easily accessible vegetation and soil data

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The paper was written and led by myself, with comments and suggestions made to the text and structure by all authors, particularly Richard Bardgett. The concept for this paper was mine and was developed with Richard in particular, but also through consultation with all authors. Andy Beanland contributed to the execution of the study through technical assistance with GIS. I conducted the majority of the analyses.

Guiding 'carbon farming' using interdisciplinary methodologies

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2 Mixed Methods Mapping

Chapter 2 preface

Chapter Two does many things: it provides a literature review, outlines the overall methodology and presents my data on the role of maps on farms in the study region. It is written for a multi-disciplinary audience and the choice of narrative style was based on a desire to draw the different disciplines together, whilst illustrating how the interdisciplined research process evolved. The chapter introduces reflexivity as part of the research process, specifically 'observant participation', which (Kitchin et al. 2013, 6) state is: "a self-reflexive exercise … in which the researcher strives to rigorously examine their own practices … charting the ways in which their research, and the reaction to that research, unfolds".

The literature review is broad-ranging – reflecting the breadth of literatures and disciplines engaged with – and attempts to provide a background context to the issue of mapping soil carbon in this region and with the particular set of stakeholders. It includes an overview of the critical and feminist GIS literatures which inspired my mixed method mapping processes (Chapters 3 and 4) and inspired the wider research methodology.

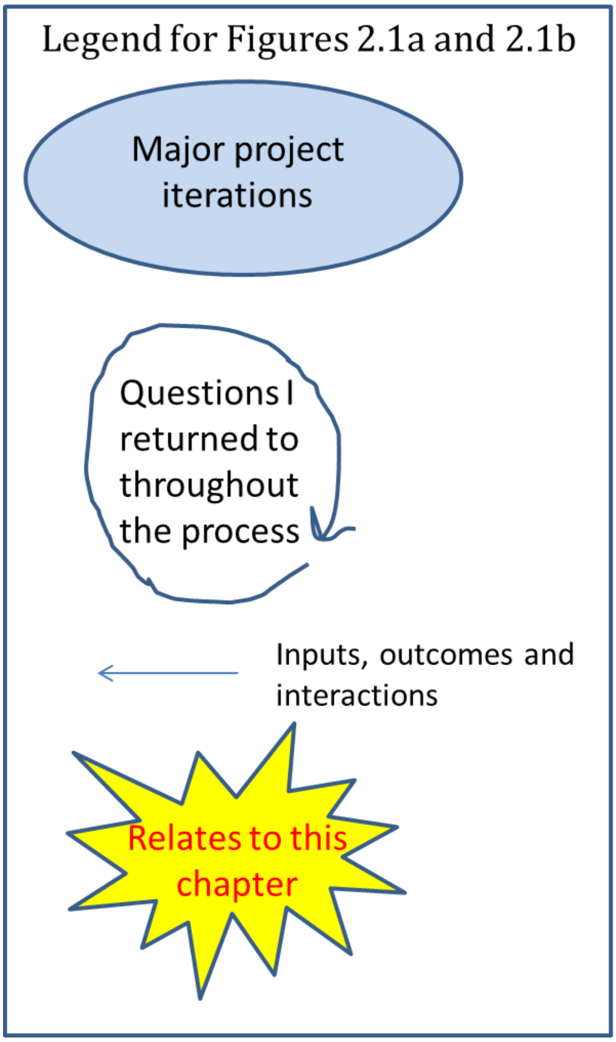
Presenting data on the role of maps on case study farms and how maps play a role in current agri-environment schemes is also included to provide context: to illustrate how any maps I created sit within a history of visualising farms and to explain how it became impossible to imagine that I could start with a blank map sheet.

Figures 2.1a and 2.1b are presented below, in this scene-setting chapter, as visual references to show how the sections and themes of the thesis fit together (Fig. 2.1a) and fit into chapters (Fig. 2.1b). The diagrams were created to be referred to throughout the reading of the thesis, rather than as something to be digested and understood in one go. The blue circles represent the major iterations in the research process – themes and approaches that I returned to again and again. It was challenging to create these figures in a way which highlighted the iterative and cyclical nature of the process and to refrain from showing a linear process towards one final ‘truth’ outcome for the thesis (section 2.1) – as one of the main conclusions (illustrated in Chapters 4 and 5) is that producing a definitive account of soil carbon on farms is problematic.

Reflexivity is an underlying theme of the thesis and is therefore shown in the centre of the figures. The main questions which emerged through the interdisciplinary, iterative research process surround the word ‘reflexivity’. The Figures 2.1a and 2.1b illustrate that Chapter 2, as well as addressing reflexivity in interdisciplinary research, elaborates on what interdisciplinarity research practice meant for this doctoral research process and the acknowledgement of different knowledge communities.

Chapter 3 and Chapter 4 both consider the spatial distribution of soil carbon on farms, with Chapter 3 taking a quantitative, scientific approach and Chapter 4 considering the contribution of qualitative data within a mixed methods approach. Chapter 4 also considers the role of mapping on farms and as an element of agri-environment schemes, as important to the ecological success of soil carbon management schemes.

Figures 2.1a and 2.1b don’t show the research dead-ends (of which there were many) nor the emotional aspects of trying such an approach (something rarely considered in interdisciplinary literature). These are issues I plan to address in a post-thesis paper with co-authors who have also attempted an interdisciplinary PhD.


Legend for Figures 2.1a and 2.1b
Major project iterations
Questions I returned to throughout the process
Inputs, outcomes and interactions
Relates to this chapter

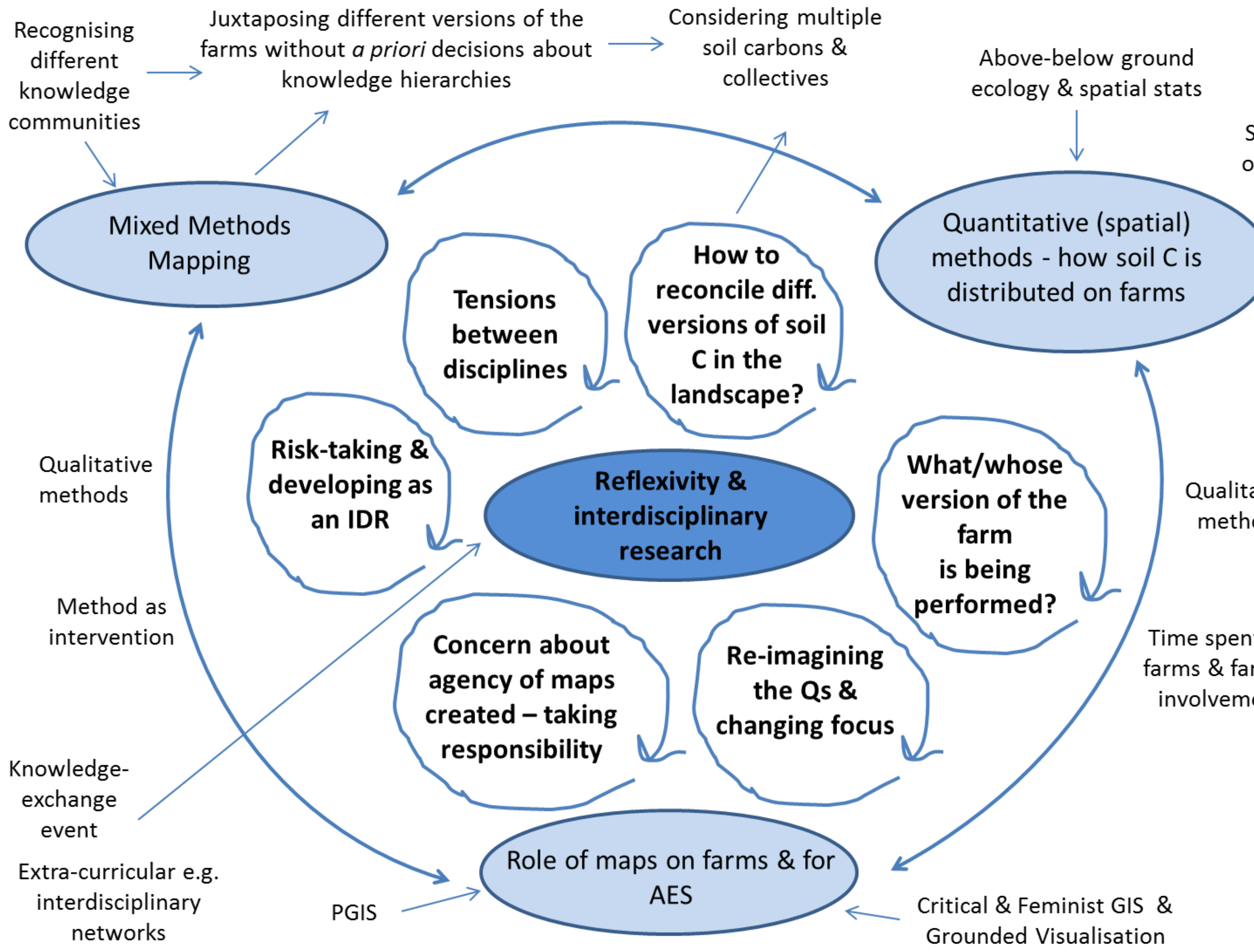

Recognising different knowledge communities
Juxtaposing different versions of the farms without *a priori* decisions about knowledge hierarchies
Considering multiple soil carbons & collectives
Above-below ground ecology & spatial stats
Scientific outcomes
Mixed Methods Mapping
Quantitative (spatial) methods - how soil C is distributed on farms
Tensions between disciplines
How to reconcile diff. versions of soil C in the landscape?
Risk-taking & developing as an IDR
Reflexivity & interdisciplinary research
What/whose version of the farm is being performed?
Concern about agency of maps created – taking responsibility
Re-imagining the Qs & changing focus
Qualitative methods
Method as intervention
Knowledge-exchange event
Extra-curricular e.g. interdisciplinary networks
PGIS
Role of maps on farms & for AES
Critical & Feminist GIS & Grounded Visualisation
Qualitative methods
Time spent on farms & farmer involvement

Fig. 2.1a

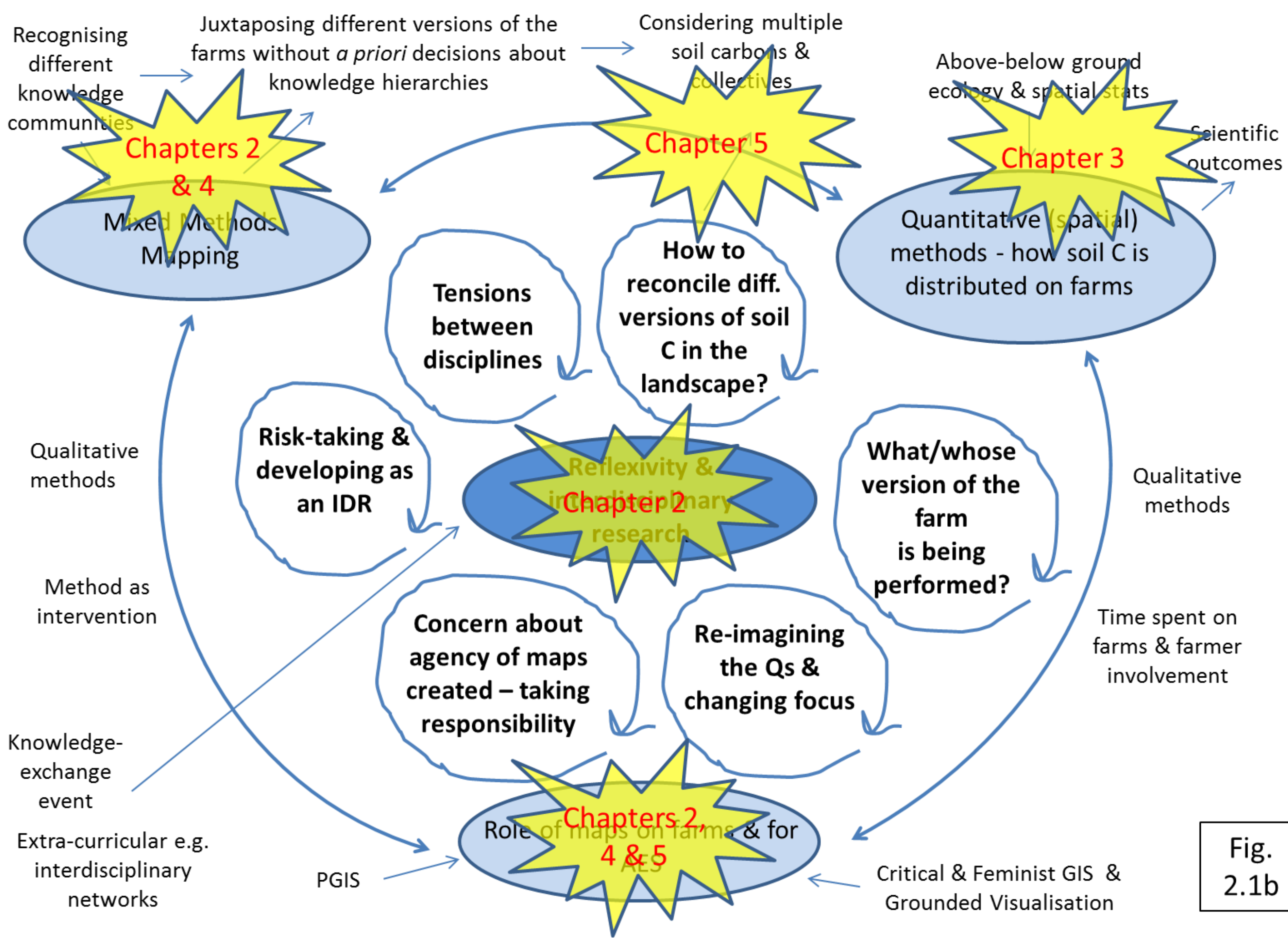

Recognising different knowledge communities
Juxtaposing different versions of the farms without *a priori* decisions about knowledge hierarchies
Considering multiple soil carbons & collectives
Above-below ground ecology & spatial stats
Scientific outcomes
Chapters 2 & 4
Mixed Methods Mapping
Chapter 5
Chapter 3
Quantitative (spatial) methods - how soil C is distributed on farms
Tensions between disciplines
How to reconcile diff. versions of soil C in the landscape?
Risk-taking & developing as an IDR
Reflexivity & interdisciplinary research
Chapter 2
What/whose version of the farm is being performed?
Qualitative methods
Method as intervention
Concern about agency of maps created – taking responsibility
Re-imagining the Qs & changing focus
Qualitative methods
Time spent on farms & farmer involvement
Knowledge-exchange event
Extra-curricular e.g. interdisciplinary networks
PGIS
Role of maps on farms & for AES
Chapters 2, 4 & 5
Critical & Feminist GIS & Grounded Visualisation

Fig. 2.1b

2.1 Introduction

This chapter describes the development of a novel method for mapping soil carbon that incorporates multiple knowledge forms from different knowledge communities. The study's interdisciplinary process was informed by empirical data and explicitly included reflexivity as a strategy for marking the new knowledge created as 'situated' (Rose 1997, described below). Moving back and forth between a 'post-representational mapping' theoretical framework and the more conventional, scientific strictures of mapping soil carbon was an iterative process (Kitchin et al. 2013 drawing from Brown and Knopp 2008). In documenting the process I aim to contribute to both the literature on the role of mapping in environmental management and also to the small but emergent literature on *doing* interdisciplinary research as an inter-disciplined researcher (IDR) (see section 1.2).

Arguably all mixed methods[10] research processes are iterative (Philip 1998) and I use the word 'iterations' (rather than 'stages', for example) as an attempt to disrupt the idea that this was a linear process towards knowledge unity, often the default position of a thesis narrative. Robinson (2008) reflects that "Practitioners of this style of interdisciplinarity do not [just] find themselves at the margins between disciplines, but in the sometimes uncomfortable borderlands between the academy and the larger world" (Robinson 2008, 72, my word addition). This led to a back-and-forth style of progress which, in part, was a direct result of needing to frequently check-in and re-centre with project participants and the environment I was trying to create new knowledge about. In addition, the iterative nature of the project developed because of a pushing-against and drawing-back from the, sometimes competing, rigours of different academic disciplines. Within my project process, progress in one research direction often necessitated the creative alteration or abandonment of another. The following sections describe the four major iterations of research process enacted.

[10] Combining qualitative and quantitative approaches (Creswell 2009).

2.1.1 Overview of the Four Iterative Stages of This Interdisciplinary Research Project

In Iteration One I used a scientific and policy rationale for mapping soil carbon at a farm scale: as a way to better understand the spatial distribution of soil carbon stocks. In describing this process I also include an overview of the literature on scientific soil mapping. This iteration and its associated chapter (Three) accepts the "mappability" of farms as a key element in the "normative procedures and practices required to realise the [Common Agricultural Policy's] CAPs agri-environment measures" (Kovács 2015, 161) and therefore the role of mapping and quantitative analysis of soil carbon in the context of an 'ecosystems approach'[11] to environmental management within European agricultural spaces.

In describing Iteration Two I address the role of reflexivity in my research and how taking responsibility for my research outputs, including the agency of the maps I created, led to re-thinking my research goals and how to achieve them.

In Iteration Three I conducted a critical examination of the current role/s of maps and other visual representations of farms in the region, drawing on Feminist Geographical Information Systems (GIS) and Critical Cartography literatures.

In Iteration Four I turned to Feminist and Qualitative GIS practices to consider how my methods could take account of this critique. I used 'method as intervention' (Browne et al. 2014) to playfully subvert (Kwan 2002c; Perkins 2009) the process of mapping soil carbon on farms, and to consider the agency of the maps I created (Wood and Fels 2008) within a post-representational

[11] An 'ecosystems approach' is a normative approach (what is considered to be the normal or correct way of doing something) to managing biodiversity (and often wider environmental management) in the UK (enshrined in the 'Biodiversity 2020' strategy), Europe (the European Union's 'Biodiversity Strategy') and globally (the 'Convention on Biological Diversity'). It is a diffusely-applied term originating from the twelve 'Malawi Principles for the Ecosystem Approach' derived from a United Nations workshop in Malawi in 1998 with an associated report presented at the Fourth Meeting of the Conference of the Parties to the Convention on Biological Diversity (Bratislava, Slovakia, 4-15 May 1998, UNEP/CBD/ COP/4/Inf.9). The UK's Joint Nature Conservation Committee describes it as "an adaptive management strategy that can be employed to deal with the complex and dynamic nature of ecosystems and counteract the lack of knowledge or comprehension of their functioning". It "takes into account that humans and cultural diversity are an integral element of most ecosystems. It applies appropriate scientific methodologies, focused on various levels of biological organisation, which encompass the fundamental structure, processes, functions and interactions amongst and between organisms and their environment." http://jncc.defra.gov.uk/default.aspx?page=6276 (accessed 24.11.15).

mapping framework (Dodge et al. 2009). In doing so, I adapted/subverted the traditional GIS framework to make the quantitative scientific maps one version of the farm, of many possible versions, and brought embodied experiences of soil carbon into the maps, along with emotion and alternative map surfaces – such as time, labour and land tenure. Each map surface was made open to questioning and contestation. In this section I also describe the empirical findings from my application of this 'Mixed Methods Mapping' (MMM) approach to three case study farms.

Chapters Three, Four and Five outline distinct disciplinary contributions derived from this interdisciplinary process. I aim to illustrate that rigorous research, as defined by different disciplines, can emerge from such an interdisciplinary approach. This could also be seen as a reversion back to disciplinary strictures and acceptance of a pervasive and inescapable disciplinary academic framework; therefore, this second chapter is an attempt to break out of those disciplinary strictures.

2.2 Iteration One – Mapping soil carbon quantitatively

In this section I explain the scientific and policy rationale for exploring and visually representing the spatial distribution of soil carbon stocks on farms using data from vegetation maps. I review previous research on the spatial distribution and modelling of soil carbon in order to situate my research aims within the wider literature. I then briefly describe the methods used to measure, analyse, predict and represent the soil carbon stocks on the three case study farms (explained in detail in Chapter Three) and how my interdisciplinary approach developed as the result of this first tranche of data collection.

2.2.1 Why soil carbon?

There is intense scientific and political interest in soil carbon and its roles in mitigating climate change and regulating soil processes (Stockmann et al. 2013). This doctoral study is predominantly focused on the former – soil carbon sequestration as a contribution to mitigating climate change by removal of carbon-based greenhouse gases (GHG) from the atmosphere over the long term. The 2008 Climate Change Act aims to reduce the UK's GHG emissions by at least

80% (from the 1990 baseline) by 2050. In 2016 the UK government will propose draft legislation for the Fifth Carbon Budget, covering the period 2028-2032. The reduction of GHG emissions via land management policy interventions could contribute to this national aim (Brockett and Wentworth 2015). Internationally, a new climate agreement is to be finalized at the United Nations Convention on Climate Change (UNFCCC) Conference of Parties (COP21) in Paris December 2015. In preparation countries have agreed to publicly outline the post-2020 climate actions they will take to 2030. These Intended Nationally Determined Contributions (INDC's) pair national policy settings to a global framework and an ambitious agreement in Paris could have implications for national land management policies, such as managing land to sequester carbon, as governments look to achieve challenging INDC targets.

Modification of agricultural practices is a recognized method of carbon sequestration (Lal 2008; Orr et al. 2008; Smith et al. 2008) as well as a way of mitigating other GHG emissions (Brockett and Wentworth 2015). Management options specific to the extensive (low-input) grazing systems, cool wet climate and associated organic or organo-mineral soils typical of my upland study region in the English Lake District include reduced grazing (Britton et al. 2005), reduced nitrogen (N) fertiliser application (Evans et al. 2006), reduced liming (to decrease soil pH) (Leifeld et al. 2013), maintaining and expanding areas of permanent grassland (Guo and Gifford 2002), and reducing land drainage and encouraging re-wetting of land that has been drained (Orr et al. 2008).

In the UK, national reviews have identified the cooler and wetter upland regions, such as the English Lake District, as strategic geographical areas for delivering soil carbon sequestration. One such review stated that "the carbon stored in many of the ecosystems found in the uplands is an important asset for the UK in relation to climate regulation" and "Quite apart from the future carbon that they may sequester, the ability of these systems to retain the carbon they already lock away is important" (Haines-Young and Potschin 2009, 5). Regional pilot projects are already underway which use voluntary land management contracts to guarantee a 'carbon offset' which is then sold on to businesses interested in offsetting their own GHG emissions (Hagon 2014).

Another option for managing soil carbon stocks within the European agricultural landscape would be through existing agri-environment policy mechanisms, such as European Union (EU) agri-environment schemes (AES) (Kroeger and Casey 2007; Bol et al. 2012; Horrocks et al. 2014). AES are funded under the EU's Common Agricultural Policy (CAP) and administered in the UK by the agency Natural England. They incentivise farmers and land managers to deliver environmental benefits on their land (Proctor et al. 2012a). These are delivered at farm level and the farm enrolment process involves creation of a Farm Environment Plan (FEP) which includes maps of farm vegetation types and quantification of environmental and cultural features-of-interest.

2.2.2 Links between vegetation cover and the spatial distribution of soil carbon stocks

Soil carbon can be studied at a range of scales, from particle to biome (O'Rourke et al. 2015). At the farm/landscape scale there is growing evidence that plant functional traits can be linked to soil processes (Cornelissen et al. 2003). Trait-based methodological approaches are therefore applied to understand how changes in plant community composition influence soil ecosystem function (Bardgett et al. 2014), such as the soil carbon cycle (e.g. Manning et al. 2015). A functional trait is a feature of an organism (morphological, physiological or phenological in plants) which has demonstrable links to the organism's function (ecosystem role) or functioning (performance) (Díaz et al. 2013). Examples of plant functional traits include leaf dry matter content and rooting depth. Functional traits reflect adaptations to variation in the biotic and abiotic environment and trade-offs among different functions within an organism (Díaz et al. 2013). The relevance of functional traits in species' response to the environment or species' effect on ecosystems is usually established empirically by observation or manipulation of the ecosystem under study or by extrapolation from other studies (Díaz et al. 2013; Bardgett et al. 2014). A shortlist of plant traits has been developed, all of which have strong predictive power concerning ecosystem responses to environmental change and/or they themselves have strong impacts on ecosystem processes (Cornelissen et al. 2003). Researchers have begun standardizing methods for measuring these traits (Cornelissen et al. 2003).

Community-weighted functional (CWF) traits (or 'community aggregated traits'; Violle et al. 2007) are effect traits weighted according to the relative abundance of species in the community. Studies have shown CWF plant traits correlate with soil properties in grasslands at the field scale (Orwin et al. 2010), landscape scale (Lavorel et al. 2011; de Vries et al. 2012) and at wider scales (Manning et al. 2015). For example, in an alpine grassland study Lavorel et al. (2011) found that the traits 'leaf dry matter content' and 'leaf phosphorous content' alone explained thirty one percent of the variation in soil carbon stocks. Grigulis et al. (2013), drawing on the concept of the 'leaf economic spectrum' (Reich 2014), found that more 'resource-exploitative' plant species (with traits such as high specific leaf area, high leaf N concentration and low leaf dry matter content) were linked to poor soil carbon storage and the more 'resource-conservative' species (with opposite traits) were linked to greater retention of carbon in soil.

Discovering the link between plant functional traits and soil properties has led researchers to explore the role of vegetation data in creating maps of the spatial distribution of soil carbon and other environmental 'goods and services'[12] (Lavorel et al. 2011), including the use of remotely-sensed imagery of vegetation (Ballabio et al. 2012). In the section below I provide an overview of the literature on soil carbon mapping.

2.2.3 Mapping soil carbon – identifying a research gap

> *maps are spatial representations which can in turn stimulate other spatial representations … representation is an act of knowledge construction (Macheachren 1995, vii)*

[12] Here I explain my framing of soil carbon stocks as an 'environmental public good' ('environmental good' throughout the rest of the thesis). "The term public good can be narrowly defined to include goods characterized by non-rival consumption (consumption by one person does not prevent consumption by another) and non-excludability (people who do not pay cannot be prevented from gaining access to the good)" (Scruton 2007). 'Environmental goods' are a sub-section and can confer benefit to humans and non-humans. There are also alternative normative framings which are used to refer to soil carbon stocks and other desirable and quantifiable entities which can be 'delivered' as 'goods and services' through appropriate management. These other terms include 'ecosystem services' – "the benefits provided by ecosystems to humans" (Millennium Ecosystem Assessment 2005), non-traditional agricultural products, and natural resources. There are also a multitude of critiques of these terms, their usage and associated policy framings. For further reading see Dempsey and Robertson (2012), Sullivan (2013) and Scales (2015). I acknowledge these critiques, draw on some of them in Chapter Five, but otherwise do not engage with them directly.

Mapping has long been a tool of natural resource managers and environmental researchers. Recent research has quantitatively mapped environmental public goods or ecosystem service provision in different ecosystems whilst attempting to take account of 'service' delivery 'trade-offs' and localised biogeophysical variations (Eigenbrod et al. 2010; Lavorel et al. 2011). This approach to mapping, coupled with policy reforms, is considered by policy makers and scientists to have significant potential in assisting in the sustainable management of agricultural land (Jackson et al. 2013). Digital soil carbon mapping and other modelling techniques utilise a variety of quantitative methods and tools, such as remotely-sensed imagery (Gillespie et al. 2008; Ballabio et al. 2012; Zhang et al. 2012), biogeochemical models such as 'RothC'[13] and 'Century'[14], land cover-based proxies (Eigenbrod et al. 2010; Muñoz-Rojas et al. 2011; Renwick et al. 2014), historic datasets (Eaton et al. 2008), and incorporate interpolation methods such as kriging (Zhang et al. 2012). Methods have been developed to enable prediction of the response of soil organic matter (closely related to SOC) to agricultural practices at the soil-profile or small-plot scales (Powlson et al. 2012) or at large spatial extents, such as national and continental scales (Renwick et al. 2014). However, the literature identifies a need to develop spatially-explicit predictive methods which accurately model soil carbon at intermediate scales to enable the provision of management guidelines for farms and watersheds (Viaud et al. 2010).

2.2.4 Addressing identified research gaps in Iteration One

This first iteration of research involved addressing two research gaps related to i) farm-scale predictions of soil carbon distribution and ii) inclusion of social science perspectives in such research.

In addressing the first research gap I used information about farm vegetation communities and measurements of pH, soil moisture and soil depth to explain the variation in and predict spatial distribution of soil carbon stocks at the farm-

[13] "RothC-26.3 is a model for the turnover of organic carbon in non-waterlogged topsoils that allows for the effects of soil type, temperature, moisture content and plant cover on the turnover process" (Coleman and Jenkinson 2014, 5).

[14] The CENTURY Model Version 4.0 models the biogeochemistry of carbon, nitrogen, phosphorus, and sulphur (Metherell et al. 1993).

level, the scale at which the majority of agri-environment policy interventions are focussed. The novelty is the utilisation of easily-accessible farm documentation – vegetation survey maps – as a proxy for plant functional trait data. These FEP vegetation maps were developed to be comparable with Biodiversity Action Plan (BAP) priority habitat codes[15] (D. Martin, pers. comm. Natural England). "The FEP was largely designed to pick these habitats up, although there are additional non priority habitat features such as semi-improved grassland (G02) and moorland grassland (M01)" (D. Martin, pers. comm. Natural England). There is also a relationship between the majority of FEP vegetation codes and National Vegetation Classification (NVC) classes (Rodwell 2006) (D. Martin, pers. comm. Natural England). The FEP 'brief' was that it to be widely useable, not just by ecologists who had knowledge of NVC, but also by Farm Environment Advisers (FEA) (D. Martin, pers. comm. Natural England). For further information about the role of FEAs and the multiple roles they have "in regulating, directing, and influencing contemporary land management" see Ingram (2008); Ingram et al. (2009); Proctor et al. (2012a, 1696). This FEP documentation is readily available, especially in this region where 71% of farms are enrolled in AES (Department for Environment, Food and Rural Affairs 2013a). The resulting models were utilised within kriging spatial interpolation methods to create predictive maps of the spatial distribution of soil carbon stocks for three case study farms.

In exploring the second research gap I undertook a pilot study and interviewed natural resource management (NRM) experts. I was made aware of current NRM research projects in Britain which are focused on catchment-scale ecosystem service delivery, including three Natural England partnership pilot schemes (Clarke 2010). However, there is a gap in understanding how such approaches will fit into the heterogeneous socio-ecological nature of farm units (S. Clarke, Natural England, pers. comm.). This study initially set out to involve farmers in the scientific process in order to improve the scientific research outcomes (an 'instrumental rationale' for farmer involvement – Stirling 2005; Tsouvalis and Waterton 2012). Case study farmers provided access to AES documentation (created by policy makers and farm environment advisers), assistance with

[15] http://jncc.defra.gov.uk/page-5718 (accessed 1.12.15)

sampling design, and validation of project maps. It was through initial discussions with the farmers and reading through their farm documentation that I realised the potential of using the farm vegetation maps in helping to predict the distribution of soil carbon stocks on farms. In later iterations I reconsidered the role and form of farmer and other stakeholder participation in my research and below I describe how stakeholder participation evolved over the course of the project and altered the direction of the project itself.

2.2.5 Method detail for Iteration One: Kitchen Table Interviewing and Farmer Involvement

In this section I provide an overview of the quantitative and associated qualitative data collection methods I used to address the two research gaps identified above. For full details of the scientific methodology see Chapter Three and for more detail on the qualitative methodology see Chapters Four and Five. After farmer recruitment (described in Chapter One) semi-formal introductory 'kitchen table' interviews were held with each farmer (often over tea and cake) and I requested that any farm documentation be made available. Such documentation was either held on-farm or retained by the associated FEA. A second farmer interview was held soon after, either in the farm yard or the farm workshop, to look over Ordnance Survey maps of the farm and any commonland access and Farm Environment Plan documentation (documents forming part of the AES enrolment process), including vegetation survey maps. We discussed the different on-farm vegetation communities and their history and geography, with particular reference to farm management practice. This interview informed the sampling design and was followed by a farm walk-over to delineate the different vegetation community sampling units.

The subsequent analysis and mapping process and findings are described in Chapter Three. Briefly, it was possible to explain a large proportion of the variation in soil carbon stocks on the farms by including information about vegetation type (from the farm survey maps), soil moisture (measured) and sample depth (measured) in the models. These explanatory variables were used to predict soil carbon stocks across the three farms in the form of quantitative maps. Generally, the soil carbon maps concurred with the farmers' understandings and experience of the carbon-rich areas of their farms: *"It's pretty good this [map], it's identified what we call the peat hole"* (Farmer W, 4.3.15).

2.2.6 Emerging issues

At the beginning of the project all three case study farmers were introduced to the research concepts (they were already familiar with some of the scientific terminology) and they expressed interest in learning more about the topic of soil carbon which is *"on everyone's lips"* and *"in the farming press"* (Farmer E, case study interview, 17.6.14). The exchange of information about the farms' social and ecological systems between interviewer and interviewee was important to the project's development. The farmers were all familiar with the interdisciplinary aims of the project from the outset and knew that I was interested in their views and input. Farmer W embraced this aspect from the start. The other two were less certain of what they could contribute and Farmer E initially expressed scepticism that he could help me in any way with my investigations. However, all three did engage and their contributions were essential to the project developments.

The field work stages of this scientific process took seven months and during this time on-going conversations with the farmers and examination of farm documentation led me to reconsider the role of maps and the mapping process on farms. I began to consider my maps' agency, and what could result from creating and making public this version of the farms: the farms as stocks of soil carbon. These thoughts initially manifest themselves in practical concerns: considerations of how best to present the maps to the farmers (on a computer screen, a tablet, on paper, how many to show etc.), how to make my assumptions and any statistical uncertainties visible in the maps, and how to encourage debate and allow contestation of the maps. I was becoming uncomfortable and dissatisfied with the narrow constraints of farmer participation within the project and began to recognise that an instrumental rationale for farmer involvement (to improve the scientific outputs) was not the interesting part of the emerging story, although it was undeniably useful. I therefore wanted to reconsider the framing of farmer participation. I also wanted to take responsibility for the research process and its outputs (Haraway 1991; Castree

1995; Massey 2004) and take some time to question my complicity in the "mappability" of farms as a key element in the "normative procedures and practices required to realise the CAP's agri-environment measures" (Kovács 2015, 161), which I was beginning to understand were problematic and contested. This is reflected in Iteration Two (2.3) and also is reflected upon deeply in Chapters Four and Five.

2.3 Iteration Two – Reflexivity, positionality and situated research

Reflexivity, as a strategy for situating knowledges, originated with Bourdieu (Bourdieu 1990) and has been developed and utilised within social and feminist theory, for example through the work of Harding (1987), Haraway (1988 and 1991), and Rose (1997). Accepting that all knowledge is situated means accepting that it is produced in specific circumstances that shape it and by researchers with a specific set of experiences, skills, expectations, ambitions, constraints, and within a certain intellectual community – i.e. with a position. Within these literatures it is argued that without reflexivity we produce knowledge with a "false neutrality and universality", which fails to recognise the power relations inherent in the relationship of researcher and researched (Rose 1997, 306).

As Rose (1997) acknowledges, writing an account of our own position within our research practice is not straight-forward, but such reflections are part and parcel of engaging with researcher responsibility. Scientific objectivity "turns out to be about particular and specific embodiment and definitely not about the false vision promising transcendence of all limits and responsibility" (Haraway 1991, 190). The partial perspective developed in Iteration One, of how soil carbon is distributed on the farm, can be held accountable for what comes after and what is generated during the research process. As Haraway (1991) suggests: "In this way we might become answerable for what we learn how to see" (Haraway 1991, 190), that is, how I learned to visualise soil carbon on the farm and how I chose to represent it. Images influence material actions (Fish and Phillips 1997 cf Morris and Holloway 2009, 323) and through engagement with feminist theory I became interested in taking responsibility for the agency of my scientific maps and the effects they would have in the world. It was at this stage of the research process that I fully embraced the tensions of being an inter-disciplined researcher (IDR). In falling between disciplinary divides, I reflected on and critiqued my own disciplinary stances – the rehearsed (and more familiar for me) mantle of ecologist creating 'universal' scientific research outcomes, alongside the critical gaze of social scientist acknowledging my work as a partial and situated view.

Reflexivity is acknowledged as a crucial part of the interdisciplinary research process (e.g. Romm 1998). The Research Council's UK 'Rural Economy and Land Use' (RELU) programme was one of the most comprehensive national interdisciplinary research initiatives ever conducted and the role of reflexivity in shaping the progress of the programme has been highlighted (Lowe and Phillipson 2006). In Chapter Five I discuss application of interdisciplinary thinking through ontological multiplicity[16] and how this can 'open up' or 'close down' research framings, effects also referred to in Lowe and Phillipson (2006). A significant step forward was made with my understanding and acceptance that different knowledges (represented as different map surfaces within the mixed method digital map, see 2.5 Iteration Four) did not have to triangulate or reach consensus (Blaikie 1991; Stirling 2010; Hesse-Biber 2012). Allowing conflicting versions of the farm to coexist became a central tenet of my interdisciplinary praxis (ideas in action).

Here, I briefly discuss the embodied experience of being an IDR because, as alluded to at the end of Iteration One, my feelings of uncomfortableness and dissatisfaction with a purely quantitative approach to mapping soil carbon proved to be a crucial turning point in the development of my research process. The role of embodied experience in research practice has been documented within a number of disciplines (e.g. Bengtsson 2012; Draper 2014), but as yet not

[16] Science and Technology Studies imported the philosophical term 'ontology' and put it in the plural: 'ontologies' (Mol 2014). Ontology is the nature of being, becoming or existence; what kinds of things can be said to exist, and in what ways. Ontological multiplicity accepts that "there are not just many ways of knowing 'an object', but rather many ways of practising it. Each way of practising stages – performs, does, enacts – a different version of 'the' object. Hence, it is not 'an object', but more than one. An object multiple." Quote taken from Annemarie Mol's contribution (Part 4) to the blog series 'A reader's guide to the "ontological turn" (Mol 2014). This is challenging to a European-American knowledge tradition which understands that different people may each have their own perspective on reality, while there is only one reality – singular and coherent – to have perspectives on (Mol 2014).

explicitly within IDR practice. However, Marzano et al. (2006, 189) report on disciplinary researchers' feelings of deflation on being devalued within an interdisciplinary research project as significant to the success of the project. They also report on the 'self-protection' strategies employed by disciplinary researchers within interdisciplinary projects when experiencing incompatibility with other discipline's ways of working. Of course, embodied experience plays a central role in the research process, whether it is explicitly acknowledged or not. However, the persistent and sometimes overwhelming feeling of never knowing enough within any one discipline and experience of 'imposter syndrome' (as two examples) seem to play a particularly significant role in IDR experiences (Evans and Randalls 2008)[17]. The embodied experience of being uncomfortable with how my research was and could be working in the world led to me opening-up the research process to actively engage with these experiences, which was largely about adopting reflexivity as an interdisciplinary praxis.

Embracing reflexive praxis enabled new reflections on the materials I had developed in Iteration One and so the development of new methodologies to address these reflections. Production of scientific soil carbon farm maps now seemed to be a clear example of performing the 'god-trick' (Haraway 1991) – claiming to see the whole whilst remaining distant from it. This led to feelings of tension and discomfort as I became dissatisfied with this false universality and neutrality. I was also uncomfortable with the instrumental role I had assigned farmers and other stakeholders. I noticed a lack of space for interesting stories to emerge and be counted within my predominantly quantitative research framework, where quantitative data was *de facto* the only legitimate type – a 'closing down' of the research process (Lowe and Phillipson 2006). I therefore set about 'opening up' the research process to explore alternative and more inclusive ways of representing soil carbon on farms. To do this I needed to understand the current role of maps and other scientific and policy performances of the farms. Performativity is used in social theory to capture the moment when the virtual becomes real or the potential for something to become real is achieved – such as

[17] Also, based on reflections from other IDRs at the North West Doctoral Training College 'Enhancing Interdisciplinarity' fora on 30.1.15 at Liverpool University and on 22.5.15 at Lancaster University https://enhancinginterdisciplinarity.wordpress.com (accessed 24.11.15).

when a scientific idea of a farm as stocks of soil carbon is made real by measuring those stocks, visualising them on a map and that map is then used to formulate a management plan. The related methods and findings are described in Iteration Three (2.4).

Within this 'opening up' I also tried to take account of the epistemic limitations and constraints of all my findings – what 'valid' knowledge is (see Chapters Four and Five in particular). This was somewhat counter-intuitive to someone trained as a natural scientist and it contributed to feelings of 'in-betweenness' as, on occasion, I felt like I was undermining my own work. Concepts of 'playfulness' and 'mess' in research (Law 2004; Perkins 2009; Donaldson et al. 2010; Dodge and Perkins 2015) became important in enabling me to experiment and move on with my research instead of being stifled by the sometimes competing or seemingly incompatible demands of disciplinary rigour, accuracy, acceptability and validity (Öberg 2011), and this is explored further in Iteration Four (2.5). As I explain in Chapter Five, mixed methods and interdisciplinary research was attempted in the belief that it is worth the effort for the natural and social sciences to work together, with others, "in full recognition of the critiques" around participation and interdisciplinary research that exist, and to view this as a productive challenge (Tsouvalis and Waterton 2012, 119).

2.4 Iteration Three: Challenging – and playing with – the current role of mapping on farms

Iteration One (described in 2.2) engaged with the scientific rationale for mapping soil carbon. Iteration Two (2.3) explained how my engagement with this quantitative, scientific way of knowing and representing soil carbon on the case study farms produced more questions and a reconsideration of my research approach, including a reconsideration of my original research questions. In this iteration I explored the current role of maps and other spatial representation of farms in this region by asking:

i. What maps already exist on farms in this region?
ii. How do farmers (and other agri-environment actors) use maps (if they are used at all), including online mapping and other spatial resources?

iii. What is the role of maps within current agricultural management interventions?

The findings were interpreted through the lens of Critical Cartography and in Iteration Four (2.5) I explain how I applied this understanding, along with inspiration from Feminist GIS, to develop a MMM process. But first, I explain what Critical Cartography is and explore how participatory mapping approaches have been applied to environmental and natural resource management decision-making processes in the past.

2.4.1 Critical Cartography

Mapping is a powerful tool. It is also a powerful set of concepts. Critical Cartography (a sub-set of Critical Geographies) recognises that maps are more than a communication process and moves us on from the idea of mapping being representation and just an act of knowledge construction (as suggested in the Macheachren quote in 2.2.3). In 1989, J.B. Harley's seminal paper 'Deconstructing the Map' called for consideration of the implicit meaning and power inherent in mapping, as well as the explicit meaning. He rethought maps as social constructions, within which there lies a representational truth of the world, where the ideology of its makers can be exposed and accounted-for through deconstruction. Harley (1989, 15) acknowledged that cartographers have created an "epistemological myth" that cartographic method reflects the "cumulative progress of an objective science always producing better delineations of reality"'. The view that the map recipient is a passive receiver of information communicated by the cartographer was challenged by decentring the cartographer from the process or making her accountable for her position within the map making (see Iteration Two, 2.3) (Rose 1997; Propen 2009). This is a challenge mirrored in much of the participatory natural resource management, participatory science and critical/alternative agricultural science literature (e.g. Kloppenburg 2009). Other critical cartographers have explored maps as capturing something of the world whilst simultaneously 'doing work' in the world – preceding and producing the territory they purport to represent (Kitchin et al. 2013 cf. Pickles 2004; Wood and Fels 2008). Later in this section (2.4.5) I explore this idea through examination of the nature I mapped in quantitatively representing a scientific account of soil carbon on the farms ('nature as controllable').

More recently (since the mid-2000's), a small group of critical scholars have re-conceptualised maps as "mappings that ceaselessly unfold through contingent, citational, habitual, negotiated, reflexive and playful practices, embedded within relational contexts" (Kitchin et al. 2013, 1). From this point on I accepted Critical Cartography's anti-foundational and post-representational theorizations of cartography and in the bullet points below I highlight the theoretical premises I drew on in my analysis of the current role of maps on farms. I then discuss how this critical understanding of mappings through an ontogenetic (maps as process) lens (Kitchin and Dodge 2007) was applied within my research, using Feminist GIS as an influence in the final iteration: MMM of soil carbon on the case study farms as praxis. In doing so I partook in the wider and on-going reconsideration of cartographic epistemology (Kitchin et al. 2013). The theoretical premises underpinning this relate to:

- *Processual (ontogenetic) understandings of mapping* – as opposed to a static map output. "Meaning and territory unfold through the work of the map" (Kitchin et al. 2013, 2) and maps are always in the process of becoming (Kitchin and Dodge 2007), i.e. mappings are never fully formed, never finished. The reproduction of a map (e.g. for this thesis) is always a snap-shot "of-the-moment", an artefact (Kitchin and Dodge 2007; Kitchin et al. 2013, 2).

- *Mapping as practice* – mappings are brought into being through embodied, technical, social and political practices (Crampton and Krygier 2005). They are therefore contingent and relational.

- *Mapping as ontologically insecure, emergent and mutable* – questioning the taken-for-granted foundational ontology whereby the world can be scientifically measured and represented and therefore objectively known (Kitchin et al. 2013). Mappings do not emerge and appear in the same way for all individuals; they unfold in context (Kitchin et al. 2013).

As with traditional cartography, geospatial technologies and the creation of digital maps have centred their quantitative processes on positivist views of the world[18]. Critiques have focused on how cartographic methods are constantly recreating the 'god trick' – the all-seeing view from nowhere (Haraway 1991), divorced from messy matters of the world. Since the late 1980s critical geographers have provided opportunity for critical application of GIS and for utilising its technologies and associated practices in ways which encourage different world views and the integration of different knowledge forms. However, early emphasis was on critique rather than active engagement in changing the way GIS was done. In 2002 M. P. Kwan proposed a reimagining of GIS as a method in feminist geography and identified where this was already happening – Feminist GIS was articulated as a geographical movement (Kwan 2002b). Since then, feminist and other critical geographers have used this reimagining to interrogate and move past GIS as a method solely connected with positivist scientific practices and visualization technologies. Feminist and Qualitative GIS are explored further in Iteration Four (2.5) as I describe how I use playful mapping and counter-mapping in this 'new epistemology of cartography' as an alternative to getting embroiled in the "grim struggles over power and rationality that embody a Foucauldian worldview" (Dodge and Perkins 2015, 38). Discovering Feminist GIS empowered me to move past my concerns with the quantitative soil carbon maps I had created and play around with the subversive-approach of Feminist Qualitative GIS (see section 2.5.2) to try out MMM of soil carbon on the case study farms. Before I describe this MMM approach in Iteration Four (2.5) I provide an overview of current approaches to participatory mapping within environmental management and how the research gaps identified, along with my findings relating to the current role of maps on farms, informed my methods.

2.4.2 Participatory mapping of natural resources using GIS – an overview of current approaches

In Iteration One (2.2) I explained the 'instrumental' rationale for my engagement with farmers – "a better way to achieve particular ends" (Tsouvalis and Waterton

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[18] The world can only be known through systematic empirical investigation of phenomena, i.e. that which can be scientifically verified or which is capable of logical or mathematical proof.

2012, 113) – in this case to improve the project's natural science research outcomes. This was achieved through farmer participation in the sampling design, the provision of access to the farm land and farm documentation, and their validation of the final maps. Such an instrumental rationale for stakeholder participant involvement is often explicitly or implicitly used by organisations, researchers and practitioners who look to engage with local communities in order to widen and diversify participation in wider environmental and natural resource management. Such approaches, which can include community mapping and Participatory GIS (PGIS), also often engage with a normative rationale for involving 'non-experts'. This rationale understands participation as a public good, as 'the right thing to do' (Tsouvalis and Waterton 2012 cf Chilvers 2008), stemming from "democratic theories that suggest that citizens have a right to influence decisions that affect their lives and is based on principles of citizen empowerment, equity, and social justice" (Tsouvalis and Waterton 2012, 112). I briefly outline examples of such participatory projects below, drawing from the PGIS literature, and then explain the opportunities and limitations of these approaches with regard to my own research.

Wide adoption of GIS and other geospatial technologies since the 1980's has provided opportunities to include and spatially analyse multiple layers of information, including information sourced from 'non-experts' through direct involvement in the planning or research process or through access to 'big data' such as 'volunteered geographic information'. PGIS is defined as an approach which encompasses decision-making processes that gather, analyse and represent local stakeholder spatial knowledge with those of environment managers and scientists at the decision-making scale (Cinderby et al. 2011). For example, Pagella and Sinclair (2014, 383) in mapping an agricultural landscape state that they are "incorporating stakeholder knowledge and perspectives" as one of their research aims, with the instrumental rationale of bounding and communicating uncertainty and to improve the maps' legitimacy. However, their adoption of 'ecosystem services' (ES) as the project's normative management framework limits the types of knowledge that can be considered to those which fit with ES's positivist and quantitative framing. This example highlights the limitations of many PGIS approaches in failing to question the ontological assumptions "underpinning the map as a way of knowing and how it undertakes diverse work in the world" (Kitchin et al. 2013, 2). In a second example, Cinderby et al. (2011) use PGIS to map a Tanzanian watershed. Their reasons for working with a "truly *participatory* GIS" (pg 1094, their emphasis) are both normative (a 'sustainable development' rationale for involvement, that it is the 'right thing to do') and instrumental (that it facilitates decision-making). They are concerned with how maps can 'better' display spatial information and how to include local knowledge which differs in "spatial and experiential" extent (pg 1095) when compared to knowledge of scientists and managers. However, they fail to critically examine the foundational ontology of the maps they produce, substantive reasons for engaging local knowledges (see next paragraph), or the assumptions of their 'intended goals'.

As is suggested above, much PGIS research applied to environmental management has limited itself to instrumental and normative rationales for widening participation. Therefore, concerns have been raised as to issues of justice (Foster and Dunham 2015) and what an instrumental and normative rationale for participation may exclude (Tsouvalis and Waterton 2012; Cook et al. 2013; Elwood and Mitchell 2013). The dominance of a scientific worldview that assumes 'natural resource management knowledge' is the only way of knowing a landscape/catchment/farm through a "particular set of social, material, and textual practices which generate natural asset value" (Verran 2009, 3), ignores other knowledge systems with different foundational ontologies and there have been recent calls for 'robust' participatory processes which integrate different voices and different ways of knowing the landscape and its features (Urquhart et al. 2011; Tsouvalis and Waterton 2012; Wilner et al. 2012; Cook et al. 2013; Eades 2015). The identification of this gap in participatory engagement connects with a third rationale for involving stakeholders – a 'substantive' rationale that states "participation leads to better ends, in both the quality of the science and the decisions made" (Tsouvalis and Waterton 2012, 113) and enhances research quality and social intelligence (Chilvers 2008). GIS, with its opportunities to include and spatially analyse multiple layers of information, is clearly a potentially useful tool in this regard. However, GIS's privileging of quantitative data over other data-types, its 'view from nowhere', high-tech, expensive nature, and its requirement for expert knowledge temper the possibilities for a substantive participatory process which includes different ways of knowing the landscape. Taking this into account I reconsidered my rationale for farmer engagement and engaged with creative ways of subverting the constraints of conventional GIS methods. In Iteration Four (2.5) below I explain how advances in Feminist and Qualitative GIS opened up options for me to continue using GIS, whilst embracing the critiques of PGIS.

2.4.3 Methods used to explore the role of maps on farms in the study region

Semi-formal interviews addressing the three questions ('What maps already exist on farms in this region?', 'How do farmers use maps?', and 'What is the role of maps within current agricultural management interventions?') were conducted with each case study farmer, with farmers attending the focus group event (see below) and with an agricultural policy officer, farmer representatives and FEAs. In addition, as I continued my scientific field work (2.2 Iteration One) I was also continuing informal conversations with the farmers, family members and farm visitors. Some were stand-alone conversations and some conversations continued over many months. This in-depth 'knowledge-exchange' would have been difficult without undertaking the scientific study at the same time, as it gave me time on the farm and also legitimacy in the eyes of the farmers who were used to people showing an interest in soil profiles and vegetation surveys. Conducting both qualitative and quantitative data collection at the same time led to interesting linked conversations. With McLafferty (1995), I argue that that quantitative methods do have a place within research which is reflexive and sensitive to the history of privileging quantitative and universal forms of knowledge, and that mixed methods can lead naturally to an open dialogue between different ways of understanding the world (McLafferty 1995). I continued to consult and analyse the AES folders for each case study farm, along with other documentation provided by the farmers, such as documents relating to on-farm legally designated sites and land tenure agreements. I used a 'grounded theory' approach (Strauss and Corbin 1994) to explore the data collected (explained further in Iteration Four, sections 2.5.3 and 2.5.4).

In order to consider the role of maps at a wider scale than the individual farm, I set up a focus group in cooperation with one of the case study farmers, Farmer W. The idea for a focus group emerged from an early interview conducted with Farmer W to introduce the research. During the conversation Farmer W commented that, despite his interest in soil carbon and carbon management – he had been to several events on the importance of soil carbon management – nobody had ever explained the science behind it. After my explanation he shared some knowledge about how farmers make silage *"it [carbon sequestration] is basically a reverse silage process"* (2.5.12). He then commented that it was a shame that these kinds of conversations did not happen more often, and we started to plan a knowledge-exchange focus group event on his farm.

As well as providing a forum for knowledge-exchange around soil carbon and its management for the more than thirty researchers, farmers, farmer representatives and farming advisors who gathered at Farmer W's farm, this event provided an opportunity to further explore the role of farm mapping with a larger stakeholder group. It provided opportunities for me to ask questions and probe shared meanings and values, normative responses and areas of disagreement about experiences of previous policy interventions (such as AES) and current management of soil carbon, as well as gather opinions about the future on-farm management of soil carbon. I was also able to explore emergent findings from the case study approach within a wider forum. I used principles from Mason et al. (2013) to plan and deliver the event as "Too often such events involve both academics and practitioners articulating their knowledges, with neither group taking the time to listen, engage or actually interact around commonalities"(pg 253). Further details about the focus group event are provided in Chapters Four and Five (sections 4.4.2 and 5.2.4).

2.4.4 Empirical findings

Despite the wealth of spatially-explicit environmental information available on externally-held databases (some available for free) and AES FEP farm maps, the farmers I interviewed did not use maps or other forms of spatial representation in day-to-day farm practice or for long term farm planning. Farm Environment Plan (FEP) maps arrived on farms with policy officers and FEAs and were filed away and rarely, if ever, referred to. Discussions of maps were entangled with farmer experience of AES; its (often problematic) history and the materialities of AES as performed on farm. Two of the case study farmers had little or no involvement in the AES enrolment process or in FEP map creation, enrolment was left to a contracted FEA, and this was a typical experience. Throughout the study the farmers articulated different values and forms of knowledge held in relation to their land, sometimes explicitly and sometimes obliquely, but within the AES processes there wasn't formal space for any considerations that weren't related to financial or practical management of the farm. The marginalisation of farmer knowledges through 'calculative agencies' (Hinchliffe 2007) is symbolised by the AES maps: quantitative and positivist mapping procedures fit with the AES framework of "numbers and neat objects" (Hinchliffe 2007, 170) – such as length of hedge, diversity of plants, number of sheep, area of hay meadow and monetary rates for management prescriptions.

S. Hinchliffe in his book 'Geographies of Nature' (Hinchliffe 2007) talks about 'calculative agencies' (the surveys, advisers, paper-based agreements, and so on) as having an effect, they make certain things more significant (e.g. stocking densities and lengths of wall) and some things invisible (e.g. labour and emotion) through the times, spaces and materialities which are enacted by these assemblages. However, many of these 'calculative agencies' are rendered invisible in the final 'blue print' – the AES 'agreement' folder – which, although imbued with much importance and status (money has been invested in it and conflicts fought and compromises agreed in order to deliver it), is often, once printed, left sitting in a pile of papers and rarely consulted by farmers. One farmer handed it over to me to take away and read, despite hardly knowing me and having recently received only one copy. The folder is mainly pages of lists of numbers; allowable maximums and minimums or payments for actions agreed. The agreement becomes concrete as things 'are made to count' (Hinchliffe 2007, 169). The easily enumerated objects take centre-stage in a prefigured agri-environment (Hinchliffe 2007 cf Verran 2001). Maps, Hinchliffe suggests,

> *are not innocent guides to the making of natures. They are not the apolitical matters of fact that can be used to judge local schemes – they are themselves*

materially heterogeneous matters that need to be understood as outcomes of associations and political processes rather than starting points for such schemas (Hinchliffe 2007, 170).

I realised that in taking responsibility for my soil carbon maps, as part of a scientific and policy imperative to explore how soil carbon can be managed-for on farms, that I needed to account for this history and materiality. That these farms were not 'blank sheets' onto which I could start mapping soil carbon.

My experience of examining the maps within the AES folders also helped to explain why they were unused by farmers. Figure 2.2 shows part of one of the maps contained in an AES land management contract folder. It is typical of the majority of the maps I was shown: two-dimensional, paper, hand-drawn and hard to interpret. There was no key on this map or on any of the other maps, nor was there any reference to them within the rest of the folder documentation. The land holding was spread across a number of sheets, making it hard to follow. The folder contained other maps of the same land area but their connection was not explained. The FEA is likely to have drawn up the map and the codes used follow instructions in the Higher Level Stewardship Farm Environment Plan Guidance booklet (Department for Environment, Food and Rural Affairs 2005), although this is not mentioned anywhere on the map nor in the folder and the farmers I worked with did not hold a copy of this guide.

Such maps are created as part of a Farm Environment Plan (FEP) which is one stage in the process of negotiating an AES on a holding. The map will be used in negotiations between the policy officer and the potential agreement holder in finalising the agri-environment management prescription on the farm. The map can also be referred to by either party at any point in the duration of the agreement period.

Figure 2.2 Image of part of a farm vegetation survey map sourced from a case study farm agri-environment scheme folder. Integrated Administration and Control System (IACS) numbers have been blacked-out to preserve anonymity.

The maps held within the AES folders are static representations of policy-relevant aspects of the farms (such as vegetation type). Their static and 'finished' nature hides (or denies) on-going or interrupted/prematurely fore-closed conversations regarding agri-environment management. Their 'smoothness' hides frictions and contested versions of the farm. The AES folders contain a series of these static and smooth farm maps as part of a fixed-term agreement and the folders will rarely be opened before the next enrolment process. This represents both the dominance of policy cycle timing (over farm cycles) and a policy requirement for (apparent) consensus. Farmer W raised concerns and frustrations that AES conversations, conflicts and the reasons for decisions were not recorded anywhere. This progressed into a discussion which identified the spatial context of many of these conversations and conflicts and an idea for creating a map which could be updated with such conversations over time, by farmer and adviser/officer. This idea was taken to the other case study farmers and to the focus group event and developed, through these interactions, as an element in the MMM approach in Iteration Four (2.5) and the idea is further explored in Chapter Six (6.3.1).

The only other spatial representations made available to me (and as I understand the only other ones in existence on the farms) were remotely-sensed images. The advent of accessible and high resolution remotely-sensed imagery and on-the-ground sensor networks has created a lot of quantitative data and, with GIS, new ways of representing landscapes and socio-ecological systems. Remote-sensing (also called earth observation) is the collection of data, using aerial sensor technologies mounted on, for example, satellites, 'drones' or aeroplanes, to detect and classify objects or phenomenon on Earth without coming into contact with the object or phenomenon (Burrough and McDonnell 1998). This involves the detection and recording of values of emitted or reflected electromagnetic radiation and can be used to monitor terrestrial, atmospheric and oceanic properties. However, there is increasing concern about the way in which 'big data', such as remotely-sensed imagery, has removed 'non-experts' from co-production of knowledge within natural resource management decision-making processes (Nightingale 2003; Smith and Brennan 2012; Rajão 2013). There are also questions around how these technologies contribute to new sensory processes by shifting the relations, entities, occasions and interpretive registers of sensing and how the interpretive practices and arrangements that develop inform policy (Gabrys 2012).

Farmer B obtained remotely-sensed images of his farm from DEFRA. In an interview he explained how such images could be misinterpreted and how using such imagery to delineate land parcels left farmers who farmed topographically-varied land at a financial disadvantage. Suspicion of how remotely-sensed imagery is interpreted and linked to surveillance for punitive reasons by external agencies was evident in other conversations with project participants. See Kovács (2015) for an explanation of how surveillance is used within the EU's normative procedures and practices in order to realise the CAPs agri-environment measures.

2.4.5 Summary and realisations

> *Once a map is drawn people tend to accept it as reality. (Bert Friesen, quoted in Chiles 2012)*

Maps are not used much on farms in this region and those that are held on farm are disengaged from the daily lived-experiences of farming. They are entangled with histories of AES interventions on the farms, and with ideas of surveillance and suspicion of externally-held data. AES folders and the farm representations within them are treated as a 'blank canvas' at the beginning of each policy cycle, however, they are inhabited, for the farmers, by the histories of the previous schemes, relationships with policy officers, and by on-going discussions. The maps represent the premature fore-closure of discussion, the end of a policy cycle, despite on-going discussion and tensions which fester after the map has been inserted into the completed folder. There is a clear primacy of scientific, quantitative data as 'evidence' but limited access to this data for the farmers. The maps provided for analysis were two-dimensional, representative of a snap-shot in time without this being made explicit and their 'smoothed' frictionless nature represents an approach to the process of farmer engagement whereby tensions and contestations are 'fixed' to fit a universal version of the farm. By investigating experience of AES and on-farm mapping simultaneously it is clear that maps have come to symbolise, for some farmers, some of their problems with previous policy intervention and the problematic process of enrolling in AES schemes in particular. Finally, I highlight the lack of situated knowledge within the maps – they represent a 'view from nowhere', with hidden assumptions, aims, epistemologies and ontologies.

So, after Wood and Fels (2008) (and drawing on the wealth of literature using non-dualistic thinking about nature and society, explored more in Chapter Five), I asked 'what nature am I mapping?' and 'am I perpetuating the problematic mapping practice I describe above?'. The digital soil maps I created were multi-layered, detailed and look assured and complete. Maps and databases contain uncertainty, assumptions, privileged knowledge, and story-making power

(Wright et al. 2009), but this was not apparent in my maps. I found that the apparent authority of the scientific process, protocols, equipment, software, presentation, and values precluded the farmers from questioning or contesting my findings. When I showed Farmer E how easy it was to alter the parameters of the map and show a farm which felt more or less 'full of carbon' (*"Fiddling with it"* Farmer E, 17.6.14) this resulted in some mild but polite scepticism about my mapping process.

Wood and Fels (2008) talk about mapping a 'possessable nature', in mapping soil carbon I suggest that I am mapping a 'controllable nature'. Waterton and Tsouvalis (2015) suggest this 'controllability' can provide a normative framework from which to work (Wood and Fels would say that maps produce the world by making propositions): we know how to interfere with soil carbon cycling, soil carbon is identifiable, quantifiable and mappable. It therefore follows that we should manage/control soil carbon on this farm using the same tools and knowledges we used to map it. This statement is not held in the map as the image alone. Wood and Fels (2008) argue that a map is actually a 'paramap' made up from two sections: firstly, the 'perimap', which is the production surrounding the map (linking back to my concerns about presenting the map – on a screen on paper, parameter choice, hidden assumptions, and so on); and, secondly, the 'epimap' which is "the discourse surrounding the map designed to shape its reception" – the thesis, presentations, journal articles and letters to reviewers which surround the completion of a doctoral degree (Kitchin et al. 2009, 14). The paramaps are how my soil carbon maps 'do work' as finished, two-dimensional, static, smooth and frictionless 'views from nowhere'.

These realisations did not sit well with me. I now recognised mapping's problematic background on-farm and its complicity in the marginalising of other knowledge forms. I now understood that I was reproducing "idealised idioms, discourses and rationalities of 'experts' whilst extracting knowledge from participants in unaccountable ways" (Tsouvalis and Waterton 2012, 115 drawing from Cooke and Kothari 2001). In addition, through on-going conversations and interviews I had started to identify other, contested versions of soil carbon on the farm – including soil carbon as embodied experience, as hard work and as hope for the future (see Chapter Five). I needed a way of finding space for these alternate versions of soil carbon, to acknowledge contestation within the maps and treat the mapping as a process of knowledge creation that did not finish with the maps printed in my thesis or in a journal article. As with Tsouvalis and Waterton (2012, 115) I resolved "to learn from critiques of participation and to approach them as a 'productive challenge'". In Iteration Four (2.5) I explore how I took responsibility for my map-making by utilising Feminist and Qualitative GIS concepts and tools to subvert and open up the mapping process through MMM.

2.5 Iteration Four – *Doing* Mixed Methods Mapping

2.5.1 Including different knowledges in spatially-explicit databases – inspiration

Two inspirational researchers, who have attempted to reveal and integrate Indigenous or other 'local knowledges'[19] in spatially-explicit databases as 'radical geospatial measures' (Eades 2015), are Helen Verran and Gwilym Eades. They work with Indigenous communities in Australia and Canada respectively. Verran and Christie's (2007) work on creating a digital database space for collective Aboriginal Australian memory was particularly inspirational. The importance of taking time and using reflexivity within the process was evident in their project reporting. They subverted the structure of a conventional digital database so it was a better fit with the Indigenous knowledge system. Verran explains that all knowledge systems share the character of localness, but that doesn't mean that we can treat all knowledge as the same (Watson-Verran and Turnbull 1994). Verran (in Verran 2002) explains that different communities have the same process whereby they justify their knowledge generalizations in reference to a metaphysical framing and this is in the collective memory of the communities. 'Doing knowledge properly' is part of community identity. The storage of such knowledge, within a map for example, should also reflect how knowledge is 'done properly'.

Eades (2015) utilises his concept of 'place memes' to add ethnographic depth, including memories, smells and feelings, "to abstract representations of toponymy and symbolic landscape", as "[i]nscribed GIS maps do not do justice to

[19] I place 'local knowledges' in inverted commas as STS also recognises scientific knowledge as a local knowledge – see Latour (1987) and Kloppenburg (2009).

life on the ground" (pg 72). Eades uses cognitive science to formulate the idea of place memes as an iterative mapping process which reinforces inscription in the brain or externally (e.g. on a map) through interaction with place from one or many viewpoints, where approaches or routes to that place are important in the formation of place. He uses three examples of Indigenous Canadians' journeys to illustrate this concept. Eades develops the counter-mapping concept of place memes as a cross-cultural cartographic device which integrates Indigenous wayfarer's performed land practices with new travellers' devices for mapping routes. In doing so he recognises that the historical role of territorial maps as 'immutable mobiles'(Latour 1987) are problematic for Canada's Indigenous peoples.

Both researchers recognise that inclusive mapping is not just about valorising the views of those who have been subjugated in previous mapping processes. Their work embraces Haraway's (1991) argument that mapping such knowledge of place is still partial, 'a view from somewhere', and Hinchliffe's (2007) argument that this is more complicated than the notion that there are a number of possible perspectives on the same thing and we can choose the 'best' or 'true' version. It is not about accepting the views of a plurality of positions as having equal validity, but understanding that partiality and situated knowledge bring new connections and unexpected openings to our understanding of place (Haraway 1991).

2.5.2 Using Feminist and Qualitative GIS to develop Mixed Methods Mapping of soil carbon

In the previous section I introduced Feminist GIS as a field of study relating to Critical Cartography and as an approach which interrogates and then moves-past GIS as a method solely connected with positivist scientific practices and visualization technologies. Feminist GIS (in particular) has developed Qualitative (QualGIS) and Mixed Methods GIS alongside more familiar qualitative and quantitative research methods as a way of bringing together different ways of knowing. Qualitative methodologies are rarely used in conventional cartographic and GIS research and visualizations. QualGIS develops critical engagement with mapping through methods which integrate qualitative data grounded on the critical agency of the GIS user/researcher (Schuurman and Pratt 2002). Feminist

GIS grounds criticism within the practices of the technology so that the investigator has a stake in the outcome (Kwan 2002c; Schuurman and Pratt 2002) – “the importance of practice cannot be overstated as change will not occur through trenchant critiques alone, but through everyday struggle with the technology in GIS labs or ‘sites’ of all kinds” (Kwan 2002b, 262). As with wider feminist studies, Feminist GIS and QualGIS hold a commitment to progressive social change – to reveal and make under-represented, oppressed and marginalised knowledges count. They aim to “disrupt the dualist understanding of geographical methods” (Kwan 2002a, 273) and recognise the partial and situated nature of all knowledges. QualGIS draws on the extensive feminist literature to ensure that actor roles are not pre-framed and actor constructions/roles not pre-decided by those privileged with the facilitation of the research.

Feminist QualGIS researchers have used interdisciplinary approaches to tackle subjects as diverse as creating alternative versions of neighbourhoods and community spaces (Knigge and Cope 2006), analysis of informal economies (Pavlovskaya 2002), and mapping women’s worlds (Kwan 2008; Bagheri 2014). However, despite increasing interest in this praxis only a few studies have incorporated qualitative local knowledge into digital spatial representations for wider environmental and natural resource management (e.g. Hurley et al. 2008; Smith and Brennan 2012). There is a need to continue creating new methodologies and approaches which apply the “feminist notion that carefully and thoughtfully incorporating multiple ways of knowing is some of the most important political work we can do” (Cope and Elwood 2009, 177) within environmental management (Urquhart et al. 2011; Wilner et al. 2012).

2.5.3 Grounded Visualisation

Grounded visualization (GV) emerged from Feminist QualGIS practices when Knigge and Cope (2006) developed a method to iteratively explore and disrupt the official classification of land plots within a community planning process. The quantitative classification system historically used within the planning process was easy to integrate into quantitative analysis describing the area but, as Knigge and Cope discovered, they hid a diversity of uses for vacant plots which supported an important social role for residents through attachments to place and in reflections of their identity, social practices, and sense of community. GV is an integrated strategy which is both recursive and reflective and builds on the strengths of visualization with the looseness of approach and open-minded progression of grounded theory[20]. Using this method they broke down the boundaries between quantitative and qualitative data and built strong theories from both concurrently.

Despite its potential utility within spatially-explicit decision-making processes that are often highly contested and include a diversity of knowledges and metrics of 'success', an academic database search yielded only one article which uses GV as an approach for mapping ecological processes or commodified units of environmental goods and services onto a socio-ecological space[21]. Hurley et al. (2008) found a GV approach useful in their exploration of the 'fringe ecology' of sweetgrass habitat as it relates to marginalized African-American sweetgrass basket-making communities. They found that the stories told by the basket-makers, when analysed alongside quantitative ecological data, revealed a partiality on both sides which would have been labelled as 'conflicts' or 'inconsistencies' in any other mapping process, but in using GV they shed light "on the ways the social and ecological impacts of urbanization … are both interwoven and uneven" (Hurley et al. 2008, 558). GV appeared to be a promising approach to mapping soil carbon onto farm spaces and so I applied it within my Mixed Methods Mapping approach.

2.5.4 Mixed Methods Mapping – my approach

My MMM approach acknowledges the benefits of treating the mapping of soil carbon on farms as a process and a way of exploring frictions and contestations – accepting that the set of relations delineating a landscape or a site are not reducible to one another. I used GIS's 'layered map surface' structure to

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[20] Grounded theory originated with the work of Glaser and Strauss (Glaser and Strauss 1967) and 'involves the collection, coding, and categorisation of qualitative data toward enabling themes to emerge through iterations of 'constant comparison' (Knigge and Cope 2006). Knigge and Cope identify four areas of commonality between grounded theory and visualization: "they are both exploratory, they are both iterative and recursive, both enable simultaneous consideration of particular instances and general patterns, and both encourage multiple views and perspectives for building knowledge" (pg 2022).

[21] Checked on Scopus 15.10.15.

juxtapose different versions of the farms[22]. In reconsidering my mapping methods I also reconsidered the framing of farmer participation in the project. My 'substantive' rationale for engagement allowed me to reconsider the interview data to explore new spatial references relating to soil carbon. I subsequently analysed material that related to: emotion, soil carbon, the farm and changes in management practice; the embodied experience of soil carbon; and, any other knowledge of soil carbon that could be integrated into the maps as geolocated data[23] (see Chapters Four 4.6 and Five 5.2.4). Drawing on a grounded theory approach (Strauss and Corbin 1994) each transcript was read through a number of times, observational notes were made and then coding and thematic analysis was carried out. Coding fractures the data and rearranges it into categories that facilitate comparison between things in the same category and aid in the development of theoretical concepts. The coding process occurs a number of times on the same transcript until it coheres around a set of emergent themes (Dey 1999). Coding was carried out using the software programme Atlas.ti (version 7.5.9, 2015, Berlin, Scientific Software Development). At the same time I was continuing field work and emerging issues and understandings continued to inform the development of the methodological process.

Working with my colleague Andy Beanland, who has computer scripting expertise, we drew on the work of Jung (2009) to create 'imagined grids' within which we could embed non-text spatial data, such as photos, sketch and other scanned paper maps, directly into GIS data structures (Figure 2.3). An 'imagined grid' is a "special layer for storing qualitative data" comprising regular grid cells overlaying other data layers which provides a spatial identifier to the qualitative data (Jung 2009, 120). The qualitative data was analysed alongside the quantitative soil carbon maps to start to draw out interesting relationships, including conflicts and uncertainty. This was done using the inbuilt software

[22] This draws on Foucault's (1986) concept of 'heterotopias'. Foucault (1986) describes a heterotopia as a "counter-site, a kind of effectively enacted utopia in which the real sites, all the other real sites that can be found within culture, are simultaneously represented, contested, and inverted" therefore "The heterotopia is capable of juxtaposing in a single real place several spaces, several sites that are in themselves [seemingly] incompatible" (pg 24, my addition).

[23] These points can have associated 'attributes' added – such as interview text http://help.arcgis.com/EN/ARCGISDESKTOP/10.0/HELP/index.html#//001t00000019000000.htm

query tool and through ‘playing around’ with the structure of GIS as a tool and concept (Perkins 2009). For example, altering knowledge hierarchies (using the layered structure), altering scale, and considering patterns in data based on time, non-traditional base maps and alternative spatial gradients such as land tenure and distance from the farm house.

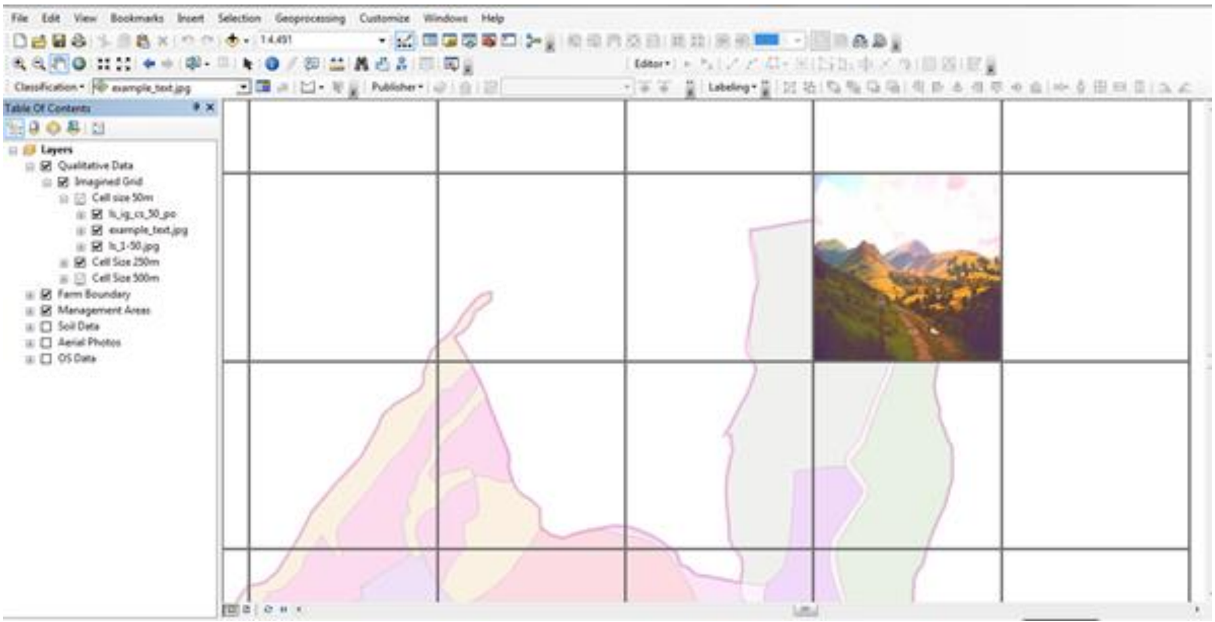

Figure 2.3 Screenshot of imagined grid in use within ArcMap (ArcGIS Desktop version 10.2.2 ESRI 2011).

The next stage of the MMM process involved exploring case study farmers’ reactions to the quantitative soil carbon mappings and to potential future scenarios for managing soil carbon. A ‘spatial transcript’ methodology was used (Jones and Evans 2012). This is a walking interview where a voice recorder and a global positioning system (GPS) are synched. The progression of the walk was plotted as a route on the digital map and the associated narrative and new theme codes were geo-located within the map’s database (see Figure 2.4). Evans and Jones (2011, 849) found that “the data generated through walking interviews are profoundly informed by the landscapes in which they take place, emphasising the importance of environmental features in shaping discussions”. This felt important in a project which recognises that experience of place shapes understandings of soil carbon in the farm landscape (see findings below and in Chapters Four 4.7 and Five 5.4). The interviews were unscripted and the focus was on elicitating lived-experience in relation to soil carbon. For example, stories linked to carbon-rich and carbon-poor parts of the farm. They were open to any topic the farmers brought up. The topics introduced by the farmers included what might follow on from this project – from the legitimation of this version of the farm – the farm as stocks of soil carbon.

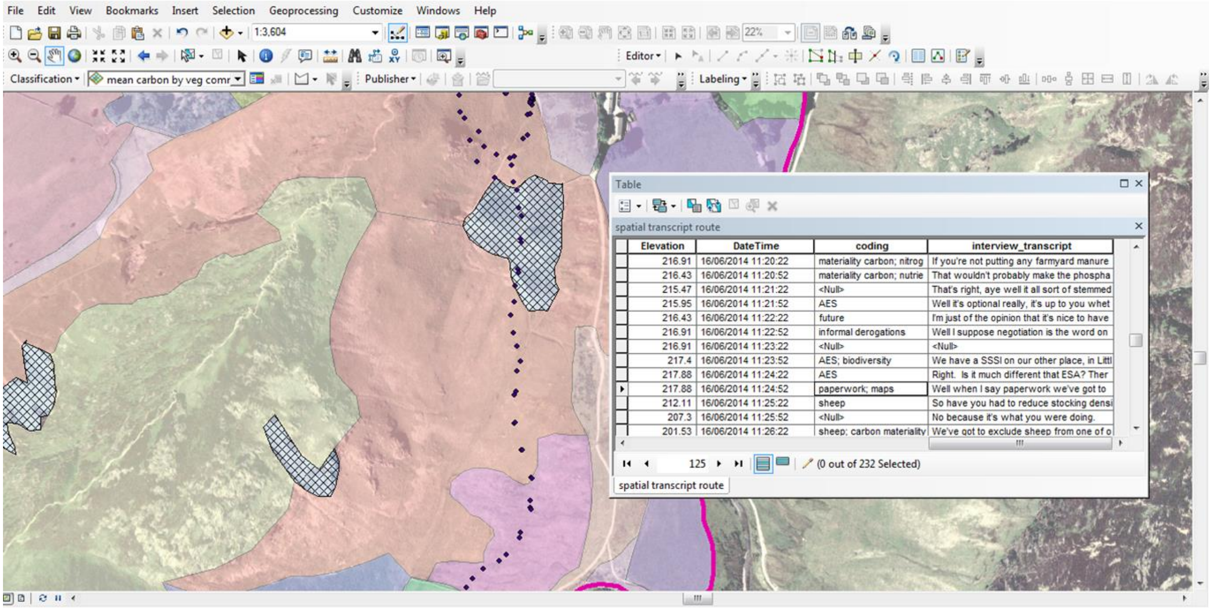

Figure 2.4 Screenshot of spatial transcript method in use within ArcMap (ArcGIS Desktop version 10.2.2 ESRI 2011).

Through MMM of soil carbon I aimed to include and analyse qualitative and quantitative data together and allow this analysis to inform the methodological process. It is understandably a very visual process. In altering the hierarchies of data, for example, it is the visibility (or not) of the different mapped surfaces which is considered. However, the process tried to make space for and creatively incorporate the other senses, emotions, contingencies and uncertainties. Mapping as process means that there was no 'teleological inevitability' about the production or form of the mappings (Kitchin et al. 2013). Rather, the mappings emerged "from a set of negotiations between different sets of knowledge, contexts and technical and expertise assemblages" (Kitchin et al. 2013, 9). To apply this approach within an agri-environment decision making process means that the mapping would never be 'finished'; which would allow for different accounts of the farm to be kept open and for on-going recording of discussions, decisions and conflicts. This 'dynamic mapping' is clearly problematic to display in a thesis format and Chapter Six (6.3.1) suggests how the approach could be improved, developed and made policy-ready and provides outline ideas for future research.

2.5.5 Findings from the case study farms

As well as a scientific entity, soil carbon was revealed as an embodied experience (Chapter Five). Land and soil properties are experienced corporeally and emotionally as well as conceptually, for example through labour. Different forms of knowledge (tacit, lay, expert, and experiential for example) are discussed in the 'knowledge literature', but a diversity of knowledges is rarely acknowledged in formalised approaches to land management. Through this interdisciplinary approach I attempted to explore what happens when different knowledges are brought into an institutional mapping context. Here I present some of the specific findings from the MMM process, which illustrate the utility of such an approach within agri-environment decision-making processes. Chapters Four and Five provide more detail and discussion.

Discussing soil carbon revealed different levels of farmer understanding and engagement with the terminology, ecology and concept of soil carbon depending on the method used. Spatial transcripts revealed a depth of knowledge about soil carbon that was not shown in static interviews. For example, Farmer E had, on a number of previous occasions in static interviews, said he knew very little about soil carbon, however during the spatial transcript interview he explained how the root structure of different plant species might affect carbon stored in the soil:

> *I mean some of these better managed fields here - you've gone down fairly deep [sampling] but yet it doesn't show as high a level of carbon really… It's maybe because with it being grassland the depth of the roots isn't that deep. (17.6.14)*

Exploration of different spatial gradients proved illustrative in explaining some of the 'inconsistencies' regarding farmer attitudes to manging their land for soil carbon storage. Some areas of farm land may appear to have the same properties as surrounding land, but for whatever reason – practical, emotional, historical or related to tenure – they will not be considered or will be considered differently in discussions about changing management practice. Distance from farm house and view sheds are two (non-Cartesian) gradients that the initial findings suggest could yield interesting results.

For all three case study farmers (and for some farmers interviewed at the focus group event) there was a perceived conflict between increasing soil carbon stocks and ‘good’ productive farming practice (i.e. production of lamb, beef and milk) and being a ‘good’ farmer. Some of the farmers interviewed, including two of the case study farmers, felt that they had not had to change land management practices to any great degree in order to qualify for previous and current AES. This confirmed for them the, important, belief that they were already stewards of the countryside. Currently carbon-rich landscapes tend to be the areas taken out of production – small areas of ‘sacrificed land’. The changes that would need to be made to significantly increase soil carbon storage overall on farms would likely be more dramatic. The associated management prescriptions would not only require a very different form of management, possibly requiring different skills, equipment, and an acceptance of a different level or type of risk, but would also move farmers further away from a productivist self-identity (Burton 2004) and the idea that upland farmers are already stewards of the countryside. This finding is explored further in Chapters Four (4.5.3) and Five (5.4.2).

These findings, and those explored in the rest of the thesis, emphasize the inherently local and place-based nature of sustainable soil carbon management and the need for meaning to emerge from within the interplay between different knowledges and local circumstance. Much of the research and policy thinking assumes farmers will be able to accept ‘carbon farming’ and associated changes in management practice given the right financial incentives and good communication about soil carbon’s global importance as a political and scientific entity. This shows a lack of understanding of the socio-ecological, material and more-than-human complexities in this landscape. Despite problematic histories I discovered that there is still a willingness for farmers, scientists and policy-makers to work together (see quote below), but I argue that this engagement needs a radical reconsideration of what soil carbon is to different people (and different epistemologies), how soil carbon is differentially performed, and what different representations of it do in the world. The rest of the thesis works to explore this further.

> *Well if you don't need us for livestock production to the degree we were needed before but you need us to help solve the carbon footprint problem and the renewable energy situation, then we need to work together. (farmer, focus group)*

3 Predicting farm-scale soil carbon stocks using easily accessible vegetation and soil data

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This paper is laid out as intended for submission, with the exception of tables and figures, which are presented in-line to aid interpretation. This paper has multiple authors and the contributions are detailed in section 1.5 and confirmed by my supervisors.

Chapter 3 preface

The introductory chapter explained the importance of being able to accurately predict, the spatial distribution of carbon stocks when developing land/soil carbon management plans (FAO and ITPS 2015). Currently, the creation of such soil maps requires time and resource-intensive field work and laboratory analysis or the use of standardised or proxy carbon storage figures (Jones et al. 2005; Eigenbrod et al. 2010). These maps have limitations with regard to how soil carbon storage is differentially affected by variation in local environmental and management conditions (e.g. McSherry and Ritchie 2013). Biogeochemical models are an alternative and can be used to model the turn-over of carbon in soils (Cerri et al. 2007; Powlson et al. 2008), however the paucity of data at sufficiently high resolution precludes farm-scale predictions, and data access and interpretation remain an issue in methods which utilise remotely-sensed vegetation data. Such data analyses can be complex and expensive (Pettorelli et al. 2014). There is therefore the need for a method which can accurately predict soil carbon distribution at the farm scale.

This chapter is written in the format of an academic journal article and is written for a soil science, soil and plant ecology, agro-ecology and agronomy audience. I experienced some tension in writing a paper for a scientific (or any disciplinary) audience within an interdisciplinary thesis. Writing for a specific disciplinary audience requires the use of specific language, assumes a certain level of disciplinary knowledge, and makes ontological assumptions. Also, the intention of the thesis is to bring different approaches to mapping soil carbon together, so a major tension emerges when I foreground the scientific findings separately and divorced from the other findings. However, I recognise that it is important to communicate findings to particular, disciplinary audiences and interdisciplinary research can contribute strongly to disciplinary (strictly disciplinary) knowledge development, whilst being reflective of broader interdisciplinary aims and outcomes.

Therefore, I decided that it was important to report on the specific applied ecology/soil science findings, which contribute to the discussion on how to predict and measure soil carbon at varying scales. I decided that this specific audience was less likely to engage if the wider approach of the thesis and associated tensions were introduced. This is a major issue in interdisciplinary research when researchers want to get their results out to an audience who are unlikely to engage with interdisciplinary journals or journals from outside their wider discipline.

3.1 Summary

1. Enhancing soil organic carbon stocks in agricultural landscapes can help mitigate climate change through removing carbon dioxide from the atmosphere in the long term. However, there is a need to develop methods for predicting existing soil carbon stocks without intensive field and laboratory work.

2. We trialled a method which used easily-accessible information on vegetation and soil properties to predict farm-scale soil carbon stocks on three study farms in the English Lake District.

3. We found that simple assessments of vegetation composition, commonly used in agri-environment schemes, and soil depth and moisture explained a high proportion of the variability in carbon stocks across landscapes and we were able to accurately predict soil carbon stocks to depth at the farm-scale.

4. Using these findings we accurately mapped soil carbon stocks across the farms using a cokriging interpolation approach.

5. *Policy implications.* Universal land management prescriptions have been shown to have heterogeneous effects on the success of schemes which aim to enhance soil carbon stocks. Our study develops an approach which accounts for local environmental variation in planning carbon management schemes.

3.2 Keywords

Soil organic carbon; agri-environment schemes; climate change; carbon sequestration; land management; extensive upland farming; kriging; soil carbon mapping; plant functional traits; above-blow ground ecology.

3.3 Introduction

Agriculture is under increasing pressure to deliver additional ecosystem services alongside food production (Power 2010), including the sequestration of carbon in soil to assist in mitigating global climate change (Smith and Bustamante 2014). Globally, three times as much carbon is stored in soil than in the atmosphere (Batjes 2014). Around two thirds of soil carbon is held as soil organic carbon (SOC) (approximately 1500 petagrams (Pg); Batjes 2014). The amount of SOC depends on the balance between primary production and decomposition, leaching and erosion, and at a local level can be influenced by soil abiotic properties, vegetation composition, climate and land-use type and intensity (Schmidt et al. 2011; O'Rourke et al. 2015). Agricultural land management practices have been shown to enhance or decrease carbon sequestration (Smith et al. 2008; Beniston et al. 2014), and the global potential for changes in agricultural land management practice to increase SOC sequestration to mitigate climate change is intensely debated (Powlson et al. 2011; Mackey et al. 2013; Smith 2014). Soils have a finite capacity to stabilize SOC (Six et al. 2002) and any meaningful intervention requires a long-term commitment to identified land management techniques, as any subsequent change in management practice can rapidly release any accumulated carbon (Beniston et al. 2014). However, as noted by several authors, agricultural land management intervention is increasingly being considered as an option for climate change mitigation and we need more research into soil carbon fluxes in different soils and how local land management practices affect soil carbon stabilization and storage (Stockmann et al. 2013; O'Rourke et al. 2015).

A number of landscape-scale studies have highlighted the potential for SOC sequestration to contribute to mitigation targets (Wang et al. 2014). However, at present, mapping actual SOC stocks relies on major sampling efforts in the field and subsequent laboratory analysis, which is time-consuming and expensive. Other options include using standardised or proxy carbon storage figures (Jones et al. 2005; Eigenbrod et al. 2010), which have clear limitations with regard to local conditions, or using models (Cerri et al. 2007; Powlson et al. 2008) where there is a paucity of data at sufficiently high resolution to enable small-scale predictions. Within Europe, SOC management could be delivered through existing farm-level policy mechanisms, such as agri-environment schemes which provide payments to farmers who subscribe, on a voluntary basis, to environmental commitments related to the preservation of the environment and maintaining the countryside (Bol et al. 2012; Horrocks et al. 2014). Another possible mechanism is Cross Compliance, which links direct payments to compliance by farmers with basic standards concerning the environment, food safety, animal and plant health and animal welfare, as well as the requirement of maintaining land in good agricultural and environmental condition (Bol et al. 2012). Given these potential mechanisms, there is clearly a need for new scientific methods that can rapidly deliver locally accurate farm-scale predictions of existing soil carbon stocks using accessible data.

Plant matter is the single most important carbon input to the soil (De Deyn et al. 2008) and previous studies have found vegetation composition and productivity to be key determinants in SOC dynamics (Fornara and Tilman 2008; De Deyn et al. 2009). Incorporating vegetation measurements into predictive soil carbon models has been shown to improve prediction. For example, Manning et al. (2015) found that national-scale surface soil carbon stocks could be predicted in agricultural grasslands using plant trait measurements and simple measures of soil and climatic conditions; Cong et al. (2014) found vegetation species richness indices predicted stocks of both soil carbon and nitrogen at field-scale in agricultural grasslands; and, Conti and Díaz (2013) found that plant community functional diversity was correlated with soil carbon storage in subtropical forests at a landscape-scale. Aerial vegetation imagery and various types of vegetation land cover maps have also been used to predict soil carbon stocks at regional, national and continental scales (Muñoz-Rojas et al. 2011; Renwick et al. 2014). However, to our knowledge, no attempt has been made to predict farm-scale soil carbon stocks by using simple vegetation maps, as commonly produced for farms within agri-environmental schemes. Vegetation mapping of agricultural land has been carried out extensively in Europe (Oppermann et al. 2012). For example, in England, farms enrolled in an Environmental Stewardship agri-environment scheme (52,300 farms in 2014) are required to produce a vegetation map as part of an obligatory Farm Environment Plan (FEP) (S. Hammonds, personal communication, Natural England). Detailed vegetation mapping is also being encouraged across Europe as a result of the European Union (EU) Habitats Directive (92/43/EEC), which requires EU Member States to identify and designate sites to be included in the Natura 2000 network (Muséum national d'Histoire naturelle and European Environment Agency 2014).

Our overarching aim was to explore the utility of simple measures of farm vegetation type derived from FEP maps commonly used in English agri-environment schemes (Department for Environment, Food and Rural Affairs 2005), along with simple soil measurements, for accurate prediction of soil carbon stocks at the farm scale. The study was carried out using data on total carbon stocks collected from three farms in the English Lake District National Park in the north-west of England. We used statistical regressions to examine the relationship between the field-collected soil carbon data and simple vegetation and soil variables, and tested whether these variables can predict soil carbon stocks at the farm-scale. We chose this region because farming is predominately based on livestock production on agriculturally unimproved, low productivity grassland and heath, which are typically associated with relatively high soil carbon stocks (Manning et al. 2015). The UK Government considers these, and other temperate upland ecosystems, to be an "important asset for the UK in relation to climate regulation" (Haines-Young and Potschin 2009), and in 2014 the region was one of the first in the UK to trial payments to farmers for enhancing carbon storage through an offset scheme (Hagon 2014). Moreover, farming in the region has been strongly influenced by government agri-environment schemes for several decades, and hence most farmers have access to farm-scale FEP vegetation maps. We asked the following questions: Is it possible to predict total soil carbon stocks, to depth, at a farm-scale within topographically heterogeneous landscapes by utilising simple measures of vegetation and soils derived from information commonly used within agri-environment schemes? Is it possible to create accurate maps of soil carbon stocks by utilising these simple measures? And, is there a role for such maps in improving soil carbon management planning?

3.4 Methods

3.4.1 Sampling Design

Our main study focus was a single 180 ha (including access to common grazing) sheep and beef farm, which includes a broad range of vegetation types representative of traditional upland farms in the English Lake District region. We also studied two additional farms (in the central and western parts of the region) in order to verify the findings from our main study farm, hereafter referred to as Main Farm. These additional test farms, hereafter referred to as T1 and T2, were 152 and 344 ha in size respectively, also rear sheep and beef cattle, were chosen as they include vegetation types additional to those found on the Main Farm, and have contrasting topography and geology. All three farms are situated within different valleys in the Lake District National Park. This is an area of upland, topographically heterogeneous, low intensity agriculture dominated by extensive grazing of sheep and cattle, containing a mosaic of semi-natural habitats relating, by varying degrees, to historic management, soil conditions and microclimate. Mean annual temperature for the region is approximately 9 °C and mean annual precipitation is around 3200 mm at higher elevations (UK Met Office, 2015).

The Main Farm is topographically diverse, ranging in elevation from 142-534 m, with relatively shallow soils (75% of sample locations had soils shallower than 60 cm). It has eight different vegetation types, as identified by the Farm Environment Plan (FEP) vegetation survey (carried out as part of an agri-environment scheme enrolment process in 1998), which include woodland, (permanent) semi-improved grassland, grass moorland, hay meadows and wetland areas. Farm T1 has less diverse topography (elevation range 51-228 m), shallower soils (85% of sample locations had soils shallower than 60 cm) and seven identified vegetation types (three in common with the Main Farm). Farm T2 has deeper soils than the Main Farm (74% of sample locations had soils deeper than 60 cm) and only three vegetation types (most of the holding is improved grassland) (see Table 3.1 for details). Farm locations are not detailed for anonymity reasons relating to a parallel social science study.

Table 3.1 Site characteristics of the study farms, including geology (DiGMapGB-625 Rock Units, Edina Digimap), soils (LandIs www.landis.org.uk/soilscapes/) and vegetation community information (derived from FEP vegetation type maps, Department for Environment, Food and Rural Affairs 2005).

Farm	**Geology majority (minority)**	**Soil types**	**Vegetation communities**
Main	mudstone bedrock; (sandstones and micro-gabbro)	slowly permeable seasonally wet acid loamy and clayey soils freely draining acid loamy soils over rock	semi-improved grassland; upland hay meadows (unimproved grassland with key functional species *Anthoxanthum odoratum, Trifolium pratense, Ranunculus acris* and *Rhinanthus minor*); unimproved grass moorland (typically dominated by *Festuca* species, *Nardus stricta*, *Juncus squarrosus* and *Molinia caerulea*); unimproved grass moorland dominated by *Pteridum aquiliunum*; upland heath (dominated by *Calluna vulgaris* and *Vaccinium myrtillus*); wetland areas (*Sphagnum* spp. and *Eriophorum* spp. frequent); upland oak woodland; and, rank vegetation (scrub)
T1	volcanic; slates, siltstones and sandstones; (basalts, andesites and mudstones)	slowly permeable wet very acid upland soils with a peaty surface loamy and clayey floodplain soils with naturally high groundwater freely draining acid loamy soils over rock	improved grassland; semi-improved grassland; Purple moor-grass & rush pastures (dominated by *Molinea caerula* and *Juncus* spp.); upland hay meadows; unimproved grass moorland; fragmented heath (dominated by species from the *Ericaceae* family, *Vaccinium myrtillus*, *Empetrum nigrum* and *Ulex gallii* in a mosaic with acid grassland); wetland areas
T2	granite; mudstone; sandstone; siltstone; gritstone; (carbonifero us limestone)	freely draining slightly acid but base-rich soils slowly permeable seasonally wet slightly acid but base-rich loamy and clayey soils freely draining acid loamy soils over rock	improved grassland; lowland dry acid grassland (semi-natural grassland generally dominated by fine-leaved grasses on nutrient-poor, free-draining soils); upland heath

The farms were divided into vegetation type sampling units based on the vegetation codes from FEP survey maps. We also worked with the farmers in interpreting and integrating the maps into the sampling design. This proved to be useful in providing additional information and nuances to the FEP maps and we recommend such an approach. The FEP vegetation survey method is based on the UK's National Vegetation Classification system (Rodwell 2006) and has been simplified by national government (Department for Environment, Food and Rural Affairs 2005) to make it usable by farm environment planners, interested farmers and other land managers (D. Martin, Natural England, pers. comm.). On the Main Farm we sampled at 10 random replicate locations within each identified vegetation type and, for the test farms (T1 and T2), we sampled at 6 random replicate locations within each vegetation type. A decision to sample a lower number of replicates for the test farms was based on the results of a power analysis conducted on data from the Main Farm.

We took soil samples at 20 cm intervals down the profile to depth (for the Main Farm we divided the shallowest 20 cm into 0-7.5 cm and 7.5-20 cm to reflect previous studies but analysis showed this to be unnecessary for the test farms). We sampled to maximum soil depth (the equipment allowed us to sample to 1 m so the majority, but not all, of the samples were to maximum depth), given that past studies have revealed significant quantities of carbon at depth (Fontaine et al. 2007) and soil carbon content will vary with depth (Kramer and Gleixner 2008), although existing soil carbon inventories rarely sample below 15 cm (e.g. Emmett et al. 2010). We also conducted comprehensive 2 m x 2 m plant surveys, to species level, within each vegetation type at each soil sample location (Rodwell 2006). The survey recorded estimated cover of plant functional groups (bryophytes, *Sphagnum* species, legumes, grasses, forbs, shrubs, trees and *Juncus* species) and a species could be recorded as being in more than one functional group.

3.3.2 Soil analysis

Soil samples were analysed to determine total carbon and nitrogen. Soil was sieved using a 4 mm sieve and stored at 4°C for a short time prior to analyses. A sub-sample of soils collected at the specific depths were dried at 60°C for 48 hours, ground using a ball mill, and analysed individually for total carbon and nitrogen by combustion and gas chromatography (Elementar Vario EL III CN analyser). Soil carbon and nitrogen concentrations were produced. We report the quantity of carbon and nitrogen stored in soil per unit volume (kg C m^{-3}, kg N m^{-3}) derived from carbon and nitrogen concentration and bulk density values. This provides an estimate of total carbon and nitrogen stocks in grassland soil (kg m^{-3}) for each sample depth increment. Bulk density provides a measure of the soil mass per unit volume in kg m^{-3} and was calculated from the mass of oven-dried soil (kg) divided by the field volume (m^3) for each of the samples collected. We also tested for pH and gravimetric soil moisture content following standard protocols (Allen 1989). Soil moisture has been shown to be correlated with soil carbon storage (Pastor and Post 1986) and soil pH has been shown to affect the soil carbon cycle (Kemmitt et al. 2006).

Total carbon measurements include both organic and inorganic carbon. In England soil inorganic carbon, typically carbonates, can make up to 15.5% of total C stocks to 30 cm depth (Rawlins et al. 2011). However, the proportion of the inorganic fraction is likely to be small in this case as the prevalence of inorganic carbon is determined by mineralogy and only one of the farms (T2) has any underlying carbonate rock. This underlies only 3% of the total area of the farm and was accounted for within the data analysis by examining the data with and without the samples overlying the limestone geology.

3.3.3 Vegetation analysis

Ten representative mature leaves were collected from each plant species which covered 1% or more of each quadrat analysed (Cornelissen et al. 2003). Rehydrated fresh material was used to determine leaf fresh weight (g) and specific leaf area (SLA) (cm^2). Plant material was then dried at 60°C for 48 hours. The following above-ground traits were measured on dried material using standard protocols (Cornelissen et al. 2003; Pérez-Harguindeguy et al. 2013): leaf dry matter content (LDMC) (mg g^{-1}), leaf nitrogen content (LNC) (%), leaf carbon content (LCC) (%), and leaf C:N ratio (the latter three using an Elementar Vario EL III). Trait values were assigned to each identified plant species and community weighted means (CWM) were calculated for each quadrat based on an abundance (plant cover) weighted mean of species leaf trait values (SLA, LDMC, LNC, LCC, LC:N) using the "FD" package (Laliberté and Legendre 2010; Laliberté, Legendre, and Shipley 2014) for R (R Core Team 2015). We calculated species richness and Shannon Diversity Index scores for each quadrat and ran a Principle Component Analysis (PCA) using the "princomp" function (Mardia et al. 1979; Venables and Ripley 2002) for R (R Core Team 2015) to summarise the leaf trait (five measurements) and vegetation composition data (eight plant functional groups) (Appendix II).

3.5 Data analyses

3.5.1 Statistical Regression

Briefly, we used linear mixed regression models (the "lme" function within the "nlme" package for R; Pinheiro et al. 2013) for R (R Core Team 2015) to establish, using restricted maximum likelihood estimation, which explanatory variables best predicted soil carbon and nitrogen stocks (kg m^{-3}) (modelled separately). Model selection was performed using a manual backwards-fitting technique and by consideration of the statistical significance of terms, applying AIC criterion to test the relative model fit, and also by examining the proportion of the variance (of the dependent variable) explained by the model by referring to the Conditional R-squared (Rsq) value. Conditional Rsq values represent the proportion of variation explained by both the fixed and random effects (Lefcheck and Casallas 2013). Model residuals were examined and Box-Cox transformations were applied where necessary to satisfy model assumptions regarding normality and homoscedascity of variance.

The explanatory environmental variables tested within each model were soil moisture, soil pH, depth of sample and vegetation type. Data for the first three variables were derived from field samples and the fourth, vegetation type, was described by a code derived from FEP maps (Department for Environment, Food and Rural Affairs 2005). Model interaction terms were also included, where appropriate, to test for interaction between the explanatory variables. Other variables tested for model fit were derived from digital mapping datasets: elevation, slope, aspect, soil type and bedrock and surficial geology. However, none of these explanatory variables were included in the final models. The sample location was included as a random effect to account for repeated measures samples taken from the same location down the soil profile. As the spatial statistical interpolation method (see below) is unable to use factorial data as covariables we also tested how well vegetation PCA scores (derived from leaf traits and vegetation functional groups) helped explain variation in soil carbon and nitrogen, as an alternative to using vegetation code. The first two PCA axes explained 75% of the variation in the leaf trait data and 79% of the vegetation composition data. The predict.glmmPQL function for R (Venables and Ripley 2002) was used to predict soil carbon stocks for all three farms combined, based on a model which included the explanatory variables soil moisture, vegetation code and sample depth. The predicted and observed carbon stock values were compared using a paired t-test within R (R Core Team 2015).

Linear models (the "lm" function within the stats package for R; R Core Team 2015) were used to test how well environmental and spatial variables (as detailed above) explained the variance in the soil carbon and nitrogen at each depth. Model selection was performed as above except for the use of Adjusted R-sq values (likelihood-ratio based Adjusted-Rsq), calculated using the 'r.squaredLR' function within the 'MuMIn' package (Barton, 2015) for R (R Core Team 2015).

3.5.2 Using spatial statistics to predict soil properties across the farm landscape

Spatial autocorrelation was identified in the residuals from the linear regression models (at each depth) by plotting empirical semivariograms using the "geoR" package (Ribeiro Jr. and Diggle 2001) for R (R Core Team 2015). Therefore, we utilised the spatial interpolation cokriging function within the Geostatistical Analyst toolkit in ArcMap (ArcGIS Desktop version 10.2.2 ESRI 2011, Redlands, CA: Environmental Systems Research Institute) to incorporate a spatial variable into interpolations of soil carbon stocks across each farm. Cokriging is a hybrid interpolation technique, which combines kriging with the use of auxiliary information (covariables) to improve predictive capability. Kriging is a powerful stochastic statistical interpolation method, which depends on spatial and statistical relationships and fits a function to a specific number or to all of the points within a specified radius to determine an output (Azpurua and Ramos

2010). Other environmental mapping studies have included covariables to improve predictive mapping by using the cokriging technique (Buffam et al. 2010).

We created a carbon stock prediction 'surface' (or map) for each soil depth using the 'ordinary' method in the co-kriging model specification (as we did not assume there was an over-riding global trend in the data and instead assumed local trends affected by the interplay of different variables). Using this interpolation method the generated cell values can exceed the value range of samples and so any negative values were converted to zeros (predicted values also exceeded measured values for a small proportion of some of the interpolated surfaces, but when tested against surfaces constrained by an artificial limit this 'over-shoot' was shown not to affect the overall results). Covariable selection was based on the best linear regression models (see above) however, as cokriging can only accept continuous covariables, we used a combination of plant leaf trait and plant functional group PCA scores in place of the vegetation type codes (see Appendix II). The trait and functional group explanatory variables, when used in place of vegetation type codes within linear models, did not perform as well but the associated model statistics were reasonable for depths from 7.5 cm to depth for all farms (depth 0-7.5 cm had variable results, see Tables S1-3, Appendix III). We also tested the data from a modelled hydrological surface for use within a replacement covariable for soil moisture field measurements. These surfaces were generated in ArcMap 10.2.2 using in-built functionality and data from digital elevation models of the farms.

The goal of spatial interpolation is to create a surface that is intended to best represent empirical reality, thus the model selected must be assessed for accuracy and validity and it is possible to calculate error surface output or 'cross-validation' statistics. Diagnostic measures (sums of squares errors, mean error and mean square deviation ratio of prediction error) were examined for each model. We compared kriging and cokriging models to establish whether the covariables improved the accuracy and validity of the predicted surfaces. We also consulted the farmers in validating the maps produced. The final predicted carbon stock surfaces, in combination with soil depth interpolation surfaces, were used to calculate average and total carbon stocks on the basis of vegetation type, depth and across the whole farm. The final interpolations and associated calculations were performed using the ArcGIS ArcPy site package which enables advanced geographic data analysis and data management using Python, an open source programming language (the supplementary material contains links to scripts). We opted for this approach for rapid reproducibility, to facilitate comparison between farms and reduce potential error in data manipulation.

3.6 Results

3.6.1 Predicting soil carbon stocks

Total soil carbon stocks on the Main Farm varied considerably across vegetation types. On average, total carbon stocks were greatest in soils under the grazed upland oak woodland at 92 kg m^{-3} and lowest under upland heath vegetation (dominated by *C. vulgaris* and *V. myrtillus*) at 25 kg m^{-3} (Table S4, Appendix III). Average soil carbon stocks by vegetation type at Test Farm 1 (T1) varied between 35 kg m^{-3} and 45 kg m^{-3}, and on Farm T2 between 22 kg m^{-3} and 76 kg m^{-3} (Tables S5-S6, Appendix III). Despite this variability we were able to predict soil carbon stocks across the three farms using a model that contained information on vegetation type, soil moisture and sample depth (there was no significant difference found between the predicted and observed stocks: $t=-0.232_{(df - 605)}$; $p=0.8169$). Total soil carbon stocks (kg m^{-3}) across the Main Farm were best described by the combination of vegetation type ($F=21.294_{(7,152)}$; $p<0.0001$), soil moisture ($F=292.513_{(1,369)}$; $p <0.0001$) and sample depth ($F=11.989_{(4,369)}$; $p<0.0001$), and explained variance was 76% (Conditional Rsq). The best models for both soil carbon and nitrogen stocks are included in Table 3.2. Both models have low residual error and high explained variance. The additional test farms T1 and T2 showed similar results: when all depths were combined, explained variance for total soil carbon and nitrogen stocks (kg m^{-3}) was 73-87% (Tables S7-S8, Appendix III).

Table 3.2 Selected models which best explain variance in soil carbon and nitrogen on the Main Farm, all soil depths combined (linear mixed model regressions). Lambda λ refers to the Box-Cox transformation value.

Predicted variable	**Fixed terms - associated F values (degrees of freedom); p values**	**Conditional R squared (explained variance)**	**Standard deviation of the residual error**
Carbon stocks kg m^{-3} (λ=0.3)	soil moisture $F=292.513_{(1,369)}$; $p<0.0001$ moisture:depth $F=21.977_{(4,369)}$; $p<0.0001$ vegetation type $F=21.294_{(7,152)}$; $p<0.0001$ depth $F=11.989_{(4,369)}$; $p<0.0001$ moisture:vegetation type $F=9.074_{(7,369)}$; $p<0.0001$	0.76	0.35
Nitrogen stocks kg m^{-3} (λ=0.38)	soil moisture $F=143.461_{(1,369)}$; $p<0.0001$ vegetation type $F=37.764_{(7,152)}$; $p<0.0001$ moisture:depth $F=17.582_{(4,369)}$; $p<0.0001$ depth $F=17.074_{(4,369)}$; $p<0.0001$ moisture:vegetation type $F=7.863_{(7,369)}$; $p<0.0001$	0.74	0.21

Total soil carbon stocks for each depth were best explained by soil moisture and vegetation type (explained variance 58-85%). There was no pattern to the variance explained for the different soil depths (Table 3.3). Residual standard error values were low for depths 7.5-60 cm (below 0.02) and higher for both the surface depth 0-7.5 cm (17.9) and depths below 60+ cm (9.0) (Table 3.3). Generally, comparison of mean carbon storage between vegetation types showed clear differences or similarities (Tables S4-S6, Appendix III), however, the comparison between *Pteridium aquiliunum* (bracken)-dominated unimproved grazing land and unimproved grazing land without the bracken cover required a statistical test to ascertain that the former was not storing more carbon ($t=1.9075_{(df\ -\ 45.744)}$; $p=0.06275$), although the result was nearly significant at $p\leq0.05$.

Table 3.3 Details of selected models (linear regressions) that best explain variance in total soil carbon stocks (kg m-3), for each depth, Main Farm. Lambda λ refers to the Box-Cox transformation value.

Depth	Transformed dependant variable?	Significant model terms	Model F statistic (degrees of freedom)	Adjusted Rsq	Standard deviation of the residual error
1 (0-7.5 cm)	N	soil moisture vegetation type moisture:vegetation type	$15.81_{(15;144)}$	0.58	17.92
2 (7.5-20 cm)	Y (λ=-0.02)	soil moisture vegetation type moisture:vegetation type	$26.94_{(15;129)}$	0.73	0.008
3 (20-40 cm)	Y (λ=0.02)	soil moisture vegetation type moisture:vegetation type	$18.32_{(14;105)}$	0.67	0.008
4 (40-60 cm)	Y (λ=-0.06)	soil moisture vegetation type moisture:vegetation type	$16.65_{(14;65)}$	0.74	0.019
5 (60-80 cm)	N	soil moisture vegetation type moisture:vegetation type	$18.33_{(12;26)}$	0.85	8.97

3.6.2 Mapping soil carbon stocks

Total soil carbon stocks across the study sites were spatially interpolated (predictive maps created) using plant trait data, soil depth and soil moisture data. We explored whether the inclusion of data from the significant explanatory variables, as covariables in the cokriging model, improved the accuracy of maps showing spatial variation in soil carbon stocks across the Main Farm (Figures 3.1 and 3.2). We found that inclusion of these environmental covariables improved the interpolation models for all soil depths, except for the surface depth on the Main Farm (0-7.5 cm). Substituting values from the modelled hydrological surface (generated in ArcMap 10.2.2), as a replacement covariable for soil moisture field measurements, was also shown to be a valid approach for predicting carbon stocks from to 20 cm (7.5 to 20 cm for the Main Farm).

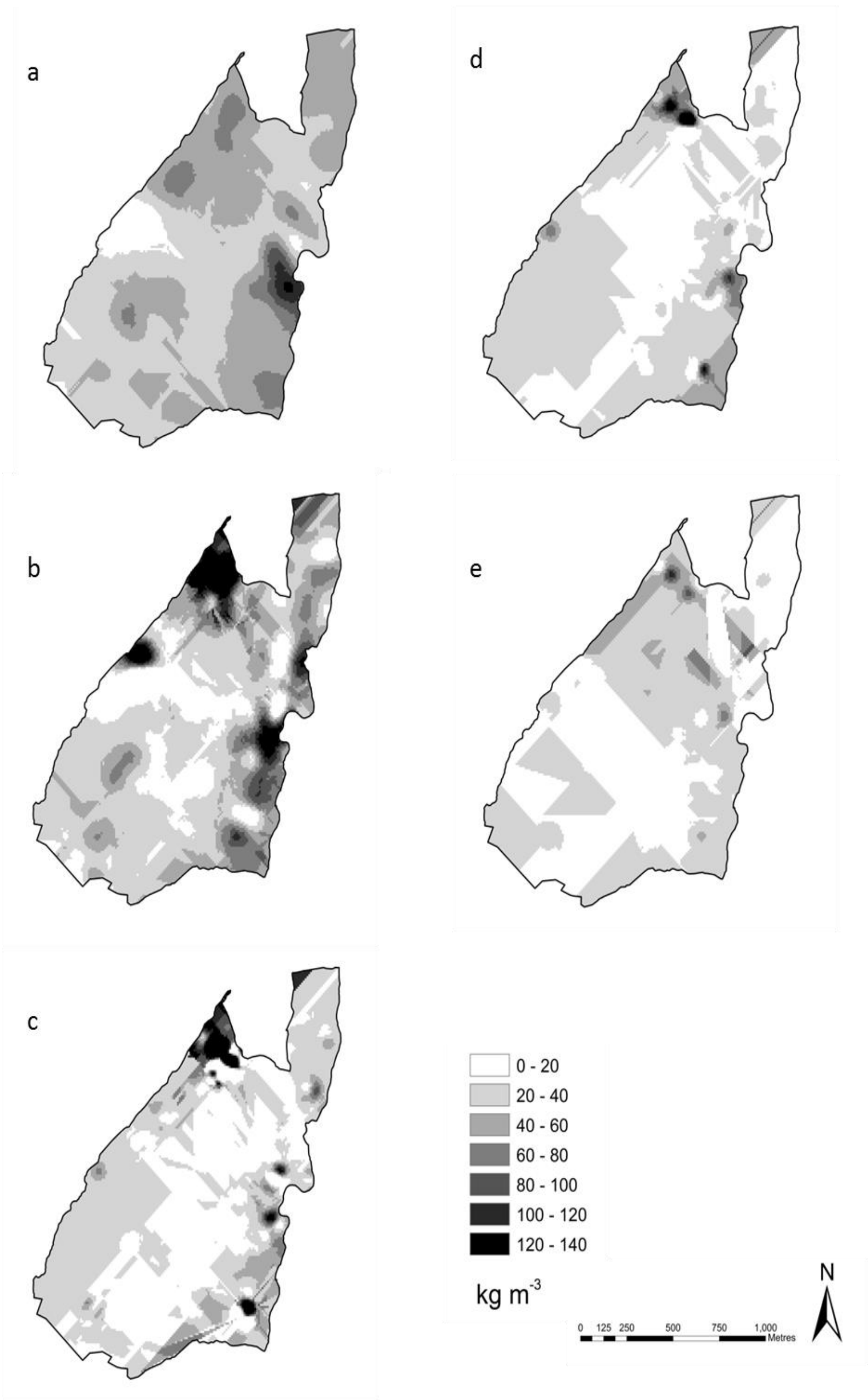

Figure 3.1 Maps a-e are interpolations of predicted total soil carbon stocks (kg m^{-3}) for each sample depth increment: a) 0-0.075 m, b) 0.075-0.2 m, c) 0.2-0.4 m, d) 0.4-0.6 m and e) 0.6-0.8 m. All six were created using combinations of field soil moisture, plant leaf trait and plant functional group data, as specified in Table S1 in Appendix III. Range was set for consistency across the figures and based on data spread and ease of interpretation. Note – the interpolations do not account for areas of bare rock, but subsequent calculations do.

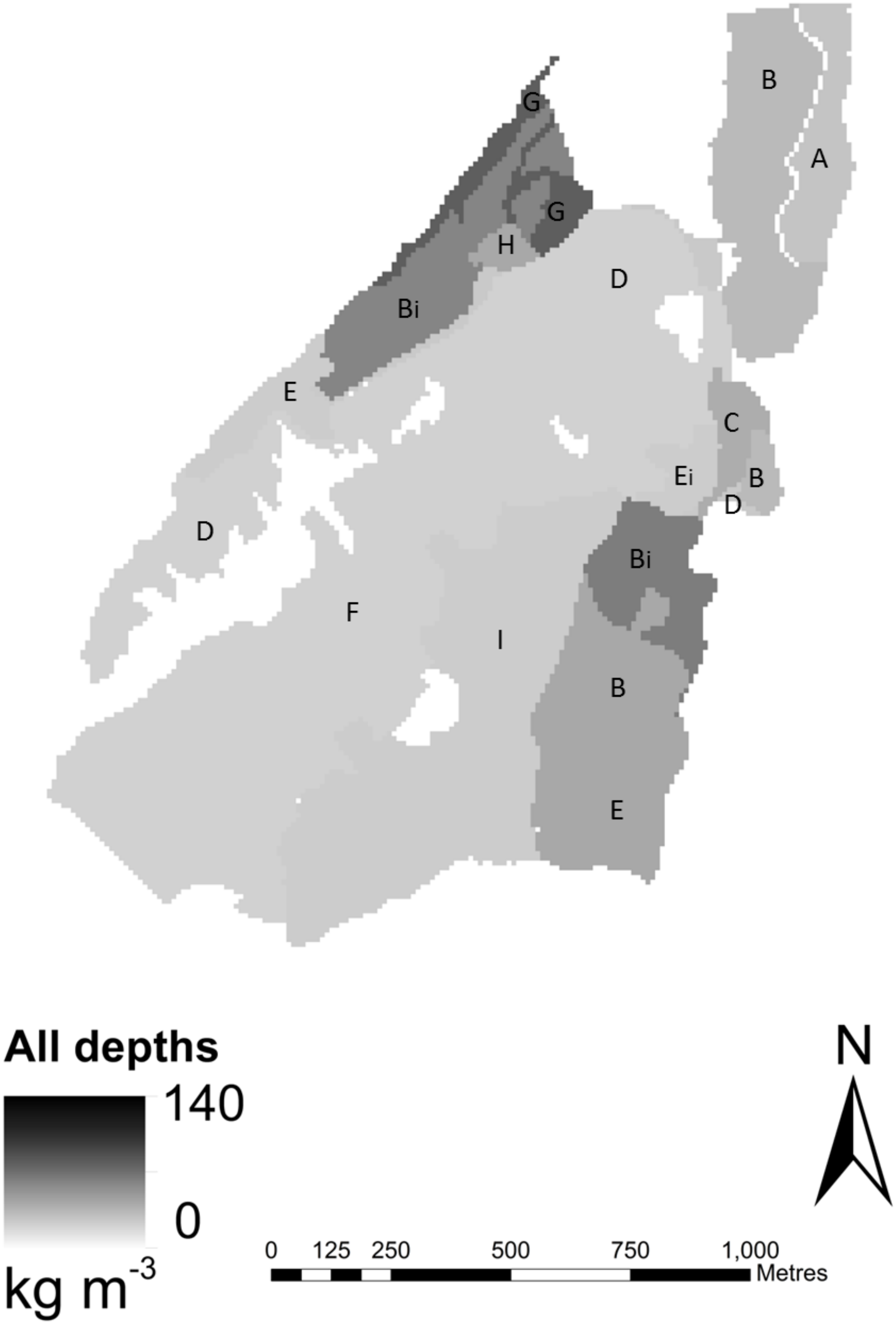

Figure 3.2 Mean carbon stock (kg m^{-3}) by vegetation type (across all depths). 'A' represents upland hay meadow; 'B' semi-improved grassland (i - wetter); 'C' scrub; 'D' grass moorland and rough grazing; 'E' upland valley mires, springs and flushes (i - wetter); 'F' upland heath; 'G' upland oak woodland – grazed; 'H' upland oak woodland – ungrazed; 'I' bracken fern (codes taken from Dept. of Env. Food and Rural Affairs 2005). White signifies areas of bare rock or scree. Created using combinations of field soil moisture, plant leaf trait and plant functional group data, as specified in Table S1 (Appendix III) in supplementary material. Range was set for consistency with Figure 3.1 (a-e) and based on data spread and ease of interpretation.

Mean carbon stocks across the Main Farm are 40 kg m^{-3} and total soil carbon stocks (all depths) are calculated to be 15,300 metric tonnes. Almost all soil carbon was found to be stored in the top 40 cm of soil and most (84%) in the top 20 cm of soil (Table 3.4). Average soil carbon stocks are greatest (43 kg m^{-3}) in this surface layer and lowest (13 kg m^{-3}) between 60-80 cm depth (Table 3.4). The vegetation types with the greatest soil carbon stocks across all depths are grazed oak woodland (92 kg m^{-3}) and wet semi-improved grassland (72 kg m^{-3}) (Table S4, Appendix III). Upland heath and unimproved grass moorland vegetation types had the greatest soil carbon stocks overall on account of the large area that they covered across the farm (2874 and 2308 metric tonnes respectively).

Table 3.4 Total soil carbon stocks by depth for the three study sites. Calculated from spatial interpolations using the kriging and cokriging functions within the Geostatistical Analyst toolkit in ArcMap and calculations scripted in PyScripter.

Depth (cm)	**Mean carbon (kg m^{-3})**			**Proportion of carbon contained at that depth (%)**		
	Main	**Test Farm 1**	**Test Farm 2**	**Main**	**Test Farm 1**	**Test Farm 2**
0-7.5	42	48	50	34	81	73
7.5-20	44			50		
20-40	33	38	33	16	17	21
40-60	21	47	23	1	0.1	4
60-80	13	38	39	<0.1	<0.1	2
80-100	x	x	19	x	x	<0.1

For Farms T1 and T2, as for the Main Farm, inclusion of soil moisture as a covariable improved the interpolation models for most depths. Including leaf trait information, as an additional covariable, improved prediction for depths 20-80 cm for Farm T1. Farm T1 stores 17,600 metric tonnes of soil carbon and T2 stores 14,300 metric tonnes in total. Overall mean stocks of carbon for T1 and T2 were similar to those of the Main Farm (46 kg m^{-3} and 43 kg m^{-3}). Soil carbon stocks by depth profile showed similar results to the Main Farm (see Table 3.4). Farm T1 had a much narrower range of mean carbon values by vegetation type compared to the Main Farm (35-45 kg m^{-3}). Farm T2 had only three vegetation types with a slightly narrower range compared to the Main Farm (22-76 kg m^{-3} average carbon stocks by management group) (Tables S5-S6, Appendix III).

3.7 Discussion

We found that simple, easily accessible information on vegetation type, soil depth and moisture, could explain a high proportion of variability in total soil carbon stocks at the farm-scale, and that accurate maps of soil carbon stocks can be created without the need for resource-intensive field measurements.

3.7.1 Predicting carbon stocks

Our findings suggest that there is a strong correlation between vegetation type and soil carbon stocks at the farm-scale within heterogeneous landscapes. Soil moisture and sample depth were also shown to be important explanatory variables, as expected (Pastor and Post 1986; Kramer and Gleixner 2008). We found similar results when modelling soil nitrogen – the same explanatory variables explained variance in total nitrogen stocks (see Table S9, Appendix III). Substituting modelled water flow values (generated using GIS software), instead of soil moisture field data, resulted in reasonable models of soil carbon stocks for soil depths to 20 cm. This suggests that more sophisticated hydrological models (more sophisticated than those within ArcMap) may be able to replace moisture field measurements and, in future, it may be possible to predict soil carbon stocks at the farm scale without the need for field and laboratory work.

Stocks of soil carbon are the product of six hundred to a thousand years of processes and we cannot state that the relationships we identified between the explanatory and predicted variables are causative. At a biome scale, total carbon stock is dominated by effects of climate (precipitation and temperature) and geology (Jobbágy and Jackson 2000), as well as land management (Smith and Bustamante 2014). Along with climate and parent material, the quality and quantity of organic material (dependent on the nature and composition of plant communities) is a key determinant of below-ground decomposition (Bardgett 2005), and so SOC quantity and composition (Lange et al. 2015). Recent research has demonstrated links between plant leaf traits and soil properties (Orwin et al. 2010; Dias et al. 2013; Grigulis et al. 2013; Legay et al. 2014; Baxendale et al.

2014; Minden and Kleyer 2015). Therefore, vegetation type is likely to be a proxy for other controlling variables, such as topography, climate, parent material, and current and historic land management, as well as contributing to soil carbon stocks directly via various biological mechanisms, including through litter input, and microbial community processes and turnover.

Our work provides a basis for scaling-up predictions to consider other farming types and regions, perhaps alongside methods which utilise sensors on aerial or satellite platforms to derive spectral and textural properties of plant communities in order to develop proxies for soil carbon stocks (Ballabio et al. 2012; Petter et al. 2013). We found that community weighted scores for plant leaf traits and functional group cover also correlated with soil carbon and nitrogen (when included with soil moisture and depth covariables) and it may be possible for plant trait databases (such as the TRY database; Kattge et al. 2011) to be used in conjunction with information on plant species (such as exists for farms within priority habitat schemes) to improve model predictions. We acknowledge that total soil carbon includes different forms of SOC with associated differentiated residence times (Hartemink and McSweeney 2014). The division of the total soil carbon pool based on soil particle size fraction has been shown to assist in predicting the residence time of carbon in soil (Manning et al. 2015; Trumbore 2000) and different size fractions are likely to respond to different vegetation types (Beniston et al. 2014). This study does not differentiate these fractions and there is potential to refine the method by accounting for this.

Almost all soil carbon was found to be in the top 40 cm of the profile, which corresponds with other studies (e.g. Bol and et al. 2012). Current inventories only consider the top 15 cm which would have underestimated total stocks by at least 17% for the two farms with shallower soils, and by over 25% for the farm with deeper soils (T3). Lowland and more intensive farms are likely to have deeper soils than our study farms and therefore sampling may need to go deeper than 40 cm. Based on these findings we recommend that soil carbon inventories should consider soil to at least 40 cm depth. McBratney et al. (in Hartemink and McSweeney 2014) state that below 50 cm environmental covariables are unlikely to explain soil carbon and we found that model residual error increased by several orders of magnitude for samples taken from deeper than 60 cm. We also found that model error was higher by several orders of magnitude for surface soils (as did Lacoste 2012). The soil surface is more dynamic, with wetting/drying cycles, temperature fluctuations and patch dynamics and Syswerda et al. (2011) highlight problems in extrapolating soil carbon stocks from surface layers to depth. However, this is opposite to Ward et al. (2013), who found the effects of management to be strongest in the biologically active layers.

3.7.2 Extending carbon management interventions

Ungrazed oak woodland stored less (49 kg m^{-3}) soil carbon on average than grazed woodland (92 kg m^{-3}). The woodlands are adjacent and on the same soil type and slope, which indicates that grazing management and previous planting has had a significant effect on soil carbon storage. We also found that, contrary to expectation and regional advice (Hagon et al. 2013) the presence of the fern *Pteridium aquiliunum* (bracken) on unimproved grazing land did not increase soil carbon stocks (although the results were nearly significant at p=0.06). These results show the heterogeneous effect of land management on soil carbon stocks and other studies have highlighted the local contingency of management practice on stocks: grazing intensity (McSherry and Ritchie 2013); liming (Kirkham et al. 2014); fertilizer application (Gärdenäs et al. 2011); re-wetting (Bussell et al. 2010); and, local-scale vegetation interactions (such as how diversity of plant species interacts with abundance of legumes in grassland swards; De Deyn et al. 2011). Management effects on soil carbon stocks may also be temporally contingent (Bol et al. 2012). Our findings add to this literature and we conclude that application of our method to predict and map on-farm carbon stocks would enable management interventions to be more dynamic and responsive to local conditions. However, it is important to note that we did identify some problems in using FEP maps for modelling soil carbon – their inability to distinguish between wet and dry forms of vegetation type did lead to difficulty in interpreting some results e.g. on Farm T1 soil under heath vegetation had low average soil carbon stocks (35 kg m^{-3}), whereas in wetter conditions on farm T2 soil under heath vegetation had high average stocks (76 kg m^{-3}).

We found that grasslands are storing large amounts of carbon across the three farms. Mean carbon stocks for semi-improved grasslands were 38-48 kg m^{-3}, improved grasslands were 31-50 kg m^{-3}, and unimproved hay meadows were 33-42 kg m^{-3}. [24] These values are high when considering the mean values for other vegetation types which are commonly the focus of carbon schemes – upland wetlands (28-49 kg m^{-3}) and ungrazed oak woodland (49 kg m^{-3}). This finding suggests that appropriate grassland management could complement current carbon offset schemes and play a major role in enabling 'productive farming' to coexist alongside 'carbon farming', an important consideration on farms where the area of improved grassland is limited (Chapter Four). However, it is important to note that such an approach has the potential to conflict with schemes delivering other environmental public goods such as biodiversity and priority habitat management/restoration; as improved and semi-improved grasslands are abundant in the UK, whereas vegetation communities such as dry heath, upland hay meadow and rush pasture are BAP (Biodiversity Action Plan) habitats, are less abundant, and have associated suites of species of interest to biological conservation. It should also be noted that the mitigation of other greenhouse gas emissions from soils (nitrous oxide and methane) have not been considered in this study and agricultural grasslands emit nitrous oxide pulses after fertiliser application or if water-logged (Moorby and et al. 2007). It is also important to note that none of these field sites were located on blanket bog – which would be expected to hold much higher quantities of carbon, in peat which can be over 1 m deep.

3.7.3 Conclusions and policy implications

Our results indicate that simple accessible vegetation and soil data from farm agri-environment documentation can assist in delivery of locally-responsive, on-farm carbon management schemes. Further, using this approach, there is potential to extend the scope of schemes to include new vegetation types and land management practices. There are further opportunities for refining and developing this work by linking into advances in remote sensing, accessing plant trait databases and additional farm-based documentation.

[24] Figures quoted are averages across the three farms.

Two major obstacles to farmer engagement with soil carbon management are perceived scientific uncertainty as to whether management interventions work at local scales, and experience of mismatches between universal prescription for soil management and local conditions (Ingram et al. 2014). Maps, such as the ones we created using cokriging analysis and accessible data, were shown to be sensitive to on-farm environment and management variability and are a powerful tool for communicating complex spatial patterns in soil properties. They could be used as a basis for discussions with farmers about management prescriptions for enhancing and maintaining soil carbon stocks, in a way which is more participatory and recognises the knowledge farmers hold about their land (Chapters Two, Four and Five). Referring to such maps in discussions with farmers could also assist in identifying where a management intervention aimed at enhancing carbon stocks would be at odds with local conditions (environmental or management-based) or where existing carbon stocks are at risk. The maps can also assist in scenario-building. For example, we were able to calculate that 15,300 metric tonnes of carbon is stored in soil on the Main Farm. This would be 'worth' between £78,030 and £2,367,522 based on a range of £5.10 and £154.74 per tonne of carbon (the range of 'internal carbon prices' used by European companies quoted in CDP's 'Carbon pricing in the corporate world' report 2015). Please note that this is playful speculation as no such mechanism for commodifying soil carbon in this way currently exists.

Our results are particularly pertinent to the current political context of a new international climate agreement, to be finalized at the United Nations Convention on Climate Change (UNFCCC) Conference of Parties (COP21) in Paris in December 2015. In preparation countries have agreed to publicly outline the post 2020 climate actions they will take to 2030. These Intended Nationally Determined Contributions (INDC's) pair national policy settings to a global framework and an ambitious agreement in Paris could have implications for national land management policies as governments look to achieve challenging INDC targets.

3.8 Acknowledgements

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3.9 Supplementary materials

See Appendices for supplementary maps and tables.

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4 Guiding 'carbon farming' using interdisciplinary methodologies

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This paper is laid out as intended for submission, with the exception of tables and figures, which are presented in-line to aid interpretation. This paper has multiple authors and the contributions are detailed in section 1.5 and confirmed by my supervisors.

Chapter 4 preface

Chapter Four, as with Chapter Three, is in the format of an academic journal article and is also written for ecologists. It introduces themes and research approaches familiar to rural sociology and human geography audiences and demonstrates how these can be useful within research traditionally deemed to be 'ecological'. It demonstrates how qualitative local knowledge can be valuable for ecological research, specifically addressing the question: which socio-ecological considerations can improve the design and delivery of an agri-environment scheme, where the criterion for success is improved soil carbon storage?

The Journal of Applied Ecology is the preferred destination journal and the article is a direct response to White et al.'s (2005) article, published ten years ago in this journal, which called for more qualitative methods to be employed internationally in conservation research. A call which has not been heeded within this journal nor, I would argue, more widely within ecology. The article also responds to McCracken et al. (2015) who, also within the same journal, used a quantitative interdisciplinary approach to examine how social drivers affected the ecological success of agri-environment schemes on individual farms. Although McCracken et al. (2015) did engage with qualitative methods, their quantification of the interview data dismissed an amount of data which had the potential to provide new insights and context to their indices and statistical results. They also failed to link to the large literature from rural sociology which asks similar questions, but from a different disciplinary perspective.

This article attempts to show how cross-pollination of the disciplines is not only possible, but that often different disciplines are using the same methods and ways of thinking, but are not engaging with the other's work.

4.1 Summary

1. There is a recognised research gap in understanding the social drivers of ecological success in agri-environment schemes, which is hampering the success of these schemes.
2. We used a mixed methods approach to explore how understanding farmers' experience of agri-environment schemes, and how farmers currently manage for soil carbon, could affect the success of future soil carbon management schemes.
3. Our analysis shows that qualitative data can be effectively used to improve understanding of ecological outcomes within environmental land management schemes.
4. We found that tensions within agri-environment schemes often concerned conflicting representations of the farm and difficulties with universal management prescriptions. This has implications for the success of proposed soil carbon management schemes.
5. Mixed methods mapping revealed farmers had multiple understandings and experiences of managing farmland to increase soil carbon and managing soil which is rich in soil carbon, and these were strongly influenced by land tenure, management history, and other place-based variables. We illustrate how GIS can be used as a useful tool in mixed methods mapping.
6. *Policy implications.* This research demonstrates the utility of qualitative methods and local knowledge in this area of applied ecological research. We show that including local, experiential knowledge alongside robust scientific assessment could confer significant benefits to environmental management schemes and suggest capitalising on recent developments in widely accessible GIS software to promote this.

4.2 Key words

Agri-environment schemes; carbon sequestration; geographical information systems; livestock farming; mixed methods; multifunctional landscapes; social-ecological; soil organic carbon.

4.3 Introduction

Agri-environment schemes have been one of the main European Union (EU) policy instruments used to encourage multi-functional agricultural landscapes. They work by compensating land managers for income-foregone in applying management practices which deliver environmental benefits, including the restoration of biodiversity. Recently, there has been increased interest in encouraging farmers and other land managers to manage soil for carbon storage, so-called 'carbon farming' (our term). Soil organic carbon (SOC) represents the largest global pool of terrestrial carbon and the long-term storage of SOC, or sequestration, is based on the premise that SOC is stable store of carbon that is not released to the atmosphere as carbon-based gas emissions in the short to medium term, i.e. under 100 years (Stockmann et al. 2013). The "4/1000 Initiative"[25] was recently (December 2015) launched as part of the Paris Climate Change Talks (Conference of Parties 21). This initiative is a voluntary action plan which seeks to achieve a 4/1000 increase in the annual growth rate of soil carbon stocks as a contribution to achieving the long-term objective of limiting global temperature increase to +1.5/2°C. It is the first specific European government-level initiative to promote soil carbon sequestration within agricultural soils, although soil carbon sequestration has been included in previous European initiatives such as fertiliser and manure management programmes where the focus is water quality (Gobin et al. 2011; Ingram et al. 2014). Agri-environment schemes provide one possible route for encouraging enhanced carbon sequestration in European agricultural soils.

Soil carbon sequestration and loss result from ecological and from human-ecological interactions. The drainage of wetland areas, land disturbance for mining projects, and deforestation are among the key land management practices that result in large fluxes of carbon to the atmosphere (Smith and Bustamante 2014). Soil carbon levels can sometimes be restored/enhanced through appropriate land management techniques, which can include re-wetting via blockage of drainage systems, afforestation and adding organic matter directly to soils, such as farm yard manure and crop residues (Ostle et al. 2009; Bussell et al.

[25] http://4p1000.org accessed 13.5.16

2010; Powlson et al. 2011). The effectiveness of these practices depends on place-specific environmental conditions; such as soil type, topography, hydrology, grazing, and climate. Effectiveness is also influenced by human factors, such as commitment to management practices, knowledge, agency and ability, financial circumstance, cultural practices, and future plans. There is therefore a need to recognise the varied human influences on the success of soil carbon management schemes, alongside examining ways of optimising the environmental conditions for soil carbon sequestration (O'Rourke et al. 2015).

Social factors, such as motivation, attitude and experience of land managers, are increasingly been included in ecological models in order to better understand why environmental management interventions, such as agri-environment schemes, succeed and fail (de Snoo et al. 2013; McCracken et al. 2015). However, within ecological studies the data, even if it was initially gathered as qualitative data (e.g. interviews), is often quantified for analysis and interpretation (e.g. McCracken et al. 2015). This quantification dismisses a rich seam of data which has the potential to provide new insights and context to indices and statistical results. Such quantification can also hide the assumptions and priorities of a scientific approach to analysing social data. This article suggests that quantifying social data is not the only way of working with it in the context of an ecological study and ecologists should consider the utility of qualitative methods and forms of analyses. White et al. (2005), in this journal, highlight the under-use and the potential for qualitative methods to be used alongside quantitative methods in developing knowledge that underpins ecological management strategies. A potential that, we argue, has not been fully explored.

This article also highlights and links to the large body of environmental social science (sociological, anthropological, geographical) research which also investigates the factors influencing the success of environmental management interventions, including agri-environment schemes. These disciplines use both quantitative and qualitative collection, analysis and interpretation methods to research how farmer identity, experience, attitude, access to advice and training, demographic variables, and other social factors, affect willingness to be involved in, and the success of, such land management interventions (e.g. Hall and Pretty

2008; Emery and Franks 2012). In doing so we recognise that there are very few ecological studies which link into this research and which consider both scientific and social ways of understanding and representing social-ecological systems together (White et al. 2005; McCracken et al. 2015).

The aim of this paper is to demonstrate how qualitative local knowledge (we use 'local' and 'farmer' knowledge interchangeably in this paper), without transformation into quantitative categories, can be analysed and interpreted alongside quantitative ecological data in a study which seeks to understand the opportunities and obstacles to soil carbon management on three upland farms in the north west of England. We address the specific question "which social-ecological considerations can improve the design and delivery of an agri-environment scheme, where the criterion for success is improved soil carbon storage?". Drawing on our results we then make policy recommendations to improve the planning, delivery, and so ecological success, of future 'carbon farming' schemes.

In England, agri-environment schemes make use of farm vegetation/habitat maps within the Farm Environment Planning process. A parallel study used existing Farm Environment Plan maps and field data to quantitatively map soil carbon on the same three case study farms (Brockett 2015) and we make use of these maps within this study. Therefore the majority our methods, both quantitative and qualitative, and our findings have a spatial element. In order to address our aim we first explored, on the three case study farms, how farmers understand, experience, and manage farmland for soil carbon, farmers' experiences of agri-environment schemes and the role of mapping in planning for and delivering agri-environment schemes. We then explored these themes within a wider focus group event. Finally, we used mixed (qualitative and quantitative) mapping methods (utilising mixed methods geographical information systems) on the three case study farms to uncover place-based farmer experiences and understandings of agri-environment schemes and soil carbon. This was in order to better understand which ecological and social factors were influencing the distribution of soil carbon on each farm and to explore how social factors affect implementation of agri-environment management and how these factors and their interaction with management change as we moved around the farms.

4.4 Methodology

Research was carried out on extensive upland livestock farms in the Lake District National Park in the north west of England. The Lake District National Park is a mosaic of vegetation communities managed since the Bronze Age and includes large areas of low-input grazed grassland, covering approximately 2300 km^2 of topographically variable land. The study farms used in this study ranged in elevation from 102 and 534 m. The region is cool (average temperatures are 14.9 ^{0}C in July and 3.1 ^{0}C in January) and wet (approximately 2061 mm precipitation per year). The combination of vegetation, climate and topography result in large areas of carbon-rich soils and there are opportunities for increasing soil carbon storage through changes to land management (Hagon et al. 2013). Many of the area's farmers have experience of agri-environment schemes (Harvey et al. 2013) and the Lake District National Park is recognised for its cultural value. The Lake District National Park therefore provides an ideal social-ecological model for addressing our research questions.

4.4.1 Phase One – in-depth case studies

The methods formed three distinct phases, with development of phases two and three informed by previous results. This kind of recursive, iterative approach proves useful in interdisciplinary research processes (Lowe and Phillipson 2006).

In phase one we undertook scientific field work on three upland livestock farms to enable production of interpolated soil carbon maps of each farm using the GIS software package ArcMap (ArcGIS Desktop version 10.2.2 ESRI 2011) (for full details see Brockett 2015). Anonymity requirements relating to the social science data prevent us from sharing information that could lead to identification of individual farms involved. We produced a range of representations of soil carbon stocks in the landscape, e.g. 'carbon stocks under-foot' and average carbon stocks under different vegetation communities. In parallel, over the same seven month period, we conducted in-depth case studies on each farm in order to explore how farmers understand, experience, and manage for soil carbon (if at all), their experiences of agri-environment schemes, and the role of mapping in planning-for, delivery- and monitoring-of agri-environment schemes. Mapping was explored as a tool, as a process, and as a way of communicating information between different stakeholders and representing different versions of the farm. The case study approach involved semi-structured interviews with the three farmers and observation methods (documenting activities, behaviour and physical aspects of the farm and farm work). The latter were used to understand how farmers' everyday farming practices accounted for soil carbon and how they used farm maps, of agri-environment scheme management prescriptions and any other maps, if at all. These case studies are not meant to be representative of all upland farms in the region; rather, they were used to uncover different types of data and insights regarding the range of knowledges and experiences of soil carbon and carbon-rich agricultural landscapes. The choice of farms was based on farmer willingness to engage, and on environmental attributes important to the ecological objectives of the wider study, which included testing whether use of agri-environment scheme maps improves prediction of soil carbon distribution across farms (Brockett 2015).

The extensive ecological field work required to produce farm scale soil carbon maps provided the ideal opportunity for associated in-depth qualitative research. We became a familiar presence on-farm which improved the qualitative data collected (Jones et al. 2008) given that we were able to participate in informal and on-going conversations about the data we were collecting and analysing and about how we and the farmers understood soil carbon on the farm. It also enabled us to exchange knowledge with the farmers about current and previous engagement with agri-environment schemes and how 'carbon farming' could be best incorporated into new schemes. The qualitative data gathered from these case studies led to the identification of themes which were explored further within focus groups, and played a central role in the development of mixed methods mapping in phase two.

4.4.2 Phase Two – focus group knowledge-exchange event

In order to gather data from a wider selection of farmers and other land management professionals, we ran a knowledge-exchange focus group on one of the case study farms. A focus group is a group interview centred on a specific topic and facilitated and co-ordinated by a moderator which generates primarily qualitative data, by capitalising on the interaction that occurs within a group setting (Sim and Snell 1996, 189). Focus groups allow researchers to probe shared meanings and values around the research topic and normative responses (establishing, relating to, or deriving from a standard or norm, especially of behaviour), as well as areas of disagreement (Sim and Snell 1996). We used the event to probe into and expand on the findings derived from the on-going case studies and to question more stakeholders. There were thirty attendees including fourteen farmers and nine farm environment advisers (see Brockett and Netto 2013 for more details).

4.4.3 Recording and analysing the qualitative data

Semi-formal interviews with farmers were generally audio-recorded, however, sometimes hand-written notes were taken or were written-up as soon as possible after the conversation had finished. Mobile voice recorders recorded all conversations at the focus group. All audio recordings were typed into full transcripts and individual contributors were given anonymous tags which could be followed throughout the transcript, where possible. Transcripts were coded by content using the software programme ATLAS.ti (version 7.5.9, 2015). Qualitative coding rearranges data into categories that facilitate comparisons: this process aids the identification of broader themes and issues within the data and the development of key themes. The coding process was carried out a number of times on the same transcript until the results cohered around a set of emergent themes (Neuendorf, 2002).

4.4.4 Phase Three – mixed methods mapping

Findings from the first two phases of data collection indicated that it was not possible to reduce farmer responses to our research questions to a few key variables. Farmer experiences and understanding of agri-environment schemes and soil carbon were shown to be ‘place-based’ – to vary with different spatial variables such as land tenure and distance from the farm house – and were contingent on land management history and farmers' relationship to the landscape (see results for further elaboration). Consequently, we introduced a spatial component into our data collection through a spatial transcript methodology, which is based on a walking interview method where a voice recorder and a global positioning system are synched to enable the interview narrative to be geolocated on a digital map (Jones and Evans 2012). The methodology enabled us to further investigate place-based farmer experiences and understandings of agri-environment schemes and soil carbon, and whether attitudes to carbon farming and motivations to apply new management practices are contingent on spatially-variable factors and, if so, which ones.

The spatial transcript method was implemented within a Mixed Methods Geographical Information Systems (GIS) approach. GIS are used to capture, store, manage, retrieve, analyse, and display spatial information (e.g. as digital maps). Mixed Methods GIS (MMGIS) works with GIS technology to incorporate multiple data and forms of knowledge, extend representational capabilities to incorporate non-cartographic information, support both quantitative and qualitative forms of analysis and illustrate that incorporating multiple epistemologies (ways of knowing) can lead to new insights (Cope and Elwood 2009). We used MMGIS to make farmer knowledge visible or 'present' within a mapping process, alongside quantitative scientific knowledge; recognised as being important if non-scientific knowledge is to be taken into account and legitimised within a policy process (Blackstock et al. 2014).

Creating MMGIS maps for each case study farm included layering the soil carbon maps (created in phase one) with other geolocated information gathered in the first two phases – such as vegetation community maps, land tenure, yield records, management practice observations and location-specific interview data relating to soil carbon and its management. These multi-layered maps were introduced into spatial transcript walking interviews with case study farmers to focus discussion on soil carbon stocks across their farms and promote discussion of current and future soil carbon management in different farm locations. The interview discussions were also directed by reference to the Lake District

National Park's 'Managing land for carbon' booklet (Hagon et al. 2013). Research has shown that data generated through walking interviews are measurably different when compared to data collected through sedentary interviews; that they are profoundly informed by the landscapes in which they take place and produce richer narratives, both in terms of the quantity of data and spatial specificity to the study area (Evans and Jones 2011). The walk progression was plotted as a route on the digital map and the associated narrative and theme codes were geo-located within the map's database (Figure 4.1). These data were then examined in relation to the different landscape variables, such as distance from farm features, land tenure, elevation, view-sheds and land parcel accessibility.

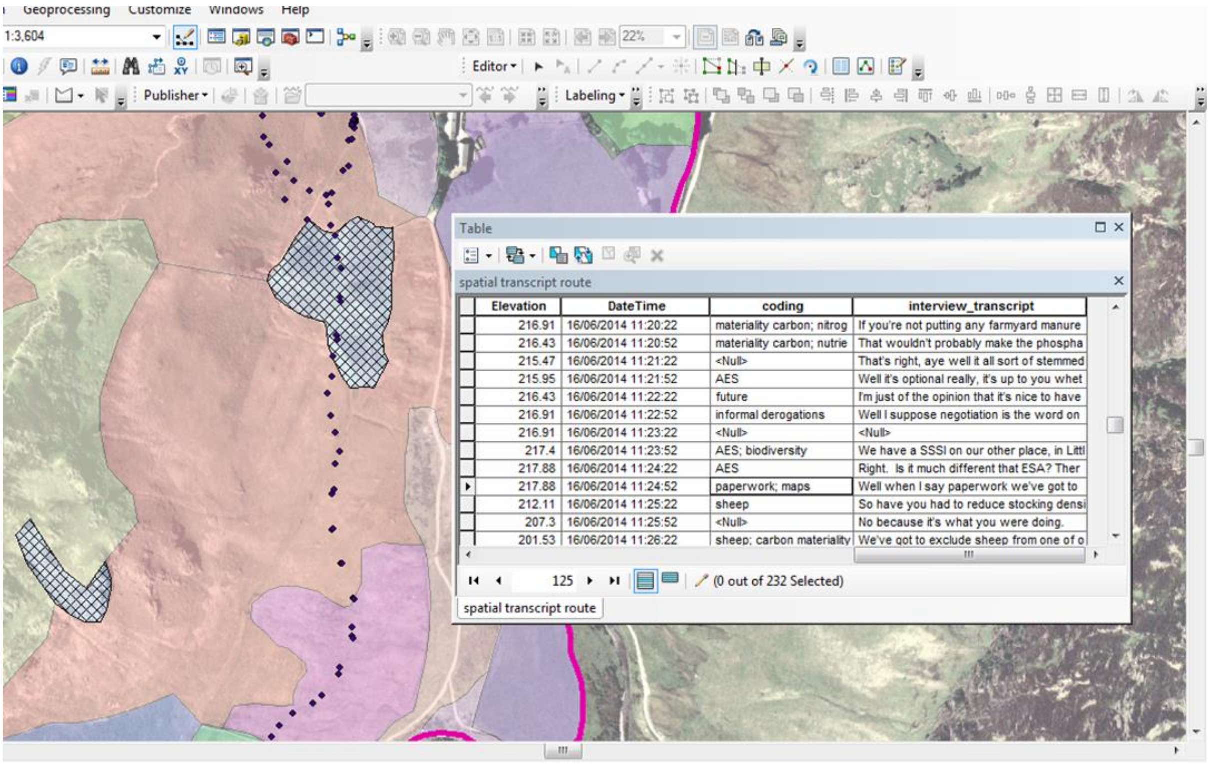

Figure 4.1 Screenshot of spatial transcript method in use within ArcMap (ArcGIS Desktop version 10.2.2 ESRI 2011).

4.5 Results

4.5.1 Farmer experience of agri-environment schemes

Adjustments to existing agri-environment schemes could be one way of encouraging more 'carbon farming' and the associated greenhouse gas emissions mitigation. Although often expressing frustrations with current agri-environment schemes processes, many participant farmers had not found adapting to agri-environment schemes requirements too onerous or different from their concept of 'good' upland farming. This was explained by one farmer at the focus group (held on 11.6.13):

> *Farmer 3: "… it's about slow processes, is farming, things don't change that much really. That's why getting compensated for what we are doing already, like the ESA (Environmentally Sensitive Area) Schemes that we've been in, that's why they've worked so well I think."*
> *Researcher 1: "And that wasn't really a radical change?"*
> *Farmer 3: "Not to be honest, no, because we were doing the things that we should have been at the time."*

Frustrations with agri-environment schemes often related to the process of altering farm environment management prescriptions, referred to as 'informal derogations' of scheme contracts (Morris 2006). Positive personal relationships with field officers were felt to be important to this process. Other agri-environment schemes issues raised repeatedly included the burden of administration associated with schemes, how the same discussions had to be repeated with different scheme officers, that discussions were often prematurely foreclosed due to agri-environment scheme deadlines, the pressure to conform to one version of the farm despite unresolved disagreements, and how such unfinished discussions festered after the agreement was in place. Frustrations over changes in policy focus were sometimes articulated humorously, for example:

> *"I'm reporting to B** at the moment" [regarding his agri-environment schemes]*
> *"I think B** is getting awr [over] old fer [for] that, so you sure it's B**?"*
> *"It's B** at the moment"*
> *"I was going to say, I remember him coming from ADAS [ex-state agricultural extension service] and telling us to spray everything and plough the rest"*
> *Laughter*
> *"Give him twenty years he'll be coming back and telling you to do that again"*
> *(Exchange between farmers at the focus group)*

4.5.2 Understanding, experiencing and current management of soil carbon

All of the farmers questioned knew about soil carbon as an area of scientific and policy concern, and there was interest among interviewed farmers in finding out more. Knowledge of soil carbon amongst study participants could be both high level and lacking in the basics at the same time. For example, some farmers were familiar with scientific terminology and which parts of their farm had carbon-rich soil, but had limited scientific knowledge about the carbon cycle. Most farmers knew about carbon calculators and a few had used them, but there was a lack of trust in the output: *"it's a lot of it is guesswork isn't it"* (case study Farmer W, 4.3.15).

Soil carbon was also understood and experienced in non-scientific and non-policy ways, for example, when contrasted with current agri-environment schemes goals, such as biodiverse landscapes, soil carbon storage was seen as intangible and even *"invisible".* Many farmers expressed an understanding of carbon in their soils in terms of rich personal experience in relation to problematic landscapes. For example:

> *"And some of the bog is real genuine blanket bog you know" (mimes foot being stuck – laughter)*
> *"That's a good demonstration, perfect in fact, yeah"*
> *Laughter*
> *"So it holds a lot of water"*
> *"It holds a lot of water yep"*
> *"And carbon"*
> *"Carbon, yeah"*
> *(Exchange between farmers at the focus group)*

Carbon farming methods are likely to be more disruptive to existing upland extensive livestock farming than current agri-environment schemes ecological goals. This is because carbon offset schemes in the Lake District National Park region are focused on tree planting and on policies encouraging rewetting (for example by blocking drainage channels) for water storage and improved water quality, which identify soil carbon storage as a co-benefit. Both of these land management interventions were associated with unproductive and problematic land by case study farmers. These farmers also associated re-wetting with poor health in sheep because wetter grazing land encourages the spread of *Narthecium ossifragum* (Bog Asphodel), which is toxic to sheep and cattle (Strugnell 2014).

4.5.3 Farmer self-identity

Most farmers consulted accepted the need for agri-environment schemes, and potentially the introduction of 'carbon farming' within schemes, but also identified themselves as producers of food first and foremost. For example, one farmer at the focus group commented: *"I think the motivation of a farmer is to farm and to farm their land on the whole to produce livestock".* The same sentiment of 'producing is good farming' was reflected in 35 other conversations within the study. Sometimes the study farmers played up to the image of a farmer 'only after the money' (the importance of financial reward was mentioned 58 times in the transcripts). However, in different conversations the same farmers spoke of their pride in the agri-environment scheme outcomes and how they would manage for the environmental outcomes, without a financial incentive or any formal scheme recognition.

4.5.4 Farmer motivation

Informal on-farm conversations provided some unexpected and valuable insights. For example, both farmers' exposure-to and understanding-of agri-environment schemes monitoring results and their personal experience of the ecological benefits of agri-environment schemes (such as the sensory experience of a hay meadow), were shown to affect their motivation to stay engaged with schemes. We do not believe we could have identified the same range of motivations through quantitative survey methods, as our understanding developed from a series of informal linked conversations and observations of farm practice on case study farms over a number of months.

4.5.5 The role of mapping, datasets and remote sensing in agri-environment schemes

We found that maps of soil carbon were a useful knowledge-transfer tool when interviewing farmers. Maps do not play a day-to-day role for the farmers questioned. Maps produced for current agri-environment schemes, such as vegetation community maps, are not interpreted for general use, are not editable, and are therefore rarely used by farmers. As one research participant (an academic researcher) reflected at the focus group:

> *"they [farmers] don't seem to have basic maps or historical information that they could use. … there's a wealth of information that potentially is out there that they could be using in their decision-making or the farm advisers could be using and it's not accessible. It's not interpreted and it's not accessible."*

We also found that mapping processes related to current agri-environment schemes can produce representations of farms which do not reflect the knowledge and experience of farmers and this makes mapping a contested process.

Freely-available online mapping and remotely-sensed imagery (e.g. via Google Earth) is also rarely, if ever, used by the farmers questioned for land management purposes and when it used it is *"not necessarily used as a management tool but so they [other farmers] can see what their neighbours have been doing"* (Farmer W, case study, 25.2.13). There was some positive interest, amongst farmers and advisers at the focus group and case study farmers, in the potential for employing mapping and remote-sensing technology to help monitor farm carbon stocks, and how this could move carbon farming schemes from income-foregone payments to payments for output delivered. However, for most of the farmers consulted there was suspicion of current and past attempts to use remotely-sensed imagery for monitoring agri-environment schemes outcomes or other purposes by external agencies. Such concerns surfaced in conversations about 'surveillance' of on-farm practices, for example in relation to stock management – *"I know that some of the farmers I talk to would feel that they are being spied on by satellites"* (farm adviser at focus group). One group of farmers and farm advisers at the focus group discussed situations when they or neighbours were caught out by such surveillance and case study Farmer B explained his frustration with external interpretations of remotely-sensed imagery in relation to farm payments. The following quote, from the focus group, illustrates another farmer's frustration with external interpretations of farm data:

"I ring them [policy officer] up and say, "We are interested in enrolling in the Higher Level [agri-environment schemes scheme]." "No we've already decided you are not on Higher Level you are Lower Level" And I said, "what are you basing that on?" And he said, "Oh, on your farm information". And I said, "Well our farm information [on the external database] isn't correct, I know we can get into Higher Level really"."

4.5.6 Mixed methods mapping and place-based understandings

The quantitative soil carbon maps we produced were consistent with the three case study farmers' understanding and experience of soil carbon distribution on their farms, e.g. *"It's pretty good this [map], it's identified what we call 'the peat hole'"* (case study Farmer W, 4.3.15). That is, the maps of the soil carbon generally reflected farmers' knowledge of the distribution of soil carbon on their farms. As we moved around the farm, referring to the quantitative soil carbon maps and the advice booklet, the spatial transcripts revealed place-based responses to carbon management scenarios and we outline three examples here. First, when discussing how grazing intensity can affect soil carbon stocks, all three case study farmers articulated a specific number of sheep or a stocking density below which they would cease to feel like 'good' farmers. This number cannot be obtained through quantitative analysis but its importance is clear with regard to future management scenarios. Second, Farmer B would only consider reducing liming on organic soils (as a way of increasing soil carbon; Moore, Ouimet, and Duchesne 2012) where his sheep had not experienced trace-element deficiency *"which if you don't catch it in time can be deadly"* (4.3.15). Third, all three case study farmers, and others at the focus group, were resistant to management changes, which would reduce the amount of improved or semi-improved grasslands available, as on upland farms these are limited in extent. Considering 'place' helped us better understand attitudes and motivation towards adoption of management change and how these can vary, quite literally, depending on where you are standing on the farm.

Attitudes towards land rich in soil carbon and towards the possibility of carbon farming varied with different map 'surfaces' – not just with Euclidean space; we found that attitudes towards land management change varied with land tenure and whether the land was attached to the main farm. For example, on one farm we observed less motivation to maintain biodiverse hay meadows on newly-acquired land when compared to hay meadows that had been part of the farm for longer, even though they were of lower ecological quality. Such patterns would not be visible through examination of existing agri-environment schemes maps and could easily be dismissed as 'inconsistencies' in a conventional survey approach.

Spatial transcripts also revealed a depth of farmer knowledge about soil carbon that had not been shown in any previous static interviews. For example, Farmer E, who had on a number of previous occasions had said that he knew very little about soil carbon, explained during the spatial transcript interview how different plant species' root structure might affect carbon stored in the soil:

> *"I mean some of these better managed fields here - you've gone down fairly deep [sampling] but yet it doesn't show as high a level of carbon really… It's maybe because with it being grassland the depth of the roots isn't that deep" (17.6.14)*

4.6 Discussion

4.6.1 Acknowledging and accounting for different forms of knowledge

Whether and how to include different forms of knowledge within a research project and subsequently how to develop new shared understandings about social-ecological systems, such as agricultural landscapes, is an intensely-debated topic in natural resource management (e.g. Cooke and Kothari 2001; Measham and Lumbasi 2013). Our research approach acknowledged that scientific measurement and the representation of soil carbon through the creation of quantitative maps is not the only type of knowledge relevant to planning for, and delivery of, enhanced soil carbon stocks through land management change. Further, we acknowledged that successful delivery of multifunctional rural landscapes should include farmer knowledge, as participation of social actors can improve social and ecological innovation (Callon et al. 2009). By employing a MMGIS approach to our mapping we attempted to move beyond thinking of scientific and local knowledges as separate and recognise that all knowledges are connected (Hinchliffe 2007) and are developed within the boundaries of epistemological constraints (different ways of experiencing and understanding the world) (Law and Mol 1995). We suggest that space should be made within soil carbon research and policy processes for non-scientific ways of experiencing and understanding soil carbon. MMGIS allowed us to layer these different spatial understandings of soil carbon in the landscape and consider them together, even when they appeared to conflict. As Fulvio Mazzocchi, a biologist and a philosopher, explains in the molecular biology journal *EMBO reports*, these different ways of creating knowledge and understanding the world should not be a limiting factor, but an opportunity that, if exploited, allows new possibilities for understanding complex systems (Mazzocchi 2008).

4.6.2 Carbon farming in tension with 'good' farming practice and positive sensory experience

Although we recorded some tensions with regard to previous farmer experience of agri-environment schemes, mainly around reducing livestock densities on priority habitats, participating farmers often reconciled scheme requirements with 'good' farming practices by making *"a few tweaks here and there"* to the scheme management prescriptions. As well as the financial incentives, motivation to engage with and stay engaged in agri-environment schemes came from a sense of success in previous rounds of the schemes. This success was sometimes communicated to farmers by researchers or statutory bodies, but was most often derived from farmers' themselves. This was both through their observations and existing scientific understanding of the scheme goals and the sensory and through practical experience of agri-environment scheme outcomes. For example, doing dry stone walling or the visual, audible and olfactory experience of a hay meadow in summer (Vergunst 2012). For example, case study Farmer E originally explained to us that his only interest in managing for agri-environment schemes outcomes was financial *"like most farmers"* (25.2.13). However, in a later interview he was clearly excited by the variety of plant species listed in our vegetation survey of his hay meadow and was proud of the quality of his hay meadow in comparison to others'. For these reasons, he wished to continue with this element in future agri-environment schemes contracts. Such practical and sensory experiences were linked by farmers to satisfaction of a 'job well done' and to farming practices of the past (which is consistent with Burton, Kuczera, and Schwarz 2008 and Burton and Schwarz 2013).

In contrast to the positive farmer experiences we identified in relation to increased biodiversity and other agri-environment scheme goals, we found that farming soil carbon has the potential to conflict strongly with upland farmers' concepts of a productive landscape and their strong self-identity as producers of food (see Burton and Wilson 2006 for further discussion of food production and farmer self-identity). Farming soil carbon also has the potential to conflict with held cultural heritage values of these landscapes. We found that farmers' views on carbon storage tend to be associated with negative experiences and unproductive words and phrases such as *"bogginess", "unproductive",* land unsuitable for machinery, losing stock in bogs and the spread of harmful plants or is considered *"intangible"* and even *"invisible"*. These findings highlight the importance of providing feedback to farmers on the success of any future soil carbon management scheme; partly because success in farming soil carbon, for the farmers, is more intangible than success in, for example, management for a biodiverse hay meadow or repairing a stone wall, and partly because there are less positive sensory experiences associated with successful soil carbon storage when compared to many existing agri-environment scheme goals.

4.6.3 'Inconsistencies' in farmer self-identity

We found that farmer responses to questions about their attitude to, and engagement with, agri-environment schemes could be strategic, multiple and appear to be contradictory or inconsistent. There is an extensive literature on farmer self-identity, especially in regard to multifunctional landscapes (e.g. Burton and Wilson 2012; Brouder et al. 2014). One branch of the self-identity literature describes how people or groups manage contradictory self-images in order to position themselves favourably in environmental schemes. A relevant example is Rajão and Marcolino's (2016) discussion of the Acapú indigenous group from Brazil and the variety of roles, identities, values and intentions they present to different audiences in relation to a forest carbon offset scheme – from the "ideal Indians" (sic) striving to achieve sustainable management, to a destructive image which shows the potential for the Acapú to contribute to enhanced forest carbon emissions if the scheme does not occur. This research reflects the way carbon projects can lead to contradictory expectations of the

Acapú and so to potentially contradictory images of self. By applying this understanding of why contradictory self-images appear within our data, rather than dismissing them as inconsistencies, we can further understand how existing structures of agri-environment schemes are positioning farmers and how they respond. Quantitative research methodology constraints may limit expression or interpretation of such complex and contingent motivations. Therefore, we believe that results reduced to one or two key behavioural or attitudinal factors should be interpreted with care.

4.6.4 Mapping and carbon farming

The quantitative, scientific maps of carbon stock distribution we produced for each case study farm (in contrast to the maps which included qualitative information about experience of managing for carbon on farms and working with carbon rich soil) proved valuable in discussions about how farmers currently manage soil carbon, and as a reference for considering future carbon farming scenarios. Maps such as these will be particularly valuable if carbon farming schemes move beyond payment for woodland management only, and consider carbon stocks across a range of on-farm vegetation communities. There is potential to make such maps accessible, understandable, and therefore more useable to farmers, as compared to maps currently produced for agri-environment schemes. Improved farmer engagement in land management prescriptions, through mapping, would likely improve ecological success rates and, in addition, the use of local and place-based knowledge for understanding the complexity and dynamic nature of on-farm soil carbon management also fits with recent ecological research findings regarding the context-specificity of management effects on soil carbon distribution (e.g. McSherry and Ritchie 2013).

4.6.5 Dynamic mapping

Different forms of knowledge, such as farmer's experiential knowledge of soil carbon in the farm landscape and quantitative interpolations of total soil carbon, were made visible through MMGIS mapping; however, this mapping process will always be incomplete as the agri-environment is dynamic. A 'dynamic mapping' approach within agri-environment scheme planning and delivery would keep the mapping process open so farmers and policy officials (and other enrolled participants) could edit and comment on different representations of the farm through an online GIS mapping platform, enabling discussions to continue and evolve throughout the life of an agri-environment scheme and beyond. This understanding of mapping as an on-going process, rather than maps as a static representation (such as the 2-dimensional vegetation community paper maps produced for farm environment plans), is inspired by the literature on critical cartography and qualitative and mixed methods GIS (for an introduction to these literatures see Kitchin, Gleeson, and Dodge 2013). Dynamic mapping taps into the increasing interest in and innovation around online and widely accessible GIS platforms and software which encourages people to share different versions of the world through spatial and temporal mapping (e.g. http://mapstory.org/).

We suggest that the introduction of dynamic mapping would lead to better relations between farmer and policy officer as there will be less repetition of conversations at each round of the agri-environment scheme planning process (and with any change of policy officer). An opening up of the mapping process also has the potential to erode the scepticism and distrust farmers hold around externally-held maps and datasets. It could also include monitoring of scheme outputs, which would link into our findings around farmer motivation to stay engaged with agri-environment schemes.

Use of scheme derogations, which are informal or formal agreements between farmers and the scheme policy officer to alter the management prescription based on unforeseen issues or unexpected outcomes, are unlikely to be 'fit-for-purpose' for carbon farming schemes as such schemes are likely to be more contentious on upland farms from the outset. Dynamic mapping would enable more locally-responsive land management prescriptions through providing a space where conflict and frustrations around farm environment planning discussions can be recorded; account can be taken of place-based attitudes, motivations, experience and values alongside scientific information; and, apparent 'inconsistencies' become a starting place for discussion and new insights, rather than reason to assert the dominance of one knowledge form over another, as often occurs (Stirling 2010).

4.7 Conclusions and policy implications

Accommodating different ways of knowing the world is a common marker of sustainability (Fish et al. 2008). Our research develops a new interdisciplinary approach that can allow different forms of knowledge to be acknowledged and studied within the same research space. We have shown that qualitative, localised and contingent data can complement quantitative data in improving our understanding of a social-ecological system, therefore helping us to improve the management of that system for ecological goals. Specifically, our research reveals that upland farmers have an existing understanding and feeling for areas of their farms, which are rich in soil carbon. This knowledge should not be dismissed in agri-environment scheme planning processes. Our findings regarding motivation to engage in agri-environment schemes and how carbon-rich parts of upland farms are experienced by farmers, lead us to question whether lessons learned from the implementation of agri-environment schemes for biodiversity can be directly applied to carbon farming schemes. We also conclude that communication of agri-environment scheme outcomes needs more emphasis generally, but for carbon farming it will be especially important because of the 'invisible' and 'intangible' nature of the material and its storage.

We reconceptualised how the mapping process could be applied to assist with farm environment planning, specifically future carbon farming schemes, through use of MMGIS. This was informed by our findings regarding how maps are currently used on farms and for agri-environment scheme implementation, their limitations and the place-based experiences of soil carbon and its management. We suggest that we need to revise the way we think about, learn from, and use maps and different knowledge forms for environmental decision-making. For example, a dynamic mapping approach to planning and delivery of carbon farming schemes would address the inadequacy of informal derogations as a 'fix' when local conditions mismatch universal management prescriptions. It would also provide a strong foundation for discussions about future management decisions.

4.8 Acknowledgements

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4.9 Data Accessibility

See Appendices for supplementary maps and tables.

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5 The multiplicities of soil carbon: a method for studying 'soil carbon collectives'

Chapter 5 preface

Chapter Five is written for an interdisciplinary environmental social science (sociology, human geography) audience. It develops the idea that there are multiple soil carbons: entities performed in different ways by 'soil carbon collectives'. Such 'collectives' include humans and non-humans related through or brought together around a concept, idea, or an approach. The thinking around 'collectives' has been developed within human geography and science and technology studies, for example through 'biosocial collectivities' (Holloway and Morris 2012; Holloway and Morris 2014) and 'new collectives' (Latour 2004).

I use and develop the concept of 'soil carbon collectives', which include, for example, scientists, farmers, scientific equipment, farm equipment, protocols and sample sites, to enable me to work with the different and sometimes conflicting ways that different people, groups, policies (knowledge communities) understand and work with soil carbon. I recognise that this is a significant departure from usual approaches to the conception and management of soil carbon and was undertaken as 'risky research' within an interdisciplinary process. A soil carbon collectives approach came about because, within my interdisciplinary field work, I was coming across versions of soil carbon which I could not directly 'map' together (practically and conceptually) without essentializing what soil carbon is based on one particular disciplinary definition or knowledge community (and so dismissing the other versions). Therefore, this approach tries to moves past decisions around which is the 'correct' soil carbon to refer to, map and manage, and was strongly influenced by the work of researchers at Lancaster University and the Centre for Ecology and Hydrology (CEH). In their Loweswater Care Project they recognised that "the potential to act, shape, and change emerging worlds lies within complex epistemological and ontological relations" (Waterton and Tsouvalis 2015, 477) and therefore they tried an approach based on "an appreciation of the radical relationality of people and things" to research and manage a water quality issue at Loweswater, a study site near to my own (Waterton et al. 2006; Tsouvalis and Waterton 2012; Waterton and Tsouvalis 2015).

I recognise that this chapter, as with Chapter Three, assumes some knowledge of the theories and disciplines that have been an influence and acknowledge this tension as a result of writing a time-bound thesis for a cross-disciplinary audience.

5.1 Introduction

This chapter contributes to on-going research into the management of carbon in soils by introducing the new methodological approach developed in this research project and considers how it contributes to the wealth of literature using non-dualistic thinking about nature and society (or 'socio-natures'). This body of work explores the interconnected and integrated way that nature's ecology is bound within a network of diverse human and non-human actants. My method shows how such dense and often broadly-inaccessible theoretical concepts can be made to work on-the-ground and it brings about new understandings and opens up new spaces for discussion in an emergent and contested environmental management setting. My methodological intervention into soil carbon management is made against a background of research into the social 'reasons' behind problems encountered when we try to manage for environmental public goods on farmland, whilst the 'facts' remain unperturbed. I argue that, rather than focusing on perspectivalism, attitudes and other social factors in order to address the problems we encounter, we should instead consider the possibility that soil carbon is multiple and that these multiple versions depend-on but also clash-with each other. Arguably, by acknowledging the multiplicities of soil carbon we can do a better job at managing for them by allowing the different ways of knowing to 'go on together' (Verran 2011, 422).

5.1.1 Why soil carbon?

Soil carbon storage, or sequestration, is gaining global attention as a way for agriculture to contribute towards climate change mitigation. Carbon sequestered in soil is commonly considered as carbon retained in soil for one hundred years or more (Stockmann et al. 2013), which reduces levels of carbon-based greenhouse gases in the atmosphere. Despite a lack of political and scientific consensus as to the degree soil carbon management can contribute to climate targets and how best it can do so (Lal 2008; Powlson, Whitmore, and Goulding 2011; Mackey et al. 2013), new ways of encouraging and requiring farmers and other land managers to engage with soil carbon sequestration are being developed (e.g. Renwick et al. 2014; Whitmore et al. 2014). Within emergent soil carbon sequestration projects it is scientists who describe soil carbon's properties and the way it interacts with the world. This object of soil carbon is then enacted into policy as either: a commodity object within global carbon offset markets; a sequestered stock of soil carbon, a manageable ally in the fight to mitigate against climate change; or, as a problematic, but potentially manageable, flux/emission from soil. Soil carbon is being treated as a Scientific[26] 'matter-of-fact', as an object with clear boundaries and well-defined properties (following: Latour 2004, 22). This is unlike the situation in other institutions and with other actors, who work with a more fluid, context-specific appreciation of matters, one which is much less settled and much more open to contestation and debate – treating them as 'matters-of-concern'. One example of this is the Loweswater Care Project's approach to understanding and managing-for water quality within a water catchment in northwest England, as described in Waterton and Tsouvalis (2015).

I argue that treating soil carbon as a Scientific matter-of-fact has the potential to shut down discussion around its management, as has been shown with management for other environmental public goods (from now on referred to as environmental goods)[27] (Phillips et al. 2010; Smith and Brennan 2012). As will be revealed throughout the chapter, the 'liveliness' of soil carbon (Bennett 2010) emerges from its entanglement in 'loose' human/non-human assemblages or collectives – labelled as 'soil carbon collectives' (Hinchliffe 2007). Soil carbon's active properties shape local geography and contribute to the history and future of climate change (Castree 1995). Soil carbon is not just a surface, physical or base natural materiality from which to understand the human histories and futures of agricultural productivity or environmental management, nor is it just a 'thing' to be observed through Scientific method. Rather, soil carbon has a materiality that is both physical and cultural (Bakker and Bridge 2006). It is in and through these diverse socio-natural entanglements and assemblages (Bakker and Bridge 2006; McFarlane and Anderson 2011) that soil carbon collectives become, perform and act out their multiplicities.

[26] The capital S symbolises a foundationalist 'S'cientific model of knowledge – "the politicization of sciences through epistemology in order to render ordinary political life impotent through the threat of an incontestable nature" (Latour 2004, 10).

[27] Also referred to as 'ecosystem services' (Daily et al. 2009), 'natural resources' or other policy framings.

It could be argued that the use of assemblages and rematerialisation of socio-natures is not novel within social theory (for example Bakker and Bridge 2006). However, methodological innovations and experimentations needed to explore these human/non-human relations are limited (McFarlane and Anderson 2011; Urquhart et al. 2011). Using an interdisciplinary approach[28] – embracing methodologies as diverse as soil science, mixed methods mapping, and qualitative, in-depth engagements with farms and farmers – I extend understandings of the materiality, performativity and politics of soil carbon collectives within agricultural landscapes. The development of these methods, I argue, is a way to open up the "dense descriptions" stemming from an assemblage and actor network theory (ANT) (and allied social theory) approach, and make them actionable and suitable for interventions into "policy processes, flows and struggles" (Urquhart et al. 2011, 245; Law and Singleton 2014, 380). My empirical data highlights the need to reconsider soil carbon as a "matter-of-concern" (Latour 2004, 22), that assembles a "complex web" (Latour 1998, 209) of human and non-human actants, as it emerges as a scientific and policy object of interest within climate change mitigation. I propose that new soil carbon collectives are emerging within upland livestock farming spaces in the English Lake District (drawing from Latour 1998; Latour 2004; Felt and Wynne 2007; Hinchliffe 2007; Waterton and Tsouvalis 2015).

5.1.2 Attending to those who manage soil carbon and a history of tension

While there is an increase in literatures that engage with the ideas of socio-natures and carbon materialities, addressing topics such as commodification of carbon and carbon offsetting (e.g. Bumpus 2011; Lansing 2012; Lansing 2015) and the production and consumption of carbon (e.g. Ormond and Goodman 2015), this chapter takes another focus by attending to those who labour in a different way within the soil carbon collective – managing land to sequester carbon within farm spaces. I believe that it is necessary to consider, alongside scientific and policy performances, how carbon is materially experienced in the

[28] I consider an interdisciplinarity approach to be one that "analyzes, synthesizes and harmonizes links between disciplines into a coordinated and coherent whole" (Choi and Pak 2006, 351). Whereas, multidisciplinarity "draws on knowledge from different disciplines but stays within their boundaries" (Choi and Pak 2006, 351). The work was also enacted with ongoing critical reflections of researcher positionality (Rose 1997). See Chapter Two for further discussion.

landscape by those who are unintentionally or intentionally enrolled in the process(es) of sequestering it – the farmers.

The history of engagements between scientists, policy makers and farmers managing for agriculture and the environment in this region is often one of frustration and contestation (as in many regions in the UK and internationally) as has been documented by studies attending to mutable and contested natures and human/non-human relations (Wynne 1989; Law and Singleton 2014; Waterton and Tsouvalis 2015). Within this study, frustration and contestation were referred to many times by interviewees in relation to previous policy interventions for managing environmental goods on farms (through agri-environment or catchment management schemes[29], for example). One example concerns the use of informal management contract derogations which may be applied, with the consent of the policy officer, as a 'fix' when generic 'universal' land management prescriptions mismatch with local environment conditions or management practices.

One farmer explained how a management prescription specifying the minimum distance required by his contract for fencing-off ditches (to prevent livestock eroding the ditch sides) prevented his machinery from clearing the ditches, as required by the same contract. He explained his frustration to his local policy officer who allowed this part of the contract to be altered, but the farmer clearly understood that this was an *"exception"* and relied on good relations with an *"understanding and experienced"* officer, which led him to express concern about what would happen regarding future mismatches when the officer retired (Farmer E, focus group, 11.6.13)[30]. Unresolved mismatches have led to a political impasse between some farmers and policy officers in this region. A number of farmers explained how they will no longer engage with voluntary management schemes, despite the financial benefits, because of a mismatch in perspective or a lack of flexibility from universal prescriptions and from policy officers. In turn,

[29] Voluntary agri-environment schemes have been used within the European Union since the 1980s as a way for agriculture to deliver environmental public goods outside of regulatory mechanisms (Smith et al. 2008; Proctor et al. 2012b). For information on catchment management schemes see Department for Environment, Food & Rural Affairs (2013).

[30] This and subsequent quotes are taken from our empirical study and the data collection process is explained within the 'Methodological approach' section.

some policy officers voiced their scepticism at some farmers' motivations to engage and fully-participate in agri-environment schemes and talked about farmer "lack of cooperation" (field notes, farm visit, 9.6.14).

This study is an attempt to avert such frustrations and political impasse which appear (as in the example of Farmer E above) when politics is enacted at the ground level and environmental goods, such as soil carbon, are discussed and managed as matters-of-fact on the farm through, for example, universal land management prescriptions. This is not to suggest that new regional or local forms of environmental governance for on-farm soil carbon management need to be based on ideas of consensus. Rather, I recognise the limitations of treating conflicts and incongruences between land managers and scientific and policy imperatives solely as the result of social factors (e.g. communication issues or lack of motivation) which have been unaccounted-for in scheme design, whilst the matter-of-factness of the environmental goods themselves remains unperturbed. I present a radical reframing of on-farm soil carbon management at a time of agri-environment policy development by attending to different performances of soil carbon – performances which both clash-with and depend-on the quantified and commodified Scientific 'aggregate' carbon and its spatialized abstraction (Robertson 2012).

To explore these issues in depth, the chapter is structured as follows. I first explain what we mean by suggesting that soil carbon is treated as a matter-of-fact, both in terms of the scientific literature and through policy implementation of soil carbon in a UK context. I then explore what it would mean to reconsider soil carbon from a matter-of-fact to, what Latour (2004) calls, a 'matter-of-concern'. This means exploring the ways the emerging 'more-than-human' soil carbon collective (Latour 1998; Latour 2004; Tsouvalis 2015) is starting to be performed through these various scientific and policy interventions. This theoretical discussion explicitly includes consideration of object-oriented and more-than-human politics, and recognition of soil carbons' material and performative multiplicities.

Second, I outline my interdisciplinary methodological approach and the way that the methods themselves became a form of intervention to challenge the representations of soil carbon as matter-of-fact. After a description of the study region and data collection I explore the multiplicities of soil carbon as they were revealed through case examples: i) Scientific accounts – these include accounts of soil carbon as organic material, performed as gas and full of fungi. These stories contain tensions which I will also explore; ii) Soil carbon as an embodied experience on-farm – where the methods revealed the materialities of soil carbon as wet landscapes, as proliferation of problematic plant species, and as lacking in the positive sensory experiences related to on-farm delivery of other environmental goods; iii) Finally, and linked to these previous discussions, I explore soil carbon as hope for the future – related to the emergent ways that soil carbon sequestration is framed as a Scientific and policy hope for future climate change mitigation.

5.1.3 Soil carbon as a matter-of-fact

> *What we normally think of as 'life' is based on chains of carbon atoms, with a few other atoms, such as nitrogen or phosphorous. One can speculate that one might have life with some other chemical basis, such as silicon, but carbon seems the most favourable case, because it has the richest chemistry. (Hawking 1996)*

> *A 'matter-of-fact' is an object "defined by strict laws of causality, efficacy, profitability, and truth". (Latour 2004, 22)*

The chemical element carbon is present in all forms of life – linked to other elements as part of more complex molecules. Soil carbon can be inorganic (derived from rock) or organic (derived from plant, animal or microbial life) and in the section 'Exploring matter-of-factness in Scientific accounts of soil carbon' we start to unpick such representations. Globally, soil stores over twice as much carbon as either terrestrial biomass (all forms of above-ground life) or the atmosphere (as carbon-containing gases carbon dioxide and methane) (Scharlemann et al. 2014) and changes to land management have the potential to either sequester soil carbon stores or increase net carbon emissions (O'Rourke et al. 2015). The potential for sequestering carbon in soils through alterations to land management, as a significant mitigation option for climate change, is an intensely-debated topic (Lal 2008; Conant 2010; Smith 2012; Smith 2014).

Soil carbon management is an integrated part of European Union (EU) programmes, such as Cross-compliance[31] within the Common Agricultural Policy (CAP) and fertiliser and manure management programmes under EU Directives, where the main focus is water quality (Penny Anderson Associates Ltd 2011; Ingram et al. 2014). Soil carbon sequestration has also been specified as a co-benefit within initiatives delivering other environmental goods such as soil fertility, food security and habitat restoration (Neuman and Belcher 2011; Goulding et al. 2013). However, unlike farmland biodiversity, for example, there are currently no specific EU or European national government policies or programmes in place for promoting soil carbon sequestration, even within those measures which directly address climate change mitigation in agriculture (Ingram et al. 2014).

Much of the scientific literature suggests that we have acquired the knowledge needed to implement systematic land management changes to increase soil carbon stocks in agricultural soils. However, what both O'Rourke et al. (2015) and Ingram et al. (2014) highlight, from different disciplinary perspectives, is that although we understand the over-arching bio-physical processes behind soil carbon sequestration we have an insufficient knowledge of how local farming conditions and practices intersect with these processes. Echoing the debates on socio-natures (e.g. Castree and Braun 2001; Verran 2009), O'Rourke et al. (2015, 3571) emphasise that soil security[32] needs to include "biophysical-, social-, economic- and political science-based dimensions". While these debates are emerging within literatures on commodification and carbon offsetting (Bumpus and Liverman 2008; Lansing 2012) there is very little research on farmers' lived realities of soil carbon which are directly affected by, and affect, the socio-political and ecological basis of the carbon economy (Lyons and Westoby 2014). The literatures emerging on the commodification of carbon ignore both how soil

[31] "Cross-compliance is a mechanism that links direct payments to compliance by farmers with basic standards concerning the environment, food safety, animal and plant health and animal welfare, as well as the requirement of maintaining land in good agricultural and environmental condition" http://ec.europa.eu/agriculture/envir/cross-compliance/index_en.htm (accessed 2.10.15).

[32] "concerned with the maintenance and improvement of the global soil resource to produce food, fibre and fresh water, contribute to energy and climate sustainability, and to maintain the biodiversity and the overall protection of the ecosystem" (McBratney, Field, and Koch 2014, 203).

carbon is 'produced' through land management and farmer labour, but also ignore the ways that soil carbon "resists or confounds its production" (Bakker and Bridge 2006, 10). That is, soil carbon itself has a vibrancy as it cycles independent of, but affected by, various human (e.g. tillage or afforestation) and non-human (e.g. grazing sheep) interventions.

5.1.4 Policy implementation of soil carbon as matter-of-fact

Below I identify three examples of how soil carbon management is enacted as a matter-of-fact within a UK context: national scoping studies investigating the potential for soil carbon sequestration in rural landscapes, options for delivering carbon management through existing policy mechanisms such as agri-environment schemes (AES), and commodification of carbon in landscapes through existing offset schemes.

Firstly, a number of national scoping studies have been commissioned to establish the potential for carbon storage within rural landscapes (e.g. Haines-Young and Potschin 2009; Moran et al. 2011; Alonso et al. 2012; Moxley et al. 2014). By managing land for soil carbon, the carbon-rich landscapes act as a counter to carbon-emitting landscapes elsewhere. Many of the carbon-rich soils in the UK are found in upland, marginal farming areas such as the English Lake District in the northwest of England and these landscapes are considered as "an important asset for the UK in relation to climate regulation" (Haines-Young and Potschin 2009, 5). Partly as a result of these studies, soil carbon has started to be attended to and politicized at a regional scale, for example, the Lake District National Park Authority (LDNPA) have produced a booklet entitled 'Managing land for carbon: A guide for farmers, land managers and advisers' (Hagon et al. 2013). This booklet contains suggestions on how to maintain and enhance soil carbon through alterations to land management practice. These suggestions, in line with treating soil carbon as a matter-of-fact, are made as generic or 'universal' management prescriptions. However, as we will describe in the section 'Exploring matter-of-factness in Scientific accounts of soil carbon', this can lead to confusion and contestation on the farm when this universal approach to soil sequestration does not 'fit' with local conditions.

Secondly, policy could implement soil carbon as matter-of-fact through existing policy mechanisms, such as AES, which assign monetary value to agricultural land based on provision of environmental 'goods and services' (other than crop production) (Kroeger and Casey 2007; Bol and et al. 2012; Horrocks et al. 2014). AES have been overwhelmingly documented as problematic (e.g. Morris 2004; Emery and Franks 2012), and what defines and influences success in AES and whether previous schemes have been successful are intensely-debated topics (e.g. Perkins et al. 2011; Smart et al. 2013; Batáry et al. 2015). This history, introduced above, will bring existing tensions to any discussion of managing soil carbon within an AES framework. Also, as will be reflected elsewhere in the chapter, some of the suggested practices for enhancing soil carbon stocks are identical to existing and contentious scheme practices (e.g. further reductions in sheep stocking rates on commons[33] and other moorlands). They are seen by some as *"incompatible with traditional farming and can erode the viability of the core farming enterprise needed to deliver the scheme"* (farmer representative, interview 13.6.12).

Scheme conflicts and problems are variously attributed within the rural sociology, ecology and conservation literatures to farmers' "cultural resistance" to schemes (Burton et al. 2008; Emery and Franks 2012), poor communication and alternative interpretations of risk (Emery and Franks 2012), lack of farmer motivation to fully engage in schemes (McCracken et al. 2015), and a mismatch of ecological process and payment spatial scales (Cumming et al. 2006), amongst other social factors. My research highlights that the conflict and frustration that arises in the process of implementing AES, arguably emerges due to the way these schemes treat goods such as biodiversity and priority habitats as matters-of-fact. Despite the existence of literature – and farmer representatives themselves – calling attention to the persistence of these problems, research and policy discourses continue to assume farmers and other land managers will embrace carbon sequestration practices with little attention to the socio-

[33] Commonland (a common) is land owned collectively by a number of people, or by one person, over which other people have certain traditional rights, such as livestock grazing rights or rights to collect firewood (https://www.gov.uk/guidance/managing-common-land).

ecological, material and more-than-human complexities in agricultural landscapes.

A third way that carbon is being enacted as a matter-of-fact is already underway – the commodification of carbon through existing global offset markets. Despite a lack of scientific consensus on the climate change mitigation potential of sequestering carbon in soil through specific land management changes, some farm and landscape-scale schemes have been set up to engage with these markets. In our study region one such scheme is the afforestation of grassland by the LDNPA through a pilot carbon-offset scheme (Hagon 2014). While an interesting example of a voluntary regional perspective on territorial carbon offsets, the scheme ignores scientific uncertainty around the carbon storage 'benefits' of converting grassland to plantation (Ostle et al. 2009). It does considerable work to transform a block of 'unproductive' grassland into "a space of commodified carbon storage" (Lansing 2012, 204) through tree planting and management agreements, in order to sell off almost 5,300 tonnes of carbon stored in new woodlands over the next 85 years (Hagon 2014). Such initiatives engage with the neoliberalization of soil carbon as a socionatural-technical complex (Bumpus 2011) through scientific performance and economic rationality and as a normative concept to guide politics (Robertson and Hayden 2008; Robertson 2012; Leach and Scoones 2013; Sullivan 2013; Lyons and Westoby 2014). Robertson (2012), in a paper which considers how such an 'aggregate measure' of commodified carbon is valued in relation to the function it provides, explains how this encounter between neoliberalism and the environment as social abstraction relies on debatably secure spatial and ecological measurements.

In these three examples we observe suggestions that soil carbon as matter-of-fact becomes problematic as a mismatch for local conditions or as it resists its Scientific boundaries and pre-defined properties. We can imagine that as on-farm soil carbon management becomes more widespread, perhaps through AES mechanisms, that such mismatches and resistances will exacerbate pre-existing tensions and manifest on-the-ground as more frustration. While a number of carbon management schemes have been critiqued within geography and the allied environmental sciences these critiques tend to focus on abstract measures of commodification and the financial structures required to make carbon 'count' (Bumpus 2011) or how it is counted and made knowable at mundane sites of everyday production and consumption (Ormond and Goodman 2015). Although the performativity of the markets is considered in these literatures, the performativity of on-the-ground practices that will deliver such economic and ecological services remains 'black-boxed' (Latour 1987). I argue that it is necessary to consider, alongside scientific and policy performances, how carbon is materially experienced in the landscape by those who are unintentionally or intentionally enrolled in the process of sequestering it. Doing so enables a radical reframing of on-farm soil carbon management as a 'matter-of-concern'.

5.1.5 Soil carbon as a matter-of-concern

Latour (2005) explains that matters-of-concern gather an assembly of relevant parties, where "materiality[34] and politics are no longer disassociated" (Tsouvalis 2015, 10). Soil carbon as a "matter-of-concern", unlike a "matter-of-fact", has "no clear boundaries, no well-defined essences", no sharp separation from its environment (Latour 2004, 24). I use the concept of a 'soil carbon collective' to consider this assembly as a 'complex web' of actants, each with transformative power (Latour 1998; Latour 2004; Tsouvalis 2015). Felt and Wynne's (2007, 55) description of a "hybrid collective" brings into the definition a concerned group of scientists, policy experts and lay people who get actively involved in the process of knowledge production, and this study engages with a number of different people who have an interest in or 'gather around' soil carbon. The methods enacted within this study extend the collective to include non-humans – a 'more-than-human' collective (Latour 2005) – and consider, for example, soil, sheep, maps, land management contracts, conversations, plants, and scientific equipment (Mol and Law 2002). Soil carbon as a matter-of-concern, centre-stage within this object-orientated and more-than-human politics, is something which is transformative and 'lively' (Bennett 2010); not only organized by human intervention but as something which organizes, has agency and helps to configure worlds as it is performed (Law and Mol 1995; Mol 2002; Waterton and

[34] The relationships, interactions and co-creation of subjects and objects and their contexts (Cunliffe and Luhman 2013).

Tsouvalis 2015). Performativity is crucial in attending to complexity – in accepting that we are not describing a pre-existing world (matter-of-fact) but that soil carbon is performed as "part of a practice of handling, intervening in, the world and thereby enacting one of its versions" (Law 2002; Mol and Law 2002, 19). Treating soil carbon as a matter-of-concern, as something that is performed, collects and transforms, helps us to contemplate multiple soil carbons (Mol and Law 2002); held together by a "looser gathering of expertise" (Hinchliffe 2007, 99) – a collective which allows for more than one kind of expert and therefore multiple materialities of soil carbon to be acknowledged (Hinchliffe 2007; Hinchliffe 2008).

There is an exciting body of work which applies this object-orientated and more-than-human politics to contested issues in environmental and agricultural management (e.g. Hinchliffe 2001; Tsouvalis et al. 2012; Morris and Holloway 2014; Waterton and Tsouvalis 2015). Within this body of literature the material multiplicity and spatial geographies of objects (such as prions, larvae and genetic technologies) are being used to understand their different sites of environmental governance as a way to envision the politics of nature whilst recognising complexity, contingency and relationality (Waterton and Tsouvalis 2015). Waterton and Tsouvalis's (2015) use of the concept of 'new collectives' (drawing on Latour 2004) in exploring water quality issues in Loweswater (also in the English Lake District) emphasises the need to break down dualisms – society/nature, human/non-human – and bring these concepts together in order to re-think the possibilities of working in a participatory way on issues that we understand to be already multiple and are already contested. The emphasis in their work is in the 'collecting', that is bringing together these multiplicities and entangling them in politics. Previously, these "dense descriptions" rarely resulted in an analysis that led to policy (Urquhart et al. 2011, 245), but these novel studies are drawing out these connections in practice – and I aimed to do the same.

Taking inspiration from these critical interventions I refused to accept that we can gaze through Scientific method on the immutable single object of soil carbon as matter-of-fact, as currently finds expression in scientific methods, pilot carbon offset projects and in emerging approaches to managing land for environmental goods. Rather, I start from the point that soil carbon is ontologically multiple (Mol 2002) and this ontological multiplicity is full of "potentially radical implications" when we question the orthodox and influential notion of policy objects as stable (Law and Singleton 2014, 380). Methods were engaged as one of the main techniques used to open up this politics. As a matter-of-concern, we explore soil carbon's multiplicity through its materiality and engage with what is socially-relevant about soil carbon (as well as what is scientifically and politically relevant) (Felt and Wynne 2007), and suggest soil carbon is not stable but constantly reproduced. Just as Waterton and Tsouvalis (2015) 'left open' the definition of the problem in their study of Loweswater, so I leave open what soil carbon is and work with different versions of context (Singleton 2012) regarding soil carbon sequestration in the agricultural landscape. I therefore focus on i) soil carbon as performance; ii) how soil carbon sequestration creates particular constructions of farmers and the agricultural landscape; and, iii) a situated example of where particular performances of soil carbon, farmers and landscape meet, interact and interfere with one another. By discussing farmer experience and understanding of soil carbon alongside scientific and policy performances, rather than as a hierarchy of knowledge, I try to achieve some kind of analytical symmetry (Law and Mol 1995; Singleton 2012). By not focusing on the contradictions between soil carbon as scientifically measured and as experienced by farmers, but by acknowledging and working with incompatibility and incongruences, the study challenges dominant ontological understandings of soil carbon as matter-of-fact within the research and policy community and opens up new spaces to discuss its management as matter-of-concern in agricultural landscapes.

5.2 Methodological approach

5.2.1 Interdisciplinarity

This was a mixed methods, interdisciplinary study that explored the different materialities of soil carbon in a 'looser' (allowing for more than one kind of expert; Hinchliffe 2007; Hinchliffe 2008), soil carbon collective (see Felt and Wynne 2007; Tsouvalis et al. 2012; Waterton and Tsouvalis 2015 for examples of other collectives) within an upland agricultural region in the northwest of England – the English Lake District. The material explored in this chapter is closely-informed by my Critical, Feminist and Qualitative Geographical Information Systems (GIS)[35] approach to mapping farm spaces outlined in Chapter Two. GIS is employed as a way to allow different types of knowledge about and materialities of soil carbon in farm landscapes to 'go on together' (Verran 2011, 422) as spatially-located performances. GIS was developed as a visualisation and analysis tool for working with quantitative data, and often involves the use of 'big data' which may represent landscapes in ways which do not reflect the experiences of landscape users (Turner and Taylor 2003). Within the last decade, a new avenue of research has developed which uses GIS critically and incorporates qualitative data (Cope and Elwood 2009). The mixed methods mapping process was used experimentally as one way of tying-together the different ways we attended to the multiplicity of soil carbon, as explored below.

In particular, through the methods, I explore scientific performance, embodied experience and on-farm management performances of soil carbon. In this way contributing to research on building 'theory in practice', which accounts for the embodied politics present in the everyday material world (Rose and Tolia-Kelly 2012). This was enabled both by my mixed disciplinary background and by the interdisciplinary approach to the subject which allowed me to 'keep the toolbox open' to suit the method to emergent understandings and insights in an iterative process. This was attempted in the belief that it is worth the effort for the natural and social sciences to work together, with others, "in full recognition of the critiques" around participation and interdisciplinary research that exist and to view this as a productive challenge (Tsouvalis and Waterton 2012, 119).

5.2.2 Method as intervention

Mixed methods were used as a methodological intervention, rather than as just a research output. I accept that methods matter and are political, "research methods generate not only representations of reality, but also the realities those representations depict" (Law 2009, 239). These methods were used to play

[35] A GIS is a computerized data management system used to capture, store, manage, retrieve, analyse, and display spatial information.

ontological politics, as a form of interference and intervention (Law and Urry 2004; Law 2009; Browne et al. 2014). The 'usual way' of doing the politics of soil carbon on farms is to identify existing or potential stocks with the most scientifically-robust or policy-friendly land management options and tell or persuade farmers to manage for those (e.g. Hagon et al. 2013; Lam et al. 2013; Renwick et al. 2014; Whitmore et al. 2014). We used mixed methods to disturb the dominant way that soil carbon is known and represented as 'natural' through scientific measurement and visualisation and through policy discourse. Using concepts of 'playfulness' (Dodge and Perkins 2015) and 'mess' (Law 2004) in social science research to consider carbon in the agricultural landscape from different epistemological and ontological perspectives, we highlight a serious issue in the way that alternative ontologies are ignored within agricultural land management schemes.

5.2.3 Grounded visualisation

A 'grounded visualization' approach was adopted for the gathering, analysing and mapping of both qualitative and quantitative soil carbon data. Grounded visualization (GV) uses GIS to integrate "the analysis of qualitative and quantitative data through grounded theory and visualization" (Knigge and Cope 2006). GV is ideal for taking a non-linear iterative, recursive and reflexive approach to research, data gathering and analysis (Knigge and Cope 2006). This is explored in greater detail in Chapter Two. GIS as a tool for visualisation and analysis lends itself well to a mixed method approach, including visualising qualitative information in a spatial context (Pavlovskaya 2006). Despite its quantitative beginnings, its layered structure (with creative manipulations) enables the juxtaposition of alternative, located, versions of soil carbon without making them irreducible to one another (Foucault 1986). Its base of Cartesian coordinates can even be subverted to foreground (usually as a background) alternative foundations (or 'base maps'), such as sketch maps, photographs or sound/noisescapes (Cope and Elwood 2009; Boschmann and Cubbon 2013). Grounded theory (originating with the work of Glaser and Strauss 1967) "involves the collection, coding, and categorization of qualitative data … toward enabling themes to emerge through iterations of 'constant comparison'" (Knigge and Cope 2006, 2024). Grounded visualisation has been utilised in critical approaches to mapping in research areas as varied as oral histories (Seegers and Giordano 2015), representations of sexual violence (Quinlan and Quinlan 2010) and mobilities studies (Jones and Evans 2012), but has been under-utilised in natural resource and land management studies[36]. Where it has been applied, in Hurley et al.'s (2008) study of sweetgrass harvesting in Southern USA, it provided a voice for those engaged at the 'ground-level' of natural resource management, who would otherwise have been a silent set of spatially-located numbers.

The wider study also embraces the "processual turn" in Critical GIS whereby maps are considered "post-representational" and look "beyond the power of material artefacts and fixed public images, so as to shift the ontological focus onto mapping and the numerous practices that bring mapping into being" (Dodge and Perkins 2015, 38). Appropriating mixed methods GIS (also referred to as Qualitative GIS) to bring together different types of data as well as different ontologies and epistemologies, literally creates space for new discussions about soil carbon and its management.

5.2.4 Data collection

Soil carbon collectives

Soil carbon collectives were attended-to at two different scales (Morris and Holloway 2014). Firstly, through three case studies at a farm scale where the collective consisted of (amongst many other actants) farmers, their family members, neighbours, sheep, cows, soil, plants, maps, farm management agreements, scientific equipment, scientists and other researchers. Secondly, I considered a more regional soil carbon collective through a focus group mechanism – actors who gathered around the concept of soil carbon at a knowledge-exchange event for farmers, farm advisors, farmer representatives and academics. This collective also included maps, remotely-sensed imagery, satellites, regional policy, scientific equipment, hand-outs, fliers and websites.

[36] Of the 89 journal articles which cite Knigge and Cope (2006) (checked on Scopus 15.10.15) only 11 are concerned with natural resource or wider environmental management and of these only one actually applied the method.

These two different scales were chosen to, firstly, enable in-depth qualitative and quantitative research on the three case study farms and, secondly, to capitalise on the interaction that occurs within the focus group setting to probe shared meanings and values, normative responses and areas of disagreement (Sim and Snell 1996). The focus group was also used to further explore insights derived from the on-going case studies and to question farmers and others from different farm contexts. The study region is described in detail in Chapter Two.

Case studies

Case study farms/farmers were enrolled based on duel criteria. The scientific study required the three farms to be contrasting in terms of vegetation communities, geology, and topography. For the qualitative data collection the study required that the farmers (and ideally others linked to the farm such as family members and farm environment advisers) would be willing to talk in informal and semi-formal static and walking interviews over a number of months. All three farms were enrolled in agri-environment and/or catchment management schemes at the time. Initial knowledge and interest in soil carbon and managing land to sequester carbon varied between the main farmer for each holding.

I empirically explored different materialities of soil carbon on the three case study farms, as a Scientific matter-of-fact and as embodied experience, over seven months. More detail on the quantitative methods is provided in the section below ('Scientific accounts of soil carbon') and in Chapter Three. Briefly, I quantitatively predicted soil carbon across the farm landscapes using field sampling and surveying, laboratory analysis, data management, statistical analysis and interpolation, and then visualised, in the form of maps, actual and interpolated carbon stocks across the farms.

Qualitative data collection involved a series of semi-formal static and walking interviews which focused on farmer knowledge and experience of soil carbon, current management of soil carbon on-farm, and future possibilities for management of soil carbon, alongside numerous informal conversations. Farmers were also asked about their experiences of AES and the role of mapping on their farms. A spatial transcript methodology (Jones and Evans 2012) (methodology is detailed in Chapter Two) – a form of walking interview – was undertaken using the farm maps created, showing actual and predicted current soil carbon stocks. These were used as an aid to discussions about current and future land management, including discussion of potential policy interventions to encourage management of soil carbon. Using a Qualitative GIS approach (Cope and Elwood 2009; Jung 2009) the qualitative data was embedded into the GIS and was able to be spatially interrogated and juxtaposed with other data 'surfaces' such as stocks of soil carbon, land tenure, vegetation community and land elevation (see Chapter Two for more detail). I also took time to observe farm management practice, especially as it related to soil carbon, such as sheep movements (relating to stocking density), and adding fertiliser to land.

As I carried out all of the data collection and analysis, with assistance, the confluence of quantitative and qualitative methods enabled a set of linked conversations with farmers, farmers' families and associated farm environment advisers which otherwise would have been unlikely to happen. Using method as intervention means, in this case, remaining open to varied performances of soil carbon in the farming landscape, keeping open what soil carbon is and how it is performed, and also concentrating on elucidating 'alternative' versions of soil carbon. To do this I considered and reflected on: the different encounters I, as researcher, had with soil carbon in the process of sampling, analysing and map-making; reflected on how soil carbon was made visible by other scientists at the focus group event, by policy makers in pilot carbon offset projects, and by other policy interventions; the embodied experience and performance of soil carbon by farmers and other agricultural professionals in day-to-day practice and through interaction with others in the soil carbon collectives; and, how soil carbon was represented and discussed within online communities, in encounters with policy makers and farm advisers and in discussions with farmers about the future of farming in the region.

Focus group

As a direct result of an early conversation with one of the case study farmers and as a co-produced event we held a knowledge-exchange focus group on his farm on the topic of soil carbon. Farmers and farm advisers were invited through personal contacts and through a local farmer network organisation via electronic and postal fliers and through their website. The knowledge-exchange element was emphasized, with farmers being asked to suggest content and style and with three farmers facilitating discussions. Thirty one people attended: 14 farmers, 10 academics, four farmer representatives and three farm environment advisers. After the event 94% of attendees said they had found it worthwhile, with a number of farmers subsequently getting in touch for further information about the topic, the research discussed (farmer- and academic-led) and to offer their farms as experimental sites[37].

The morning saw three outdoor 'stations' set up: one facilitated by two farmers who discussed a farmer-led biodiversity monitoring initiative on carbon-rich common land; the second and third facilitated by ecologists who discussed their work and fielded questions about plant-soil carbon dynamics and soil health. In the second session participants gathered at different tables in the farm workshop to discuss how to manage land to store carbon, the use of maps and remotely-sensed imagery on farms and on-farm experiments into soil health and carbon dynamics (run by both academics and farmers).

5.3 Exploring matter-of-factness in Scientific accounts of soil carbon

Soil carbon has attracted significant scientific investment and investigation within the last few decades (Schmidt et al. 2011). I considered how soil carbon is performed through a scientific lens in a number of different ways, how "invisible" soil carbon is made visible and made to count through techno-scientific assemblages, using an approach that is well-rehearsed throughout the Science and Technology Studies literature (e.g. Latour 1999). The following stories, based on data from the empirical work, highlight how treating soil carbon as a Scientific matter-of-fact can lead to local mismatches and subsequent tensions.

5.3.1 Soil carbon performed as organic material

Within the scientific narratives of agricultural soil carbon management, soil carbon is mostly considered as soil organic carbon (SOC) (rather than inorganic

37 For more information about the event visit
http://planetearth.nerc.ac.uk/features/story.aspx?id=1513 and
http://landbridgeblog.blogspot.co.uk/2013_07_01_archive.html (accessed December 2015).

soil carbon; Monger in Hartemink and McSweeney 2014). Soil organic carbon (SOC) is biologically-derived and the amount in soil is related to the balance between the amount of organic matter entering soils, from plants and animal wastes, and the amount that is released by decomposition, which is largely performed by soil organisms (Ontl and Schulte 2012). SOC is often referred to in its solid state, which can be described at a variety of scales. Particle scale SOC is associated with mineral particles and is considered a basic unit in soil science (Christensen 2002; O'Rourke et al. 2015). Aggregate scale is where microaggregates of mineral particles, bound together by clay and organic materials, are themselves bound together into macroaggregates by fine roots, fungal hyphae and carbohydrates (O'Rourke et al. 2015). Pedon scale is discussed in terms of biologically-derived carbon within the smallest unit of soil that contains all the soil horizons of a particular soil type, with some carbon as quickly cycled (labile) and some as more stable and stored (recalcitrant) (O'Rourke et al. 2015). At the landscape scale the amount of soil carbon is affected by natural and anthropogenic processes occurring in lateral and vertical dimensions (O'Rourke et al. 2015). At the biome scale we talk about 'drivers' of soil carbon being vegetation, geology and climate (O'Rourke et al. 2015). Finally, at the biosphere scale, soil carbon is as an important part of a global carbon cycle and instrumental in contributing to or mitigating climate change (O'Rourke et al. 2015).

Already, we have numerous soil carbons which are measured, mapped and modelled – the 'waters are muddied' – which is a good place to introduce dissolved organic carbon which leaches out of soils and into water courses (and can also be mapped and modelled). But even in choosing the landscape scale alone – the focal scale of this research – there are a number of different soil or soil-derived carbon chemical states, dependent on the different 'bundled hinterlands' (Law 2004) of scientific methods, instruments and processes. These are described as they were performed and experienced within the study, and with regard to how their multiplicity is rationalised as 'soil carbon'.

I begin by describing the scientific and technological processes used to measure and visualise soil carbon on the three case study farms. The chosen method of soil carbon measurement involved performing it as SOC (see Chapter Three for more details). Taking what looks like a large apple corer (see Figure 5.1 below) my assistants and I extracted cores of soil from across the three farms – the sample design required ten replicates of these cores within each vegetation community (eight communities on one farm, seven and three on the other two). These vegetation communities were delineated based on existing policy (AES) maps and with a 'practised eye' and farmer input. The soil cores were split into sections based on specified depths and bagged. The specificity of the depths appears to be more traditional than anything else with 0 to 7.5 cm as the first delineation, then 7.5 to 20 cm and at 20 cm intervals after that, as deep as is possible to go. The samples were placed into cool boxes to try and slow down ongoing biological processes and were transported back to the lab for processing. Processing involves sieving, weighing, recording, drying, grinding and finally wrapping a fraction of a gram of dried, ground soil in what looks like a tiny foil take-away tray and combusting it at 900 degrees Celsius. The reading from the machine tells you how much carbon (and nitrogen) was in the soil as a percentage. This 'total carbon' can include labile and recalcitrant, and micro and macro-aggregate carbon. The derived columns of numbers are applied to statistical models and interpolated across spatial surfaces to create maps of estimated soil carbon across the farms using GIS software (Chapter Three), ignoring (or black-boxing) the complexity of the different 'types' of carbon within the label 'total carbon'. This black-boxing can be rationalised in the write-up (see Chapter Three).

Figure 5.1 Sampling a core of soil.

5.3.2 Soil carbon performed as a gas

Soil carbon was also performed, within the wider study, as a gas. One of the discussion stations at the knowledge-exchange focus group event[38] was coordinated by scientists who explained to the assembled group of farmers, advisers and representatives about their work measuring carbon as carbon dioxide emitted from soil[39]. Figure 5.2 below shows one of the scientists, Sue, explaining how the infra-red gas analyser works. It is two vessels (which look like divers helmets in the photo). One is covered in foil, and so is impermeable to light, and the other is clear – "it's just a very simple plant cloche with a bit of soil pipe on it". One at a time they are placed over a piece of land, in this case grassland, "and the whole idea is it is enclosing a bit of air in here, what it will tell you over time is how much CO_2 is building up". The clear cloche allows light in and so the plants can photosynthesize and store carbon (in their tissues and

[38] Date of focus group (and so quotes) was 11.6.13.
[39] Methane (CH_4) was mentioned at the same event, as a carbon (greenhouse) gas that is more expensive and complicated to measure.

eventually in the soil via roots or dead tissue) and at the same time the soil biota is releasing carbon dioxide from the soil via respiration. The foil-covered cloche doesn't allow for photosynthesis to occur and so the only carbon dioxide flux will be that of emission. The measurements (parts per million of CO_2) are shown on the screen of the meter (on top of the box in the photo). The net amount of carbon dioxide being emitted or stored is calculated by taking the measurement from the covered cloche and subtracting it from that of the clear cloche. Soil carbon storage is the absence of carbon as a gas in the cloche. So this is still soil carbon, but soil carbon which relies on a different set of protocols, equipment, routine, understandings and inferences than soil carbon as SOC.

Figure 5.2 Sue demonstrates how to use the infra-red gas analyser.

Sue brings with her not just the equipment but also experience of carrying out hundreds and hundreds of these measurements to establish which types of land are storing soil carbon and which are emitting soil carbon – and it turns out that the plant species present are important, as well as the light conditions. So even if local conditions mean that one example does not perform as expected Sue can draw on her experience and understanding, as part of the performance, to explain what she thinks should be happening under these local light and vegetation conditions:

> *I'd expect today, just from experience of knowing, even though there's only a little bit of sunlight, it probably is photosynthesising more than it's respiring so it [the piece of land] is probably a net fixer of CO2 at this time of day (Sue, scientist, focus group, 11.6.13).*

5.3.3 Soil carbon performed as full of fungi

Soil carbon was also described at the focus group in terms of a fungi-rich soil. In order for the soil to be fungi-rich, it will simultaneously be bacteria-poor, as the different organisms proliferate in contrasting conditions. For fungi to proliferate the soil will have more carbon than a soil where bacteria proliferate. In this instance soil carbon is the relative amount of an organism, in comparison to another type of organism. Below, one of the scientists explains how they are working on ways to manipulate the biology of the soils to bring about benefits in terms of soil carbon storage:

> *what we're trying to do in our research is to look at how we can actually change the abundance of those [soil] organisms, change their diversity, in a way which reaps benefits for nutrient cycling, making it more efficient, but also brings benefit for things like carbon storage in the soil and also the emission of greenhouse gases like carbon dioxide, methane and nitrous oxide.*

This manipulation of micro-organisms in order to mitigate carbon emissions at a biosphere level introduces a new scale of technological intervention into soil carbon storage. This focus on manipulation at the micro-scale contrasts with current policy discussions around land management change, which focus on macro-scale landscape alterations: afforestation, where carbon is sequestered in tree biomass as well as being fixed in the soil through the photosynthesizing trees; re-wetting land, as wetter soils tend to contain more carbon overall as there is less carbon oxidation by soil microbes; and, changes to existing farming practice, such as reduced liming or fertiliser application on certain soil/vegetation types (see below).

5.3.4 Tensions within Scientific narratives

These three stories reveal different versions of soil carbon in Scientific narratives – dependent on scale of examination, chemical state, and whether they are considered as a store (stocks) or a process (flows). The multiplicity of soil carbon starts here in the multiple ways that soil carbon can be understood as matter-of-fact. Scientists may argue that these are representations of an immutable object of soil carbon, however, through Lansing's (2012) interpretation I suggest that these acts of revealing soil carbon are "at once abstract representations and practices that are imbued with a materiality" and that the "slipperiness between abstraction and materiality" means that such practices are not just descriptions but also artefacts of the performance through which they were revealed (Lansing 2012, 207). They become material interventions which are emergent, deployed and have effects among the collective of human and non-human actants who, through their actions, perform and experience soil carbon in the landscape.

What happens when these Scientific matter-of-fact performances of soil carbon are introduced into the messy, social world of farming and what happens when they don't match up to local farm conditions and experiences? Firstly, I introduce as a tension, mismatches between universal scientific prescriptions for liming and managing for certain vegetation types to enhance soil carbon storage and soil carbon as locally-performed. The prescriptive booklet produced by the LDNPA 'Managing Land for Carbon: A guide for farmers, land managers and advisors' (Hagon et al. 2013) advises that liming[40] soils which contain a high proportion of organic material will result in a reduction of carbon stored in the soil and this has been verified in a number of studies (e.g. Hobara et al. 2013; Leifeld et al. 2013). However, a different performance of soil carbon is also at play:

> *the general idea is liming will reduce carbon storage; it will increase breakdown of organic matter and increase carbon loss. But we have found that it can have the opposite effect: so it [adding lime] can actually increase carbon, because what it does, well it breaks it [carbon-containing organic matter] down and the*

[40] To treat soil with lime – a calcium-containing inorganic material - to reduce acidity and improve fertility or oxygen levels.

matter gets incorporated in the soil aggregates and it gets locked up in the aggregates where it's protected (scientist, focus group, 11.6.13)[41]

Uncertainty, or local dependencies leading to different performances of soil carbon, is made explicit in some of the scientific literature (e.g. Ostle et al. 2009; Bussell et al. 2010; McSherry and Ritchie 2013) but the Science of soil carbon management is being presented and fixed in booklets and conversations with scientists and policy officers as matter-of-fact. We can observe the effect of this mismatch in action on Farmer B's case study farm. During the walking interview (4.3.15) we reach a grassy field which, Farmer B explained, is *"improved land"* which has had more lime added to it, and had the bright green colour associated with fertile, improved grassland. It was one of his *"best fields"*. We discussed the LDNPA booklet's advice regarding liming – *"the leaflet [from the LDNPA] says that you should reduce liming as acid soil stores more carbon"* (Farmer B). Reducing liming (and allowing the pH of soil to drop) in 'in-bye' fields is seen as problematic by many upland farmers due to an associated drop in grass production. Farmer B therefore associated soil carbon with acidic, less productive, browner vegetation. Yet the measurements and our map said that the bright green field in front of us was storing more carbon than the surrounding, duller green, land. Farmer B confirmed that the surrounding land has had less lime added and was surprised that the map showed it to have comparatively less soil carbon. We discussed this inconsistency between universal prescription, local measurement, experience and any possible explanations, such as it being the 'wrong' type of soil[42]. Farmer B then explained this inconsistency away through reference to the general complexity of the whole system and then, later in the conversation, talked about it as something which undermined the usefulness of the booklet. It remained as an unresolved tension.

This was not a unique occurrence in the study – universal management prescription (derived from the LDNPA booklet) clashed with other versions of soil carbon on the case study farms. On Farmer E's farm, grasslands dominated

[41] Also described in Fornara et al. (2011).
42 Perhaps the soil doesn't have enough organic material to make this prescription work – as soils with lower amounts of organic material have been shown to increase soil carbon storage with liming (Paradelo et al. 2015).

by bracken fern *(Pteridium aquilinum)* did not store more carbon than grasslands without bracken (Chapter Three). This was in contrast to the booklet's advice and to farmer expectation, when brown equals more carbon – *"they always reckon where the bracken grows there's a lot of soil. And it's all mainly brown, if you dig in"* (Farmer B, case study walking interview, 4.3.15). The association between bracken and carbon was continued on Farmer E's farm when a farm neighbour told us he had heard that bracken was associated with carbon and expressed a hope that this wasn't true. The proliferation of bracken is another tension on farms in this region as a recent herbicide ban has drastically reduced available methods of controlling this plant, which harbours disease-bearing ticks and shades-out grass.

On the same farm grazed oak woodland unexpectedly stored a lot more carbon than the ungrazed woodland. The woodlands were adjacent, on the same geology and according to the booklet and other scientific accounts the grazed woodland should have stored less soil carbon, or perhaps the same amount. When this incongruence was discussed with Farmer E it transpired that he was getting paid through a government scheme for enclosing the ungrazed part to make it a 'livestock excluded woodland' – the part that was storing less carbon (although it should be noted that the livestock exclusion is not for carbon management reasons).

As a final example of this type of tension we return to informal derogations of agri-environment management contracts – introduced at the beginning of the chapter as part of the history of tension and frustration in this region. AES do not include management for soil carbon at present; however, one of the management prescriptions often applied in this region is reduction in stocking density (reducing the number of livestock on a given area) to encourage plant biodiversity in areas of priority habitat. The same management intervention is suggested for increasing soil carbon stocks (by scientists at the focus group event, in the LDNPA booklet and in the literature e.g. Bol et al. 2012). Another case study farmer, Farmer W, had been told ten years ago to take his cows off some commonland in order to comply with this management prescription, *"Now he was told that some species of plant are becoming too dominant - so they [the* *policy officers] want the cattle put back on. Farmer W says he told them that this would happen"* (Farmer W, case study interview, field notes 2.5.12).

What happens when we act *despite* or *with* such mismatches and incongruities? This is not, of course, a new issue. Previous AES have either dismissed these mismatches as 'environmental heterogeneity' or dealt with them as "social factors, political dimensions or irrational aspects" as distinct from the matters-of-fact (Latour 2004, 23). The schemes continue to operate, in spite of mismatches and incongruities, by application of 'informal derogations' of the management contracts, which are locally-negotiated between farmer and policy officer. Such derogations proved to be a focal point for farmers in our discussions around the possibility of 'farming for soil carbon' – the majority of the time as a feature of frustration and conflict (also written about in Morris 2006). Even if we accept the utility of informal derogations and ignore the set of negative relations which accompany their use, are informal derogations fit for purpose/the right approach when planning for and delivering the management of soil carbon within the farm landscape? We return to this question and in the section 'Comparing the embodied experiences of managing for carbon with managing for other environmental goods' we discuss the wider question of whether we should linearly apply learning from previous schemes to schemes which encourage or impel farmers to manage for soil carbon.

I now introduce a second type of tension - wherein soil carbon storage is in opposition to 'productive' farming. We encountered many instances where carbon-rich landscapes were described implicitly or explicitly as in opposition to 'good', productive farmland: *"The better the land is for agricultural purposes the poorer it is for carbon storage"* (Farmer W, case study interview, 4.3.15). It is known that the amount of soil carbon stored in the landscape is related to vegetation type (as referred to above, explained in Bardgett et al. 2014 and in Chapter Three) and at the focus group the scientists talked about their research into how different grassland plant attributes can lead to different soil carbon outcomes:

> *So it might be that longer roots could help with carbon allocation because the carbon can be transferred from the leaves to the root and transferred deeper*

into the soil and stored in the soil for much longer. Or it might be that if a plant has more of a woody consistency of its tissue then its stores the carbon in its tissues for much longer and it sort of stays in the plant instead of going back as litter or returned back to the soil system (scientist, focus group, 11.6.13)

The attendant farmers were keen to know which grassland plant species promote soil carbon storage:

Farmer: Have you got any clues now then as to what plants are more efficient at putting carbon into the soil, or is it too early days?
Scientist: It's early days, but there is a lot of emphasis on the legumes, particularly red clover, a colleague of ours is working on an experiment where it showed that the presence of red clover was better for carbon storage in the soil … But the problem with all these kind of things is that the plants which are probably best for carbon storage are those which are probably the worst for yield (focus group, 11.6.13)

At this point farmers voiced dissatisfaction with the perceived mismatch between scientific endeavour and farming practice. The scientists soon reframed the discussion and zoomed out to a wider scale to consider agricultural grasslands at a scale in which they become useful again for soil carbon storage:

the grasslands are the backbone of the livestock industry and food production but more and more it's been recognised that they're important for carbon capture (scientist, focus group, 11.6.13)

We can see through this exploration of how soil carbon is performed through scientific and policy interventions that Scientific matters-of-fact have produced mixed messages as to whether these are 'good' or 'bad' landscapes for storing carbon. Rather than stopping here with a critique of soil carbon as a Scientific matter-of-fact, I now bring in other materialities of soil carbon. In the section below I first explore the farmers' and my embodied experience of soil carbon on the farm and then compare it to the embodied experience of more tangible environmental goods for which farmers have managed in the past, such as plant diversity and weasel habitat.

5.4 Soil carbon as embodied experience

Ormond and Goodman (2015, 120) examine the practices by which the "messy materiality" of greenhouse gas emissions, being accounted for in the production of a pint of milk, are rendered legible as discrete entities by use of carbon counting boundary objects. Boundary objects inhabit different knowledge communities and are both plastic enough to adapt to the local needs and constraints of the different parties employing them, yet are immutable enough to maintain integrity across sites (Star and Griesemer 1989). Boundary objects not only enable soil carbon to be made visible and knowable for these different communities but they construct administrative domains and stable framings, amenable to certain forms of political and economic rationality (Ormond and Goodman 2015, 129). Using the concept of boundary objects enables us to highlight the tensions which emerge when data collection models, which are to make complex technical and biophysical on-farm processes commensurable, meet the messy and uncooperative social world of farming and how the models, or the interpretation of the models, are required to adapt. Here, I propose that we are not seeing the adaptation of soil carbon to the messy social world of the farm through boundary objects, but are gazing upon different, mutable objects of soil carbon. By suggesting that the tensions and mismatches we highlight cannot be explained away by reference to "social factors, political dimensions or irrational aspects" as distinct from the matters-of-fact (Latour 2004, 23) I extend this engagement with soil carbon and consider the practices and embodied aspects of soil carbon; how soil carbon is performed at different sites by those involved in its management – the farmers.

Embodiment is the experience of being in the world as lived, enculturated beings. It is a non-dualistic way of thinking about the body and being human, starting from the perspective that is there is no separation of mind and body (McHugh 2007). Embodiment is explored through situatedness in the research process and in the creation of soil carbon maps in Chapter Two, drawing on Feminist GIS critiques. Here, I consider the corporeal experiences of soil carbon in the landscape as a way of exploring a different way of knowing soil carbon (different from the dominant scientific way of knowing soil carbon). The tension between scientific ways of knowing and associated practice and farmers' embodied experience of the landscape is alluded-to here by one of the farmers at the focus group (11.6.13):

this is something that really frustrates me seeing what, you know, the farming in practice and then the scientific side of things. The two just don't add up and the communities are just not talking to each other or not sowing the right kind of scientific knowledge into the practice to make things actually work.

5.4.1 Soil carbon as difficult, wet and unproductive landscapes

During the focus group event, scientific versions of soil carbon were dominant in any discussion involving scientists, but when farmers were discussing carbon amongst themselves, with farm advisers or with farmer representatives the materiality of soil carbon changed. Within the study transcripts, the dominant experience of soil carbon in the landscape was as negative embodied experience. Carbon-rich landscapes were described as difficult to farm, *"they really aren't farmable"* (farmer, focus group, 11.6.13), with varied embodied reactions to this difficulty *"this is challenging land, yes, we kind of get our kicks farming this really, really difficult land"* (Farmer W, case study interview, 4.3.15) and *""It is hard work. Not good fertile land ..." Farmer E seemed tired – his energy dipped when talking about it"* (case study interview field notes with Farmer E, 17.6.14).

In the UK, policy narratives around management for carbon storage often focus on afforestation (as explored in the section 'Policy implementation of soil carbon as matter-of-fact'). However, management interventions can also include re-wetting land schemes[43]. In this region re-wetting is usually achieved by blocking ditches ('grikes' or 'grips') which were originally dug for drainage to increase livestock production on the upland peat habitats or 'moors' (which tend to become dry heather-dominated heaths after drainage). The wetter carbon-rich landscapes were described by farmers as landscapes being *"managed for everything ... good grass, good sheep common but quite a lot of Sphagnum, rushes, Nardus [stricta] grass, not much heather. Not been drained in the last 100 years. Holds a lot of water and carbon"* (farmer, focus group field notes, 11.6.13).

These carbon rich landscapes are also places where things get stuck – sheep, equipment and soil scientists. During one sampling expedition on Farmer E's farm I was following my navigation device to a previously-located sampling site. I was in a field where the ground was fairly flat, cows were dotted about. I was not

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[43] Often within 'integrated catchment management' initiatives undertaken by water companies.

paying a great deal of attention to where I was going. Quite suddenly I was thigh-high in mud, in carbon-rich mud. I was rescued, with over-played ceremony, by my field assistant with the aid of a soil corer and spade laid across the liquefied ground. After recounting my experience to a tickled Farmer E the farmer then explained how he has lost sheep in that same spot. A sobering revelation about the qualities of some carbon-rich areas, and one illustrated again in this fragment of discussion between farmers, from the focus group (11.6.13):

> *Farmer 1: Some of the bog is real genuine blanket bog you know (mimes foot being stuck)*
> *Farmer 2: That's a good demonstration, perfect in fact, yeah*
> *[Laughter]*
> *Farmer 3: So it holds a lot of water?*
> *Farmer 1: It holds a lot of water, yep*
> *Farmer 2: And carbon*
> *Farmer 1: Carbon, yeah*

These wet landscapes are also talked about as in opposition to the "good old days":

> *I would consider wet land not to be much use really for farming… some of these environment schemes at the moment are paying the graziers to sort of stop up the ditches that have been dug in the wet land … A lot of this was drained, that was in the good old days when they were trying to promote agriculture and production. We had a grant scheme on when I was about [Farmer E's son's] age and we put a lot of good drains in but some of them are starting to block, so there's wet bits through it now (Farmer E, case study interview, 17.6.14).*

Our data begins to reveal that carbon-rich spaces, so valorised in current policy, are often viewed as problematic landscapes by farmers where soil carbon is sensed and experienced in ways divorced from the scientific performance.

5.4.2 Soil carbon as problematic plant species

Carbon-rich landscapes were also associated by farmers at the focus group and by case study farmers with the spread of three problematic plant species (although all three are seen as desirable for biodiversity aims). The first two species were explicitly associated with the re-wetting of land:

1. *Juncus* species (hard and soft rushes) are prevalent on wetter land:

When a field becomes infested with rushes it becomes a very non-production field not only for farming but for wildlife as well. Because when rushes die back they leave big mounds of earth and to be honest with you it's a barren landscape with rushes in it, that's it (farmer, focus group, 11.6.13).

(A managed amount of rush cover is important for breeding wader habitat).

2. *Narthecium ossifragum* (Bog asphodel) is poisonous to sheep (Strugnell 2014) and spreads as a result of re-wetting land (however, it is also seen as a desirable species for biodiversity conservation in upland wet habitats). It was independently mentioned by all three of the case study farmers in discussions about re-wetting schemes.

3. These 'problematic' carbon-rich landscapes are not confined to wet conditions – it was generally accepted by the scientists at the focus group event that reducing grazing impact (by lowering sheep stocking levels) would enhance soil carbon storage, a management intervention also suggested in other documentation (e.g. Bol et al. 2012; Hagon et al. 2013). However, farmers cited previous livestock reductions, a component of AES for plant diversity reasons, as a cause of land becoming dominated by *Molinea Caerula* (Purple Moor-grass), which is a poor quality fodder grass (although is a major component in the Purple Moorgrass and Rush Pasture Biodiversity Action Plan habitat): *"in the ten years the Common has been in the ESA [an agri-environment scheme], the Moor grass, which is the white grass that animals don't tend to graze, has come back. I can't believe that that is the type of grass you're really looking for growing back"* (farmer, focus group, 11.6.13).

As explained in previous chapters individual plants, the prevalence of different plant species and overall plant diversity will affect soil carbon storage and fluxes. The agency of these proliferating plants is unaccounted for in versions of soil carbon as wet land or land with less sheep. Stocking density is already a contentious issue for many farmers; with some arguing that densities are getting to ‘tipping point’ whereby hefted flocks[44] are straying onto land under others’ grazing rights (‘encroachment’) because the sheep are so sparsely distributed. The loss of heft means extra hard work for farmers trying to round them up – *“it is a beggar when you go to gather them in”* – and may even result in farmers having to give-up farming – so ‘lost sheep’ also have a transformative power in this soil carbon collective.

There is also a more hidden concern to this issue of reducing stocking density. Through the case study work it was revealed that there is a unique number of sheep or a stocking density that farmers hold as necessary to *“feel like a farmer”* (Farmer E, case study interview, 25.2.13). This ‘number’ may not be articulated and may be present as ‘just a feeling’ but each case study farmer alluded to it at some point during our discussions. The sense of being a farmer is tied up with material aspects of farming like sheep stocks and the engagements between sheep, farmers, and the landscape – in this way farming can be seen as emotional, embodied, affective labour that involves complex interconnections between the human/non-human, material and affective. When considering the future of farming in this region, the importance of these entanglements is clear. Farmers feel like farmers, like good farmers, when they are farming for production and much of the management interventions associated with accumulating or maintaining soil carbon feel in opposition to this, challenging embodied feelings of ‘productive’ farming.

5.4.3 Comparing embodied experiences of managing for carbon and managing for other environmental goods

The motivations behind farmer engagement with AES (or ‘farming the environment’) was not a focus of the study, but it was discovered that the embodied experience of previous AES outcomes was important for the farmers.

[44] “Hefting is a traditional method of managing flocks of sheep on large areas of common land and communal grazing. Initially, sheep had to be kept in an unfenced area of land by constant shepherding. Over time this has become learned behaviour, passed from ewe to lamb over succeeding generations. Lambs graze with their mothers on the “heaf” belonging to their farm instilling a life-long knowledge of where optimal grazing and shelter can be found throughout the year. On many tenanted farms there is a ‘landlord’s flock’, which goes with the farm whenever there is a change of tenant. This ensures that the land continues to be successfully grazed by its resident ‘hefted’ flocks of sheep. The Lake District is particularly well known for hefting but it is also practised on common grazings in other areas of the country” (Department for Environment, Food and Rural Affairs 2015).

The experience of creating upland hay meadows was very important for case study Farmer E – hay meadows have very sensory outcomes: you can see if they are species rich, the colour contrasts of the different plants is striking, the hum of the insects is ever-present, the smell of hay is incredibly emotive, as is experiencing the practice of hay-making. These were all positive features Farmer E alluded-to when discussing whether it was *"worth"* him continuing with their management (20.6.12). Another case study farmer, Farmer W, talked about his positive sensory experience with weasels and their habitat:

> *"I have weasels in a hole in my wall and I just love them" (he lit up when talking about them). "Young habitats can be good. Quarries are good aren't they? We have some limestone quarries near here and I love sitting in them watching the weasels with the tweeting all around. Could sit there for ages" (interview field notes, 2.5.12)*

Contrast the above embodied experiences with the embodied experiences and descriptions of carbon-rich parts of the farm above – as problematic and *"nuisance bits"* of land (Farmer E, case study interview, 17.6.14). Soil carbon is not visible in the same way as hay meadows and weasels; it reflects vastly different embodied, material, and affective entanglements. As experiencing the outcomes from novel management practice is important, as a visible cue or through other senses, this suggests that we should not be applying learning from AES as part of a linear progression towards improving the planning and delivery of carbon sequestration schemes on farms, but we should be considering a different politics. This politics should include explicit discussion of the sensory, embodied experiences of performing different types of farming to management for agri-environmental goods, and recognition that these experiences are inconsistent and vary with whether you are working for biodiversity or for soil carbon stocks. These sensory, affective, embodied experiences should be examined as performances of soil carbon with the same legitimacy as scientific maps, and within a forum where these different knowledge forms are equally open to debate (Waterton and Tsouvalis 2015).

5.4.4 Do these different soil carbon materialities over-spill the farm?

In the introduction I referred to a version of soil carbon which connects to global policy and financialisation projects. The "new regime of carbon accounting" (Ormond and Goodman 2015, 119) is pervasive and far-reaching. It is therefore unsurprising that, even in an exploration of the materiality and embodied experience of soil carbon on a farm-scale, it 'spills-over' (Callon 1998) attempts to contain it in farm spaces and attempts to map it. As Tsouvalis (2015, 9) explains "Materialities leak, spread, and proliferate". Here we record a farmer's global experience of soil carbon on his farm – in this case soil carbon as performed on his farm in the Lake District by planting trees as an offset for emissions created in China:

> *the British Woodland Trust are really helpful, they support us in loads of different ways. They bring specialists in to give us advice and they'll buy trees, you know plants for us and pay for the tree guards and I said to the local guy, "How can you afford to do this?" And they actually support themselves by trading carbon with China. Every time China, you know, emits all the stuff that they do out of their factories there's somebody in Britain plants them 100 trees. So China is paying for our environmental management indirectly through us planting trees and consequently storing carbon. You know if you are ploughing them [peaty soils] all the time you just wasting millions tonnes of carbon all the time aren't you? It's OK though the Chinese pay for it – laughter (Farmer W, case study interview, 4.3.15)*

Such carbon-rich, treed landscapes act as a counter to carbon-emitting landscapes in China. It is in these ways that the soil carbon collective also becomes international and therefore links the experiences, labour and hopes of carbon on farms to new international markets and incomes.

5.4.5 Soil carbon – embodied experience of hope for the future

As stated above, the management of carbon in these landscapes is playing out against a history of engagement with AES, whereby farmers have been paid for 'income foregone' in managing for environmental goods. Many of the farmers in this region have taken part in such schemes and their interest in soil carbon management can be partially attributed to their need for additional income. A report on agriculture in the nearby Loweswater Valley nearby found that in 2008 a typical farm business income from 'traditional' agricultural sources (production of food and other crops) was just £7,000 per year (Rockliffe 2009) and half the hill farmers (a sub-section of upland farmers which represents two of my case study farms) in England lost money from their actual farming activities in 2011/12 (Harvey et al. 2013).

Soil carbon has been explored as a negative embodied experience and as a problematic landscape in the previous sections. However, across the farming interviews and focus groups there was an interest in how carbon farming might work in the future, recognition that it is a new topic and one where farmers could work *with* scientists and policy makers – *"I mean farmers are with science in that case. Yes we need to make better use of that [problematic] land and we could do that by [carbon management] schemes"* (farmer, focus group, 11.6.13). There was a tangible feeling of excitement and interest at the focus group meeting – *"I'm just really interested in how this might work for us in the future"* (farmer). At the focus group people gathered around a new topic that is *"on everyone's lips"* and *"in the farming press"* (Farmer E, case study interview, 17.6.14). Soil carbon management is particularly significant for farmers who recognise the need to diversify on-farm income and 'non-production based support' to make the farms financially viable, but there was also an interest in soil carbon for the *"health"* of the land, *"helping with the livestock"*, learning more about this *"completely new way of thinking"* and in discovering *"how it works in the plants and in the soil"* (farmer, focus group, 11.6.13; Farmer E, case study interview, 17.6.14; Farmer W, case study interview, 25.2.13). I found that soil carbon sequestration is seen by many farmers as a way to ensure that they, and future generations, can continue farming on family farms and perhaps as a way to 'save' farming in this region – as a space of hope. It was also embodied with feelings of excitement and relief for farmers who have sons or daughters who want to take over the family farm and for the next generation farmers themselves:

> *Farmer E is third generation. His youngest son is keen "it would be nice to carry it on" (case study interview field notes, 20.6.12) and two years later I had a discussion with his son about him finishing school and starting college in Sept in 4 days and helping on the farm. He is excited about it (case study field notes, family member, 17.6.14).*

In Chapter Two I theorise how these apparently incompatible spaces of hope and problematic land can be juxtaposed (not reconciled) and can, like the other versions of soil carbon explored here, be acknowledged and worked-with within the same process.

5.5 Conclusion

This study highlights how the current, singular, ways of performing soil carbon (and other environmental goods) through Science and policy, restrict what is possible. Using methods as intervention the research approach considered senses, bodies and histories as part of the analytical process (Rose and Tolia-Kelly 2012). The study also answered, through consideration of a soil carbon collective, calls within the human geography and natural resource management literatures to consider "the difference assemblage might make to methodology" (McFarlane and Anderson 2011, 164) and to apply the "dense descriptions" in Actor Network Theory (ANT) and assemblage theories 'on-the-ground' and make them relevant to policy (Urquhart et al. 2011, 245). The methods show how such ontological multiplicity can be engaged-with and revealed within a project that also engages with the epistemological validity, quality and accuracy of scientific investigation. The empirical data describes soil carbon as multiple; loose human and non-human collectives that gather around, perform, affect and are affected by each other – whether these soil carbons are experienced on-farm through land management practice or other farmer lived-experiences, or as Scientific or policy performances. Thinking in this way enables us to examine how failure to recognise the movable emergent properties of the object under study leads to tension. In Chapter Two I set out a way of working with this ontological multiplicity to create map spaces for new conversations about managing land for soil carbon. Soil carbon turns out to be a very different matter-of-concern when compared to other environmental goods managed-for in previous AES. In particular its wetness, the way it makes land difficult to manage and its performance as unproductive land, with problematic plants and lost sheep forming part of its collective – leads us to suggest that soil carbon needs to be attended to within policy intervention in a very different way from hay meadows, weasels and plant diversity.

5.5.1 What does it mean to make these multiple soil carbons visible?

Making soil carbon visible has a performative power which shapes the worlds it is embroiled in (see Chapter Two and Tsouvalis et al. 2012) and this revealing or making visible can render alternate versions of the entity invisible, impotent and mute (Latour 2004, 10). Indeed, the same research and policy tools (or method assemblage) which made soil carbon visible can, paradoxically, also make it invisible, if certain practices or modes of seeing are privileged at the expense of others (Law 2004). Through this chapter the privileging of Scientific ways of knowing soil carbon in farm spaces is made explicit, situated in theoretical and empirical research on exclusion and privileging of knowledge (e.g. Berkes 1999).

The spatial predictions of soil carbon made through Scientific performance led to on-farm discussions about how carbon-poor land can be made to store more carbon – which became a normative concept to guide decision-making. Revealing wet land on the farm as rich in soil carbon led to discussions which identified potential land to re-wet. However, the Scientific methods failed to account for wet, carbon-rich land as proliferating problem plant species which are transformative and part of the dynamic cycle of carbon storage and emissions themselves. The plants' agency also extends to affecting the health of livestock and so the 'health' of the farm – the same farm that is increasingly enrolled in international policy as one which (could or should) actively manage for soil carbon. Attending to these different versions of soil carbon as multiple entities and thinking the social and the scientific together recognises that they will assert their transformative power anyway (Tsouvalis et al. 2012). We therefore suggest that it is better to attend to these multiplicities early on. The alternative is to try and contain the mismatches and tensions (perhaps with informal derogations of contract) which can lead to failure to adhere to management contracts and missed environmental targets.

5.5.2 How to deal with incompatibility

This study has revealed soil carbons that depend-on but are also incompatible with each-other: Scientific soil carbon, soil carbon as spaces of hope and soil carbon as problematic embodied experiences. Foucault's third principle of heterotopias helps us to think about these different versions of soil carbon together in the landscape: “The heterotopia is capable of juxtaposing in a single real place several spaces, several sites that are in themselves incompatible” (Foucault 1986, 26). Theorising spaces through a politics of hope is considered productive in other, very different, settings. For example, Mavroudi (2013) explores these new methods to overcome political impasse and create hope and peaceful alternatives in spaces of conflict. In Chapter Two I used mixed methods GIS, informed by critical and feminist critiques of GIS, to apply digital mapping as process to hold these different, spatial, objects of soil carbon on the farm in juxtaposition, by enabling the different materialities of soil carbon to be mapped onto the same space. In that chapter there is more detail on the benefits of treating the mapping of farms as a process and as a way of exploring frictions and contestations – the idea that the set of relations that delineate a landscape or a site are not reducible to one another and that the surfaces we can juxtapose may be incompatible (Foucault 1986).

5.5.3 What has this process opened-up?

This study has shown that scientific performance and economic rationality are not the only ways to know soil carbon. Through a mixed methods intervention I suggest that considering soil carbons’ material multiplicity can be an alternative to the typologising discussions which frame farmers in relation to Scientific versions of soil carbon. These are questions of ontology and epistemology. Although the use of more-than-human and object-orientated politics is an approach often applied in geography, sociology and allied literatures, it is a radical departure for most agricultural environmental management discourses. It is hoped that along with the rest of this thesis, this methodological intervention is seen as one actionable way of bringing critique and new ways of thinking to what can seem to be intractable problems and stagnated relationships within agri-environment management settings. By refusing to focus on the contradictions between carbon as Scientifically performed and as corporeally-experienced, but by acknowledging and working with tension and ‘incompatibility’, we challenge dominant ontological understandings of soil carbon and its sequestration in the landscape.

5.5.4 Next steps for research

This chapter has hinted-at but not fully-engaged with an assertion that it is not just about the knowledge and skills employed in performances of soil carbon, it is about labour and effort too, and the combination of these things. World-making takes effort (Mol 2002) and the farmers' 'hesitations' (Stengers 2010) about managing farmland for soil carbon are born of engaging with soil carbon in the landscape and finding it hard work and problematic. Accounting for labour and opening up for debate its role in discussions about managing farmland for soil carbon is a further challenge to working with the ontological multiplicity of soil carbon.

This chapter has also hinted-at the ability of carbon to 'cycle' without human intervention – its liveliness. Perhaps soil carbon is a prime example of Bennett's (2010) ontological multiplicity: in its refusal to be wholly animate or inanimate; alive and dead matter entangled and consisting of microbes, soil animals, plants and their products – a continuum of degradation; its definition dependent on scale, context and state; both a stock and a flow; dependent on geology but with the organic elements emphasized by science and policy. It is a human/non-human assemblage of doing and effecting. Is it any wonder we experience policy stagnation and impasse when we try to discuss soil carbon management without considering it as an actant in its own multiplicity?

6 Conclusions and Future Work

6.1 Introduction

This thesis has taken a novel approach to mapping soil carbon on farms, in a region which contains landscapes important for soil carbon sequestration. This research is highly relevant and timely given the political importance of these landscapes in contributing to global climate change mitigation, the current interest in participatory approaches to managing the environment, and new developments in critical and qualitative GIS (QualGIS). Although the focus of the study is the north west of England, the broader findings are adaptable to other geographical areas and to other spatially-explicit environmental problems. The research makes a clear case for the consideration of interdisciplinary Mixed Methods Mapping (MMM) within agri-environment schemes and other decision-making approaches to managing socio-ecological systems. It raises questions about which knowledge practices are privileged within agri-environment schemes and how other ways of knowing soil carbon can be made to count. The thesis then goes on to provide a theoretical and methodological foundation for addressing these questions. Headline contributions by chapter and suggestions for further research are made below.

6.2 Thesis summary and headline contributions

6.2.1 Chapter Two

The research presented in this thesis used an interdisciplinary mixed methods approach that integrates spatial, quantitative and qualitative data collection, and the analysis and representation of different versions of soil carbon within farm spaces. This was achieved through an iterative approach (Kitchin et al. 2013 drawing from Brown and Knopp 2008) outlined in Chapter Two. There are two headline contributions from this chapter: firstly, the research showed how Feminist QualGIS practices can be applied to environmental management using a MMM approach; and secondly, it is a contribution to the literature on doing inter-disciplined research.

Chapter Two highlights the benefits of treating the mapping of farms as a process and of recognising that the map surfaces we can juxtapose (overlay) are not necessarily superimposable (compatible). It shows that the utility of mapping is in what is revealed as the maps emerge, rather than as a final representation of a farm. The need to keep accounts of the farm open was a clear finding and is linked to the ability (agency) of stakeholders to contest other versions and representations of the farm. Keeping accounts open and editable provides an alternative to maintaining a consensus from which to manage land through 'fixes', such as informal contract negotiations and derogations. Conflicts and contested map surfaces are used as places to start interesting conversations and ask new questions, rather than 'smoothing' them over to create a landscape of apparent consensus whilst frustrations continue to fester off-map. Applying a MMM approach enables conflict to be accepted as part of the decision-making process and not something to be avoided; something that can be recorded without the need for an immediate decision as to the 'correct' version of the farm or of the dominant form of knowledge.

MMM uses quantitative science-ready data and qualitative locally-sensitive data in a way that is attentive to QualGIS as a theoretical and practical tool. MMM includes different forms of knowledge and experience and is a 'substantive' engagement with participants. Participation was attended to, not as a "flat equality of relativism", but as the "equality of opportunity within deliberation" (Cook et al. 2013, 758). In this instance, participation enabled different versions of soil carbon to be recorded and made to count (links to Chapter Five), whilst delivering robust scientific findings (Chapter Three) and exploring the utility of different ways of knowing the farm within a policy framework (Chapter Four).

Chapter Two also provides empirical evidence of the current role of maps and other spatial representations on farms in this region, with emphasis on mapping within AES. This evidence uncovered tensions around how farms are mapped within the AES enrolment process, access to externally-held data, and how such data is applied 'on the ground'.

The findings from this chapter have implications for natural and social science researchers interested in participatory environmental management processes. The research is also relevant to the work of practitioners – those most often tasked with the challenge of achieving a process and outcomes which are both scientifically robust and sensitive to a range of stakeholders' knowledge systems, values and priorities. (For a start to this knowledge exchange work see Appendices V-VIII. Future work will include dissemination of maps and findings to case study farmers and a summary for a local farmer network website and a practitioner blog site).

The second headline contribution of Chapter Two is the way it lays out the iterative nature of the research process as a way of contributing to the, currently small, literature on being an inter-disciplined researcher (IDR) and on doing an interdisciplinary PhD. There have been a number of papers published which focus on the interaction and joint working needed to bring the knowledge claims and conventions of different disciplines into dialogue with each other (Lowe and Phillipson 2009; Donaldson, Ward, and Bradley 2010). These dialogues occur internally for an IDR. Although problematic for a researcher who desires a stable research framing throughout the research process, experiencing this internal dialogue develops insight and empathy within the individual IDR, which can then be applied within multi-researcher interdisciplinary projects. The current lack of focus on the role IDRs play/could play in the research community is surprising in a world rapidly waking up to the necessity for truly interdisciplinary approaches to tackling 'messy' and 'wicked' problems. As researchers engaged in interdisciplinary projects "struggle to penetrate the knowledge and ideas informing other researchers' disciplines" (Marzano et al. 2006, 189), empathy for and insight into different research positions, disciplinary constraints and opportunities becomes important. As the idea that an individual can hold an interdisciplinary way of thinking and working becomes accepted it seems sensible to nurture a generation of IDRs who have faced an internal struggle to produce coherent interdisciplinary research, despite different disciplinary ideas of rigour and soundness.

There are a number of areas of further work that flow from the reflections in Chapter Two. For example, recent progress in environmental management has been strongly influenced by advances in remote-sensing and the collection and analysis of other forms of 'big data' and by normative policy framings dominated by the largely-quantitative and positivist concept of 'ecosystem services'. QualGIS offers theoretical and methodological tools for creating outcomes that are conceptually rich as well as practically transformative. Therefore, there is a need for further investigations into how QualGIS can contribute to processes which embrace the potential contributions of big data and the 'ecosystem services' framing whilst attending to other epistemologies and ontologies.

6.2.2 Chapter Three

The main contribution of Chapter Three is to reveal the utility of easily-accessible on-farm vegetation data in predicting the distribution of soil carbon stocks at a farm scale. The Farm Environment Plan (FEP) vegetation mapping approach is being taken forward in the new Countryside Stewardship scheme, "with one or two tweaks" (D. Martin, Natural England, pers. comm., April 2015). Other such datasets exist on farms and some of these could hold potentially useful information for mapping and managing goods and services, beyond their original remit.

The work described in Chapter Three contributes to the literature showing the heterogeneous effect of land management on soil carbon stocks. Further work to develop a model for predicting soil carbon distribution that can be applied to any farm which has access to FEP data, along with soil moisture and depth information, could be of great benefit to soil carbon management schemes. Using the findings from Chapter Three as the starting point for creating such a model would enable management interventions to be more dynamic and responsive to local conditions. The usability of such a model would be improved through testing with advanced hydrological models to negate the need for field moisture data. It is recommended that such a model would be used within a MMM approach.

6.2.3 Chapter Four

There are two headline contributions from this chapter: firstly, evidence of the place-based nature of farmers' ability and willingness to manage for environmental goods and services on their farms; and secondly, it highlights the utility of qualitative research methods in ecological research.

A dualistic mode of thinking (scientific vs local knowledge) has caused many problems in the planning and delivery of environmental management schemes. Chapter Four moves past this by recognising that all knowledges are situated and connected (Haraway 1988; Rose 1997; Hinchliffe 2007) and by refusing to automatically put 'conflicting' knowledges in opposition. The chapter also highlights the importance of considering the following in advance of introducing any 'soil carbon farming' scheme: the sensory experiences of AES outcomes; the potential for 'soil carbon farming' to conflict with upland farmers' concepts of a productive landscape and their strong self-identity as producers of food (Burton and Wilson 2006), as well as held cultural heritage values of the landscapes (Tsouvalis, Waterton, and Winfield 2012); and, consideration of the embodied experience of soil carbon as wet, unproductive and problematic farm spaces, which are often hard work to manage (discussed in depth in Chapter Five).

The insights that can be achieved from retaining the richness of qualitative data, for better ecological outcomes as well as better social outcomes, will not be news to many in the social sciences nor to many conservation biologists. However, this will be a challenging message for some practitioners who rely on quantitative spatial assessments and there remains scepticism amongst some natural scientists as to the utility of qualitative methods in ecological research. Qualitative contributions are often 'squeezed' into quantitative indices and participation is often tacked-on to an existing scientific framework. Chapter Four is intended for submission to the Journal of Applied Ecology. In a search of the journal's archives the most recent article found which used qualitative data without transforming it into quantitative indices or a ranking system was from 2005, when White et al. (2005) wrote an article calling for more qualitative methods to be employed in conservation research. Chapter Four is a direct response to McCracken et al. (2015) who, within the same journal, used a quantitative interdisciplinary approach to examine how social drivers affected the ecological success of AES on individual farms.

6.2.4 Chapter Five

Recently, researchers have asked what might happen if policy makers considered and responded to environmental issues of concern through application of ontological multiplicity and accepted that "forms of knowledge – including policies – and realities – are irretrievably situated" (Law and Singleton 2014, 392). Urquhart et al. (2011) have suggested that we need more research which applies 'dense' theoretical concepts to analysis that leads to environmental policy. The main contributions from this chapter are: i) use of the 'dense' theoretical concept of ontological multiplicity within a practical and policy-relevant context; and, ii) in doing so, proposing a new strategy for dealing with impasse and conflict in environmental management.

A journal article utilising the material from this chapter could further explore the 'liveliness' (Bennett 2010) of soil carbon and consider the implications of soil carbon as a human/non-human assemblage of doing and effecting. It could also further explore how labour can be accounted for and its role in discussions about managing farmland for soil carbon sequestration.

6.3 Policy implications and knowledge exchange

On a policy level, a MMM approach offers a spatially-explicit theoretical and methodological tool to assist in managing socio-ecological systems in a way which engages with current AES and catchment strategies and with policy imperatives for participatory engagement. In section 6.3.1 I suggest developments for a proposed policy tool. The use of such a tool could improve the relationship between farmers and policy officers, as well as opening up the management process to consider new knowledges to enable better decisions to be made.

The involvement of farmers and other research participants was key to the direction this project took and it is hoped that the research will influence how farmers are involved in developing agri-environment decision-making processes in the future. It is also hoped that this research will make a contribution to the small, but growing, trans-disciplinary movement who practice research which crosses the academic/non-academic divide and is transcultural, transnational, and encompasses ethics, spirituality, and creativity (Thompson Klein 2004; Toomey 2015).

6.3.1 Dynamic mapping

As explained in Chapter Two, the idea of a 'dynamic' and editable map emerged from a conversation with a case study Farmer. Farmer W described his frustration with an AES enrolment process. Ten years ago he had been told to take his cows off a piece of land for vegetation diversity reasons and he was now being told to put them back on as some species of plant were becoming too dominant. He explained that he had told the policy officer at the time that these plant species would become too dominant if cows weren't grazing them. His frustration was clear. We discussed the idea of a 'dynamic map' which records farmer suggestions and concerns and could act as a learning tool for both farmers and policy officers (field notes, July 2-11 2013). The 'dynamic map' idea was broached with other farmers and with farm environment advisers (FEAs) at the focus group and received a positive response. I emphasize that this idea has not been discussed with policy officers nor have the technical aspects been considered in any depth, but I outline some of the possible features below.

An online 'dynamic' farm map, editable by farmers and associated policy officers and FEAs, could be integrated into the AES process or any other externally-driven process for managing 'non-traditional' goods and services on farms. Its processual nature would go some way to addressing current problems with policy timeframes which lead to premature fore-closure of discussion and the need to come to an apparent consensus on the enrolled version of the farm. It would also serve as a reference point for policy officers new to the area and the existence of such a record would lend a degree of continuity to the relationship between farmer and government. Inclusion of externally-held environment data within the map would encourage more farmer use of such information. The explosion of online map-making (e.g. http://mapstory.org/ and www.openstreetmap.org/) has opened up the social, task-oriented and ephemeral nature of cartography (Perkins 2009) and the 'dynamic map' would assist in moving everyday mapping practices onto the farm.

6.4 Final Reflections

Current approaches to managing public environmental goods on farms rely on scientific knowledge and quantitative data, often marginalising alternative ways of knowing the farms. The mapping methodology presented here engaged with ways of knowing the farm which are usually 'hidden' during formal management planning processes. In doing so, the research process worked creatively with different ontologies and epistemologies to contribute methodologically and empirically to our understanding of how we can improve soil carbon management in these landscapes. The research findings have the potential to be developed further with application to other areas of environmental management, for example through 'dynamic mapping' presented in 6.3.1. The research presented in this thesis also contributes to a better understanding of how and why we might encourage the next generation of academic researchers to consider doing an interdisciplinary PhD.

7 References

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Appendix I – Glossary of terms

Actants – political, cultural and biophysical actors.

Actors – 'social actors' are either individuals or collectives (e.g. political parties, trades unions, social movements) who exercise agency as opposed to constraining social structures.

Agency – the ability of individuals to affect change, make autonomous and independent choices and act in self-determining ways. *From: O'Leary, Z. (2007). The social science jargon-buster. London, United Kingdom: Sage UK.*

Agri-environment scheme - Government programmes set up to help farmers manage their land in an environmentally-friendly way. Important for the conservation of farmed environments of high nature value, for improved genetic diversity and for protection of agro-ecosystems. *From: European Environmental Protection Agency online glossary http://glossary.eea.europa.eu/terminology*

Assemblage - The process by which a collective entity (thing or meaning) is created from the connection of a range of heterogeneous components. An aggregate with a certain consistency being created from an active, *ad hoc* and ongoing entanglement of elements. The concept has been put to work notably in science and technology studies (STS), the work of Jacques Derrida, and the combined writings of Gilles Deleuze and Félix Guattari. *From: Bingham, N. (2009). Assemblage. In D. Gregory, The dictionary of human geography. Oxford, United Kingdom: Blackwell Publishers.*

Commonland (a common) – land owned collectively by a number of people, or by one person, over which other people have certain traditional rights, such as livestock grazing rights or rights to collect firewood. *From: https://www.gov.uk/guidance/managing-common-land*

Dissolved organic carbon – a broad classification for organic molecules of varied origin and composition within aquatic systems. An operational classification.

Ecosystems approach – a normative approach to managing biodiversity (and often wider environmental management). It is a diffusely-applied term originating from the twelve 'Malawi Principles for the Ecosystem Approach' derived from a United Nations workshop in Malawi and included in the Convention on Biological Diversity in 1998.

Ecosystem services – a neoliberal normative policy framing for valuing natural systems; the benefits provided by ecosystems to humans. *From: Millennium Ecosystem Assessment. 2005. Ecosystems and Human Well-Being: Synthesis Report. Island Press.*

Environmental public good – The term public good can be narrowly defined to include goods characterized by non-rival consumption (consumption by one person does not prevent consumption by another) and non-excludability (people who do not pay cannot be prevented from gaining access to the good). 'Environmental goods' are a sub-section and can confer benefit to humans and non-humans. *From: Scruton, R. 2007. 'Public Goods'. In Palgrave MacMillan Dictionary of Political Thought., online. Basingstoke, United Kingdom: Macmillan Publishers Ltd. http://ezproxy.lancs.ac.uk/login?url=http://search.credoreference.com.ezproxy.lancs.ac.uk/content/entry/macpt/public_goods/0.*

Epistemology – Epistemology is the philosophical subdiscipline that studies the evaluative dimensions of cognition, their metaphysical bases, and, increasingly nowadays, the language we use to ascribe cognitive achievements. The nature and scope of knowledge is the central focus of epistemology. *From: B. Kaldis (Ed.), (2013). Encyclopedia of philosophy and the Social Sciences. Thousand Oaks, CA: Sage Publications.*

Extensive farming – low input grazing systems.

Fell – a high and barren landscape feature, such as a mountain range or moor-covered hills.

Geographical Information System – a system designed to capture, store, manipulate, analyse, manage, and present spatial or geographical data.

god trick – Donna Haraway describes the position of scientific vision as a "god trick" (pg 582), a move that places the sciences as an omniscient observer. *From: Haraway, D. 1988. 'Situated Knowledges: The Science Question in Feminism and the Privilege of Partial Perspective'. Feminist Studies 14 (3): 575–99.*

Heft, heaf, hefting, hefted – "a traditional method of managing flocks of sheep on large areas of common land and communal grazing. Initially, sheep had to be kept in an unfenced area of land by constant shepherding. Over time this has become learned behaviour, passed from ewe to lamb over succeeding generations. Lambs graze with their mothers on the "heaf" belonging to their farm instilling a life-long knowledge of where optimal grazing and shelter can be found throughout the year. On many tenanted farms there is a 'landlord's flock', which goes with the farm whenever there is a change of tenant. This ensures that the land continues to be successfully grazed by its resident 'hefted' flocks of sheep. The Lake District is particularly well known for hefting but it is also practised on common grazings in other areas of the country". *From: Department for Environment, Food and Rural Affairs. 2015. 'Assessment of the Impact of Hefting (heafing or Learing). Project BD1242'.*

Heterotopia – "a counter-site, a kind of effectively enacted utopia in which the real sites, all the other real sites that can be found within culture, are simultaneously represented, contested, and inverted" therefore "The heterotopia is capable of juxtaposing in a single real place several spaces, several sites that are in themselves incompatible" (pg 24). *From: Foucault, M. 1986. 'Of Other Spaces'. Translated by J. Miskowiec. Diacritics 16 (1): 22–27.*

Hill farm – extensive farming in upland areas, often classed as a Less Favoured Area by the Department for Environment, Food and Rural Affairs.

Immutable mobiles – truth claims employed to do work in the world, produced by Western scientific knowledge. Bruno Latour in his book 'Science in Action' (1987) used the example of cartography to explore this phenomenon. *From: Latour, B. 1987. Science in Action : How to Follow Scientists and Engineers through Society. Cambridge, Mass: Harvard University Press.*

Improved land – land to which nutrients have been applied. Also a classification (G01) within the 'Higher Level Stewardship: Farm Environment Plan Guidance handbook', with associated characteristic vegetation community. *From: DEFRA. 2005. Higher Level Stewardship: Farm Environment Plan Guidance Handbook. Department for Environment, Food and Rural Affairs, UK.*

Interdisciplinary – research that "analyzes, synthesizes and harmonizes links between disciplines into a coordinated and coherent whole" (pg 351). *From: Choi, B.C.K., and A.W.P. Pak. 2006. 'Multidisciplinarity, Interdisciplinarity and Transdisciplinarity in Health Research, Services, Education and Policy: 1. Definitions, Objectives, and Evidence of Effectiveness'. Clinical Investigations in Medicine 29 (6): 351–65.*

Inter-disciplined researcher – a researcher who works with different knowledge claims and disciplinary conventions to bring different disciplines into dialogue with each other.

Labile – easily broken down or displaced (chemistry).

Map surface – in cartography, a two-dimensional perspective representation of a three-dimensional surface. Surface maps usually represent real-world entities such as landforms or the surfaces of objects. In QualGIS can also represent other, non-Cartesian and non-physical, surfaces (such as geolocated noise – 'noisescapes').

Multidisciplinary – "draws on knowledge from different disciplines but stays within their boundaries" (pg 351). *From: Choi, B.C.K., and A.W.P. Pak. 2006. 'Multidisciplinarity, Interdisciplinarity and Transdisciplinarity in Health Research, Services, Education and Policy: 1. Definitions, Objectives, and Evidence of Effectiveness'. Clinical Investigations in Medicine 29 (6): 351–65.*

Noisescape/soundscape – a map surface representing the distribution of noise or sound across a geographical area.

Ontogenesis – maps as produced and used through multiple sets of practices. From: *Kitchin, R., C. Perkins, and Dodge. 2009. 'Thinking about Maps'. In Rethinking Maps: New Frontiers in Cartographic Theory, edited by M. Dodge, R. Kitchin, and C. Perkins, 1–25. London ; New York: Routledge.*

Ontological multiplicity - accepts that there are not just many ways of knowing 'an object', but rather many ways of practising it. Each way of practising stages – performs, does, enacts – a different version of 'the' object. Hence, it is not 'an object', but more than one. *From: Mol, M. 2014. 'A Reader's Guide to the "ontological Turn" – Part 4 | Somatosphere'. Article. Somatosphere: Science, Medicine, and Anthropology. http://somatosphere.net/2014/03/a-readers-guide-to-the-ontological-turn-part-4.html.*

Ontology – the nature of being, becoming or existence; what kinds of things can be said to exist, and in what ways.

Praxis – ideas in action.

Participatory GIS – an approach which encompasses decision-making processes that gather, analyse and represent local stakeholder spatial knowledge with those of environment managers and scientists at the decision-making scale. From: *Cinderby, S., A. de Bruin, B. Mbilinyi, V. Kongo, and J. Barron. 2011. 'Participatory Geographic Information Systems for Agricultural Water Management Scenario Development: A Tanzanian Case Study'. Physics & Chemistry of the Earth - Parts A/B/C 36 (14/15): 1093–1102.*

Positionality – all knowledge is situated means accepting that it is produced in specific circumstances that shape it and by researchers with a specific set of experiences, skills, expectations, ambitions, constraints, and within a certain intellectual community. *From: Rose, G. 1997. 'Situating Knowledges: Positionality, Reflexivities and Other Tactics'. Progress in Human Geography 21 (3): 305–20.*

Qualitative GIS – develops critical engagement with mapping through methods which integrate qualitative data grounded on the critical agency of the GIS user/researcher. *From: Schuurman, N., and G.Pratt. 2002. 'Care of the Subject: Feminism and Critiques of GIS'. Gender, Place & Culture 9 (3): 291–99.*

Recalcitrant – resistant, stable (chemistry).

Reflexivity – circular relationships between cause and effect: a strategy for situating knowledges originating with Bourdieu (sociology). *From: Bourdieu, Pierre. 1990. In Other Words: Essays towards a Reflexive Sociology. Stanford University Press.*

Remote-sensing – the collection of data, using aerial sensor technologies mounted on, for example, satellites, 'drones' or aeroplanes, to detect and classify objects or phenomenon on Earth without coming into contact with the object or phenomenon. *From: Burrough, P.A., and R.A. McDonnell. 1998. Principles of Geographical Infomation Systems. Spatial Information Systems and Geostatistics. New York: Oxford University Press.*

Semi-improved grassland – land to which nutrients have been applied, but less than to 'improved land'. Also a classification (G02) within the 'Higher Level Stewardship: Farm Environment Plan Guidance handbook', with associated characteristic vegetation community. *From: DEFRA. 2005. Higher Level Stewardship: Farm Environment Plan Guidance Handbook. Department for Environment, Food and Rural Affairs, UK.*

Situated knowledge – a form of objectivity that accounts for both the agency of the knowledge producer and that of the object of study (Science and Technology Studies). *From: Haraway, D. 1988. 'Situated Knowledges: The Science Question in Feminism and the Privilege of Partial Perspective'. Feminist Studies 14 (3): 575–99.*

Soil organic carbon – biologically-derived; the amount in soil is related to the balance between the amount of organic matter entering soils, from plants and animal wastes, and the amount that is released by decomposition, which is largely performed by soil organisms. *From: Ontl, T.A., and L.A. Schulte. 2012. 'Soil Carbon Storage'. Nature Education Knowledge 3 (10): 35.*

Soil inorganic carbon – carbonate; predominantly geologically-derived.

Stratified sheep system – whereby particular breeds occupying specific environments to which they are adapted and are connected by the movement of lambs and older animals from higher, to lower ground.

Suckler cows – animals that have given birth to at least one calf and is used to suckle the calf or other calves.

Toponymy – the study of place-names of a region or language.

view from nowhere – a type of relativism, described by Haraway (1988) as offering a view from nowhere, while "claiming to be everywhere equally" (pg 584). *From: Haraway, D. 1988. 'Situated Knowledges: The Science Question in Feminism and the Privilege of Partial Perspective'. Feminist Studies 14 (3): 575–99.*

Appendix II – PCA results

Main Farm

We measured 5 leaf trait variables (SLA, LDMC, C, N, C:N) and 8 functional groups (% cover). We calculated community weighted means for the leaf traits and functional group cover for each sample location. We also had species richness values and Shannon diversity index scores for each sample location. We ran a PCA on the leaf trait data and the functional group cover data to reduce the number of terms.

For the leaf trait data, the first two PCA axes explained 0.75 variation in the data. The first axis (0.46) was influenced by all traits, except SLA. The second axis (0.29) was represented by all 5 traits.

When plotting axes 1 vs axes 2 – C, SLA and LDMC were loosely clustered. The other traits plotted separately.

Zuur's correlation matrix showed that PCA1 is highly correlated with N, CN, C and LDMC. All these seem to represent something biologically similar. SLA represents something different.

We then ran a PCA on plant functional groups (percent cover of legumes, trees, grasses, forbs, shrubs, *Sphagnum spp.,* all bryophytes, *Juncus spp.*). Less of a clear picture. Four axes explained 79% of variance in data set. Axis 1 loadings are predominantly for grass and forbs plus bryophytes and *Sphagnum spp*. Axis 2 loadings are predominantly for shrubs and legumes.

Test farms

T1 - For the leaf traits – PCA1 and PCA2 explained 0.84 of the variation. The plot of PCA1 and PCA2 shows SLA and N clustering, the rest are separated. PCA1 is associated with SLA (0.9), N (0.9) and CN (-0.9). PCA2 is associated with LDMC (0.8).

T1 - For the functional groups – PCA1 and PCA2 explained 0.81 of the variation. The plot of PCA1 and PCA2 shows legumes, forbs and grass clustering, as well as bryophytes, Sphagnum and *Juncus spp.* clustering, shrubs are separate. PCA2 is associated with shrubs and PCA1 is associated with the rest.

T2 - For the leaf traits – PCA1 explained 0.92 of the variation.

T2 - For the functional groups – PCA1 explained 0.92 of the variation. The plot of PCA1 and PCA2 shows legumes and forbs clustering, as well as bryophytes, shrubs and *Juncus spp*. clustering, grass are separate.

Appendix III – Supplementary Tables S1-S8

Table S1. Chosen linear regression models explaining variance for carbon stocks on the Main Farm, where measured vegetation data (PCA scores) is substituted for vegetation community code information. Including a combination of PCA trait scores and functional group cover scores is an acceptable replacement for vegetation community code for depths 2-5.

Depth	**Transformation of the dep. variable**	**Sig. model terms**	**Model F statistic**	**Model p value**	**Adjusted Rsq**	**Standard deviation of the residual error**
1 (0-7.5cm)	N	soil moisture t=4.542; p<0.0001 PCAtrait1 t=-3.828; p=0.0002 Shannon index t=2.021; p=0.045	$10.19_{(3,156)}$	p<0.0001	0.15	25.61
2 (7.5-20cm)	Y (λ=-0.02)	soil moisture t=-5.193; p<0.0001 PCAtrait1 t=4.417; p<0.0001 PCAfunction1 t=2.311; p=0.02232 PCAfunction2 t=2.694; p=0.00792 PCAfunction3 t=-2.488; p=0.01403 PCAfunction4 t=2.814; p=0.00560	$12.72_{(6,139)}$	p<0.0001	0.33	0.01199
3 (20-40cm)	Y (λ=0.02)	soil moisture t=8.247; p<0.0001 PCAtrait1 t=-5.475; p<0.0001 PCAfunction1 t=-3.141; p=0.00214	$34.98_{(3,116)}$	p<0.0001	0.46	0.01217
4 (40-60cm)	Y (λ=-0.06)	soil moisture t= -10.363; p<0.0001 PCAtrait1 t=3.789; p=0.0003	$54.86_{(2,77)}$	p<0.0001	0.58	0.02333
5 (60-80cm)	N	soil moisture t=5.018; p<0.0001	$25.18_{(1,37)}$	p<0.0001	0.39	17.84

Table S2. Select linear regression models explaining variance for carbon stocks on Test Farm 1, substituting measured vegetation data (PCA scores) for vegetation community code information. As for Main Farm, these results show that this combination of covariables is suitable for use in a cokriging analysis, except for depth 1.

Depth	**Transformation of the dep. variable**	**Sig. model terms**	**Model F statistic**	**Model p value**	**Adjusted Rsq**	**Standard deviation of the residual error**
1 (0-20cm)	Not good model					
2 (20-40cm)	N	soil moisture t=17.572; p=0.0003 PCAtrait1 t=7.809; p=0.01	$12.69_{(2,25)}$	0.0002	0.46	14.16
3 (40-60cm)	Y (λ=-0.6)	soil moisture t=4.7747; p=0.04779 (PCAtrait1 t=2.6515; p=0.12743)	$3.713_{(2,13)}$	0.05	0.27	0.02885
4 (60-80cm)	N	soil moisture t=12.0998; p=0.0177 PCAtrait1 t=82.1049; p=0.0003 (PCAtrait2 t=4.1556; p=0.097)	$32.79_{(3,5)}$	0.001	0.92	23.21

Table S3. Select linear regression models explaining variance for carbon stocks on Test Farm 2, substituting measured vegetation data (PCA scores) for vegetation community code information. These results show that soil moisture alone should be included as the covariable for Test Farm 2.

Depth	**Transformation of the dep. variable**	**Sig. model terms**	**Model F statistic**	**Model p value**	**Adjusted Rsq**	**Standard deviation of the residual error & DF**
1 (0-20cm)	N	soil moisture t=111.49; p<0.0001	$111.5_{(1,46)}$	<0.0001	0.7	21.6
2 (20-40cm)	Y (λ=-0.1)	soil moisture t=193.2608; p<0.0001 (PCAtrait1 t=2.361; p=0.13334) PCAtrait2 t=7.8685; p=0.00816	$67.83_{(3,35)}$	<0.0001	0.84	0.01716
3 (40-60cm)	Y (λ=0.2)	soil moisture t=15.09; p<0.0001	$227.6_{(1,25)}$	<0.0001	0.9	0.1446
4 (60-80cm)	Y (λ=-0.51)	soil moisture t= 4.174; p= 0.0005	$17.42_{(1,19)}$	0.0005	0.45	51.35
5 (80-100cm)	N	soil moisture t= 2.820; p= 0.0129	$7.954_{(1,15)}$	0.0129	0.3	4.796

Table S4. Mean carbon stocks (kg m^{-3}) based on vegetation community, Main Farm. Vegetation type details are derived from the Higher Level Stewardship: Farm Environment Plan Guidance handbook (Department for Environment, Food and Rural Affairs 2005).

Vegetation code	Vegetation type	Description	Mean carbon stock (kg m^{-3})
M04	Upland heath	Heath vegetation with at least 25% cover of dwarf shrubs. Dominated by *Calluna vulgaris* & *Vaccinium myrtillus.*	25
M01	Grass moorland & rough grazing	Unenclosed acid grassland in moorland & enclosed species-poor acid grassland, typically dominated by bent and fine-leaved fescue grasses, *Nardus stricta*, *Juncus squarrosus* & *Molinia caerulea.*	25
V02	Bracken	As M01 but dominated by *Pteridium aquilinum*	27
M08	Upland valley mires, springs & flushes	Wet moorland communities. Mires in valley topography and springs and flushes, generally with water movement. Usually wet, with bog-mosses (*Sphagnum spp.*) &/or cotton-grasses (*Eriophorum spp.*) at least frequent. Very wet with mean bulk density 110 kg m^{-3}.	28-29
G09	Upland hay meadow	Species-rich enclosed neutral grasslands on free-draining or moist neutral soils in the North Pennines & Cumbrian uplands. Cut for hay, with aftermath grazing. Typical grasses include: *Dactylis glomerata*, *Agrostis capillaris*, *Cynosurus cristatus*, *Festuca rubra*, *Poa trivialis*, *Anthoxanthum oderatum*, *Holcus lanatus.*	33
G02	Semi-improved grassland	Occurs on a wide range of soil conditions derived by agricultural improvement. Typical grasses include: *Dactylis glomerata*, *Agrostis capillaris*, *Cynosurus cristatus*, *Festuca rubra*, *Poa trivialis*, *Anthoxanthum oderatum*, *Festuca pratensis*, *Alopecurus pratensis*, *Phleum pratense*, *Holcus lanatus.* At least two of the following must apply: ● Cover of *Lolium spp.* & *Trifolium repens* between 10% & 30%. ● Sward is moderately species-rich with between nine & 15 different plant species per square metre. ● Cover of wild flowers between 10% & 30%.	38-48
V04	Scrub	Rank vegetation, *Ulex spp.*-dominated	45
T12	Upland oak woodland	Ungrazed. *Quercus spp.* usually dominates (usually *Quercus petraea*), although *Betula spp.* is usually present in the canopy & can be the dominant species. *Ilex aquifolium*, *Sorbus acuparia* & *corylus avellana* vary as the main understorey species.	49
M08	Upland valley mires, springs and flushes	As above but drier. Bulk density mean 237 kg m^{-3}.	49
G02	Semi-improved grassland	As above but wetter, with *Juncus spp.* present	70-74
T12	Upland oak woodland	As above, but grazed by sheep for part of the year.	92

Table S5. Mean carbon stocks (kg m^{-3}) based on vegetation community, Test Farm 1. Vegetation type details are derived from the Higher Level Stewardship: Farm Environment Plan Guidance handbook (Department for Environment, Food and Rural Affairs 2005).

Vegetation code	**Vegetation type**	**Description**	**Mean carbon stock (kg m^{-3})**
M02	Fragmented heath	Relict upland heath, generally in a mosaic with acid grassland. Less than 25% dwarf-shrub cover, but with dwarf shrubs frequent. Dominated by *Calluna vulgaris*, *Vaccinium myrtillus* & *Ulex europaeus.*	35
G07	Purple moor-grass rush pasture	Species-rich, semi-natural grassland with abundant *Molinia caerulea* and/or *Juncus spp.*, on poorly drained neutral & acidic soils of the lowlands and upland fringe. Often associated with springs, seepage lines & slopes surrounding water-logged depressions & hollows. Typical grasses include: *Agrostis stolonifera, Cynosurus cristatus, Alopecurus geniculatus, Festuca rubra, Anthoxanthum odoratum.*	35
G01	Improved grassland	Most grass fields on agricultural land will count as G01. At least two of the following must apply: ● Grassland with a cover of *Lolium spp.* & *Trifolium repens* of more than 30%. ● Sward is species-poor with eight or fewer different plant species per square metre. ● Cover of wild flowers less than 10%.	39
G02	Semi-improved grassland	Occurs on a wide range of soil conditions derived by agricultural improvement. Typical grasses include: *Dactylis glomerata*, *Agrostis capillaris*, *Cynosurus cristatus*, *Festuca rubra*, *Poa trivialis*, *Anthoxanthum oderatum*, *Festuca pratensis*, *Alopecurus pratensis*, *Phleum pratense*, *Holcus lanatus.* At least two of the following must apply: ● Cover of *Lolium spp.* & *Trifolium repens* between 10% & 30%. ● Sward is moderately species-rich with between nine & 15 different plant species per square metre. ● Cover of wild flowers between 10% & 30%.	40
M08	Upland valley mires, springs and flushes	Wet moorland communities. Mires in valley topography and springs and flushes, generally with water movement. Usually wet, with bog-mosses (*Sphagnum spp.*) &/or cotton-grasses (*Eriophorum spp.*) at least frequent. Very wet with mean bulk density 110 kg m^{-3}.	40
G09	Upland hay meadow	Species-rich enclosed neutral grasslands on free-draining or moist neutral soils in the North Pennines & Cumbrian uplands. Cut for hay, with aftermath grazing. Typical grasses include: *Dactylis glomerata*, *Agrostis capillaris*, *Cynosurus cristatus*, *Festuca rubra*, *Poa trivialis*, *Anthoxanthum oderatum*, *Holcus lanatus.*	42
M01	Grass moorland & rough grazing	Unenclosed acid grassland in moorland & enclosed species-poor acid grassland, typically dominated by bent and fine-leaved fescue grasses, *Nardus stricta*, *Juncus squarrosus* & *Molinia caerulea.*	45

Table S6. Mean carbon stocks (kg m^{-3}) based on vegetation community, Test Farm 2. Vegetation type details are derived from the Higher Level Stewardship: Farm Environment Plan Guidance handbook (Department for Environment, Food and Rural Affairs 2005).

Vegetation code	**Vegetation type**	**Description**	**Mean carbon stock (kg m^{-3})**
G05	Lowland dry acid grassland	Semi-natural grassland generally dominated by fine-leaved grasses on nutrient-poor, free-draining soils in the lowlands & enclosed upland fringe. Mosses &/or lichens are sometimes frequent. Managed primarily by grazing. Typical grasses include: *Agrostis capillaris, Danthonia decumbens, Festuca ovina, Anthoxanthum odoratum, Deschampsia flexuosa.*	22
G01	Improved grassland	Most grass fields on agricultural land will count as G01. At least two of the following must apply: ● Grassland with a cover of *Lolium spp.* & *Trifolium repens* of more than 30%. ● Sward is species-poor with eight or fewer different plant species per square metre. ● Cover of wild flowers less than 10%.	31-50
M04	Upland heath	Heath vegetation with at least 25% cover of dwarf shrubs. Dominated by *Calluna vulgaris* & *Vaccinium myrtillus.*	76

Table S7. Selected models for Test Farm 1. Details of selected models which best explain variance in soil properties, all depths combined (linear mixed model regressions).

Predicted variable (boxcox transformation – value of lambda)	**Fixed terms (associated F values, degrees of freedom & p values)**	**Conditional R squared (explained variance)**	**Standard deviation of the residual error**
Carbon stocks kg m^{-3} (0.3)	vegetation community $F=17.052_{(6,57)}$; $p<0.0001$ soil moisture $F=13.644_{(1,36)}$; $p=0.0007$ moisture:depth $F=13.026_{(3,36)}$; $p<0.0001$ moisture:vegetation community $F=3.861_{(6,36)}$; $p=0.0045$ (depth not sig.)	0.85	0.22
Nitrogen stocks kg m^{-3} (0.38)	vegetation community $F=17.882_{(6,57)}$; $p<0.0001$ moisture:depth $F=15.277_{(3,36)}$; $p<0.0001$ depth $F=4.924_{(3,36)}$; $p=0.0057$ moisture:vegetation community $F=2.411_{(6,38)}$; $p=0.0462$ (soil moisture not sig.)	0.87	0.13

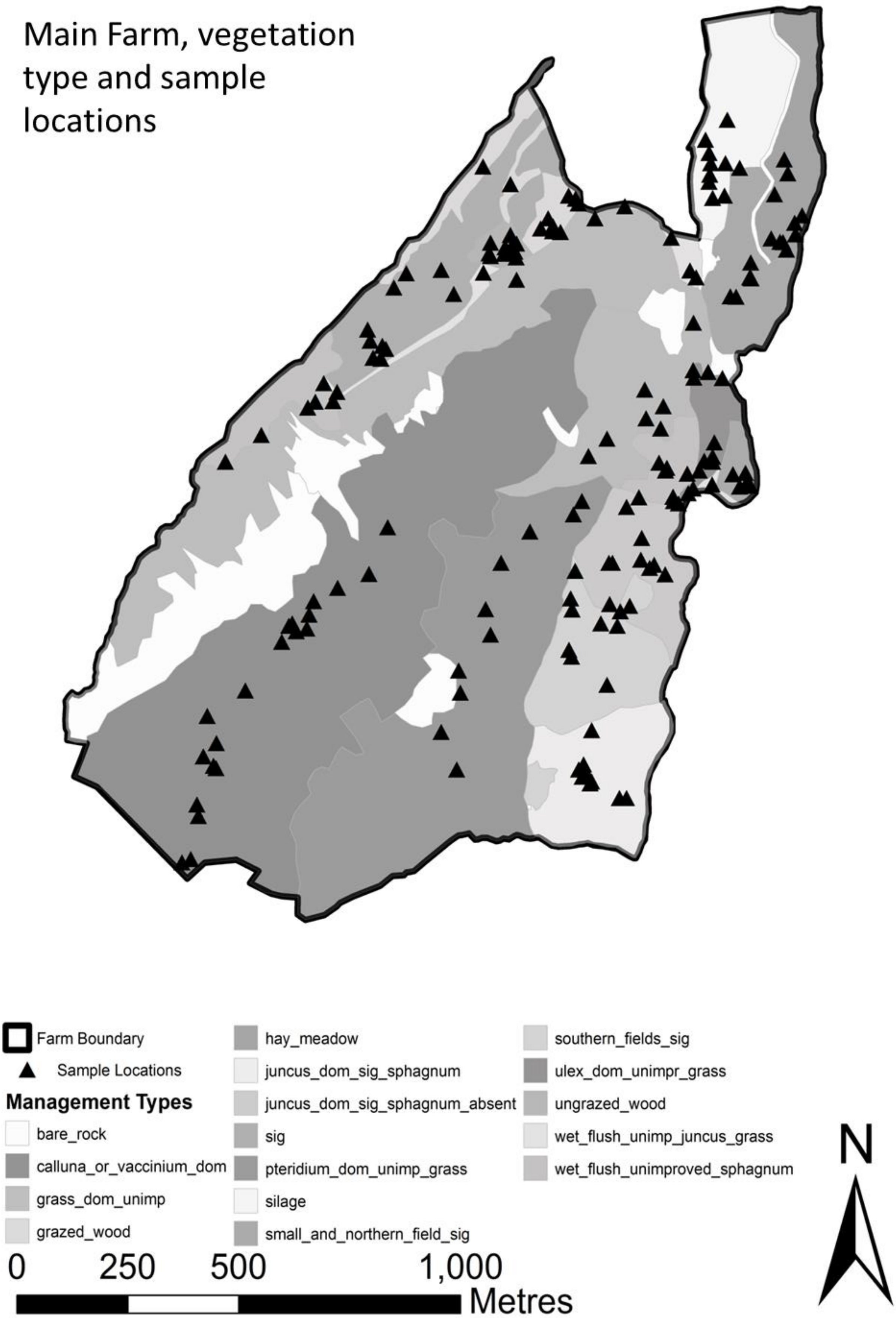
Table S8. Selected models for Test Farm 2. Details of selected models which best explain variance in soil properties (mass of carbon per volume of soil), all depths combined (linear mixed model regressions).

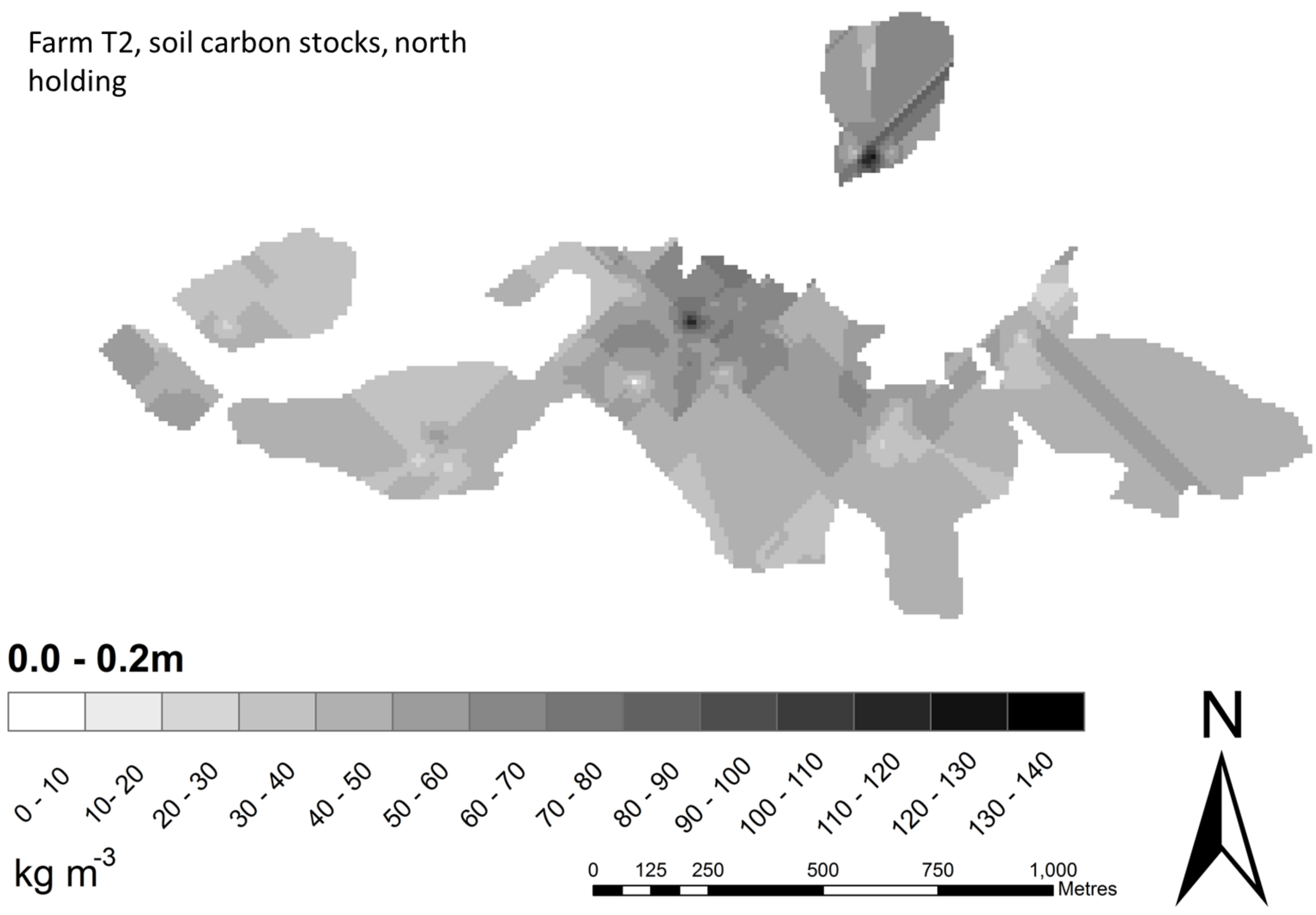
Predicted variable (boxcox transformation – value of lambda)	**Fixed terms (associated F values, degrees of freedom & p values)**	**Conditional R squared (explained variance)**	**Standard deviation of the residual error**
Carbon stocks kg m^{-3} (0.02)	soil moisture $F=295.7_{(1,91)}$; p <0.0001 moisture:depth $F=8.2_{(4,91)}$; p<0.0001 depth $F=3.5_{(4,91)}$; p=0.0101 (vegetation community $F=2.6_{(2,49)}$; p<0.08)	0.79	0.01
Nitrogen stocks kg m^{-3} (-0.14)	soil moisture $F=242.89_{(1,91)}$; p<0.0001 depth $F=20.92_{(4,91)}$; p<0.0001 moisture:depth $F=6.39_{(4,91)}$; p<0.0001	0.73	0.04

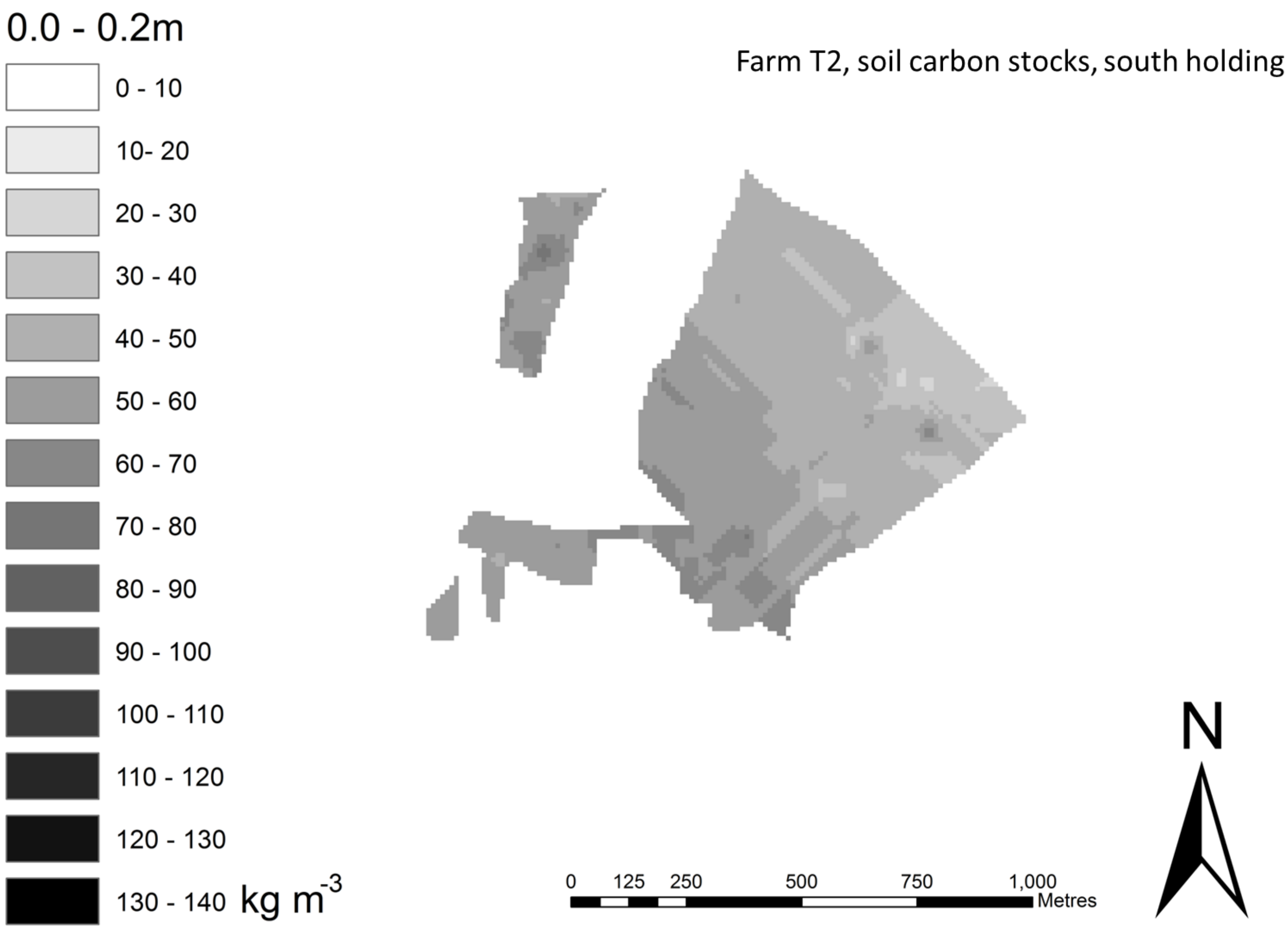
Table S9. Selected models for Main Farm. Details of selected models which best explain variance in soil properties (mass of nitrogen per volume of soil), all depths combined (linear mixed model regression).

Predicted variable (boxcox transformation – value of lambda)	**Fixed terms (associated F values, degrees of freedom & p values)**	**Conditional R squared (explained variance)**
Nitrogen stocks kg m^{-3} (0.38)	soil moisture $F=143.46_{(11,369)}$; $p<0.0001$ depth $F=17.07_{(44,369)}$; $p<0.0001$ vegcomm $F=37.76_{(47,152)}$; $p<0.0001$ moisture:depth $F=6.39_{(4,91)}$; $p<0.0001$ moisture:vegcomm $F=7.86_{(37,369)}$ $p<0.0001$	0.74

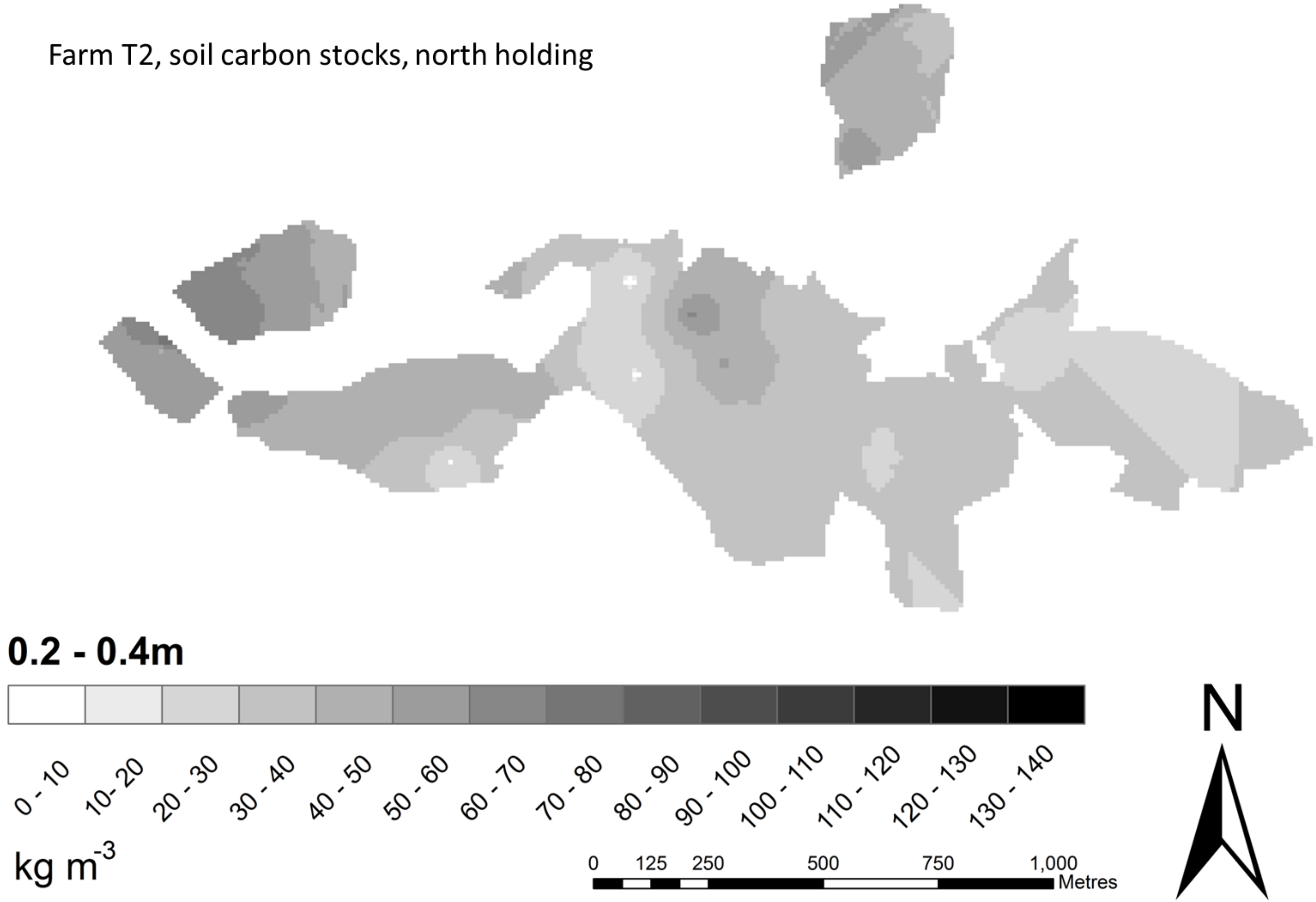
Appendix IV – Supplementary maps


Main Farm, vegetation type and sample locations
Farm Boundary
Sample Locations
Management Types
bare_rock
calluna_or_vaccinium_dom
grass_dom_unimp
grazed_wood
hay_meadow
juncus_dom_sig_sphagnum
juncus_dom_sig_sphagnum_absent
sig
pteridium_dom_unimp_grass
silage
small_and_northern_field_sig
southern_fields_sig
ulex_dom_unimpr_grass
ungrazed_wood
wet_flush_unimp_juncus_grass
wet_flush_unimproved_sphagnum
0
250
500
1,000
Metres
N

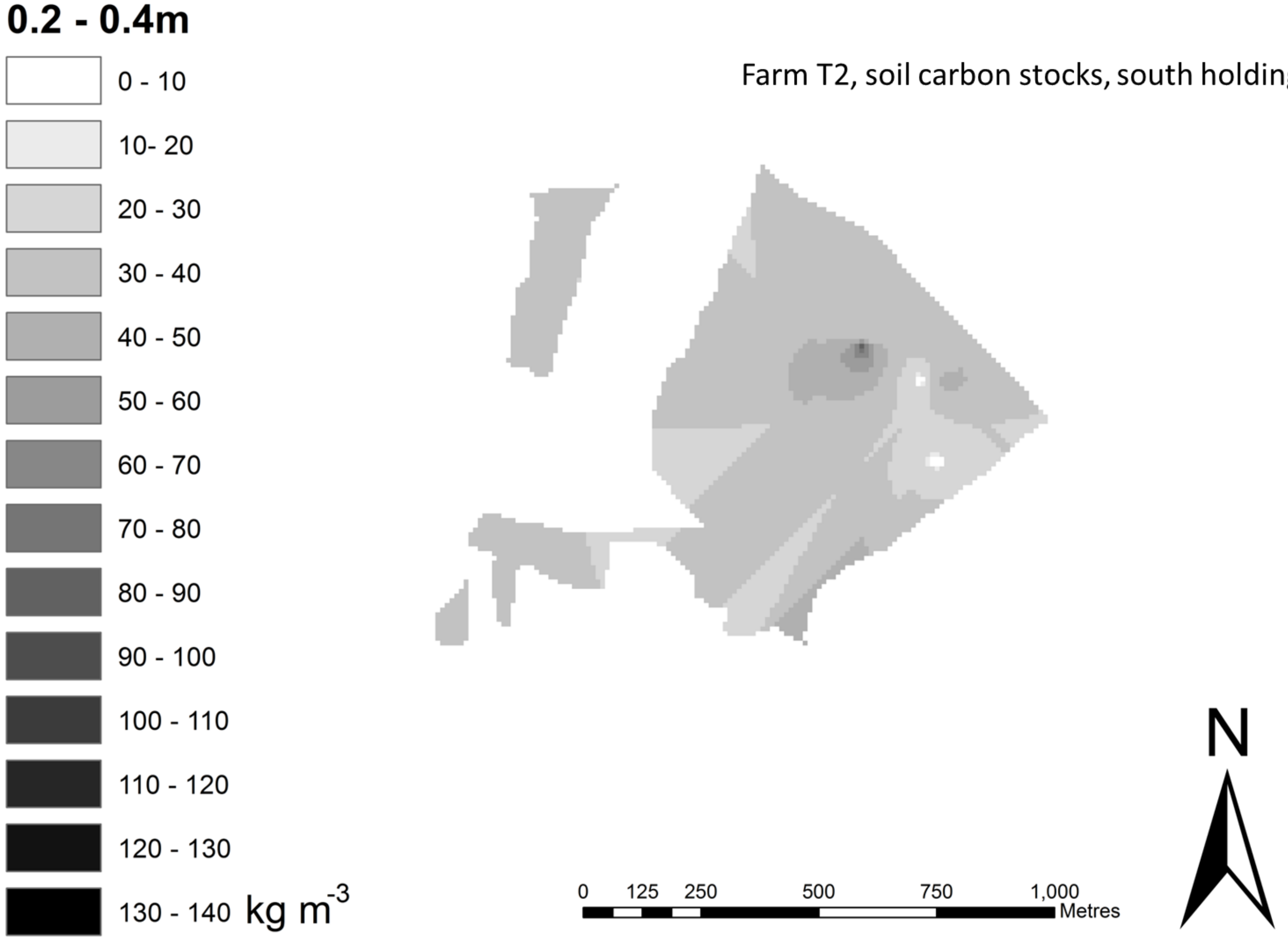

Farm T2, soil carbon stocks, north holding
0.0 - 0.2m
0 - 10
10- 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 100
100 - 110
110 - 120
120 - 130
130 - 140
kg m-3
0
125
250
500
750
1,000
Metres
N

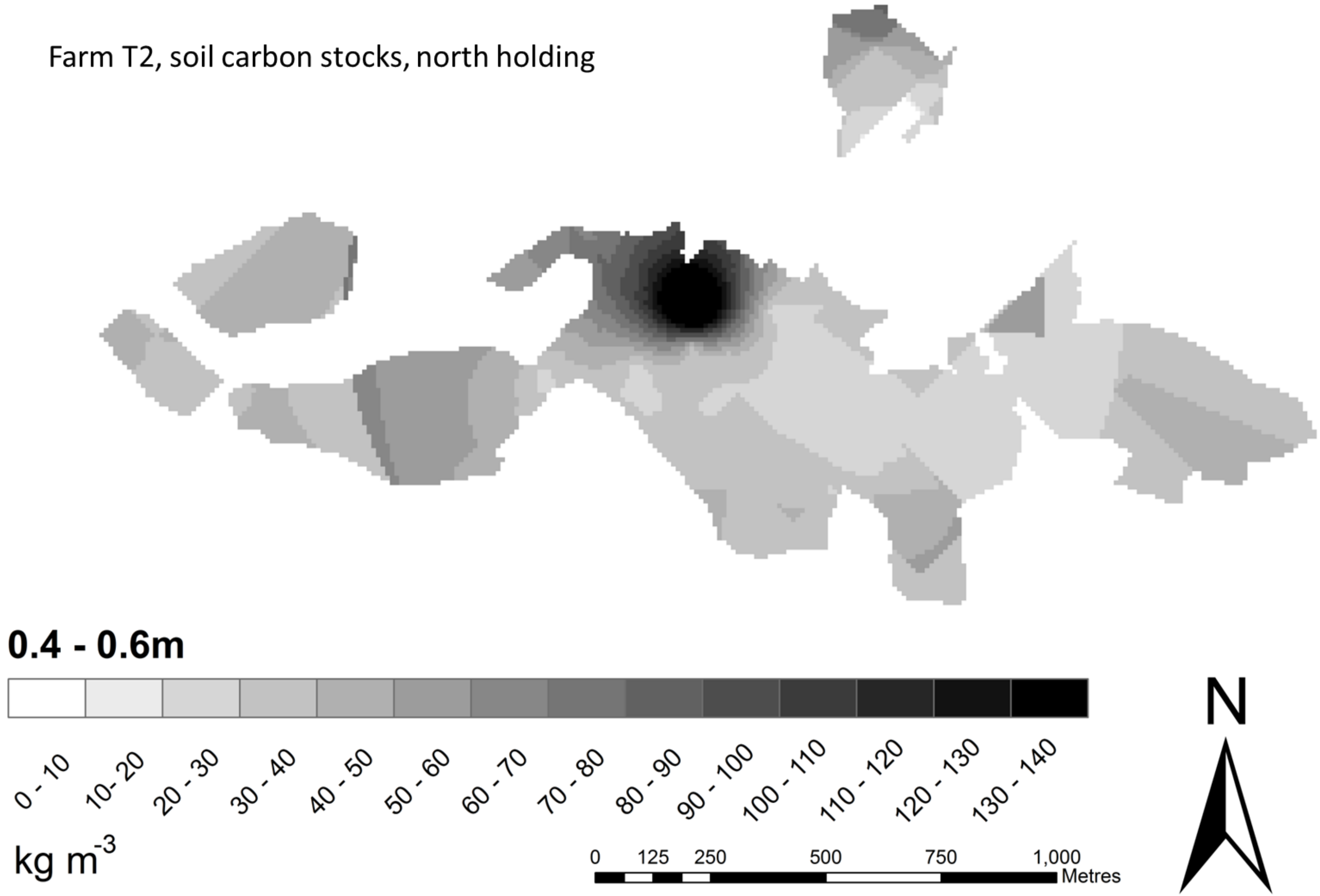

0.0 - 0.2m
0 - 10
10- 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 100
100 - 110
110 - 120
120 - 130
130 - 140 kg m-3
Farm T2, soil carbon stocks, south holding
0 125 250 500 750 1,000
Metres
N

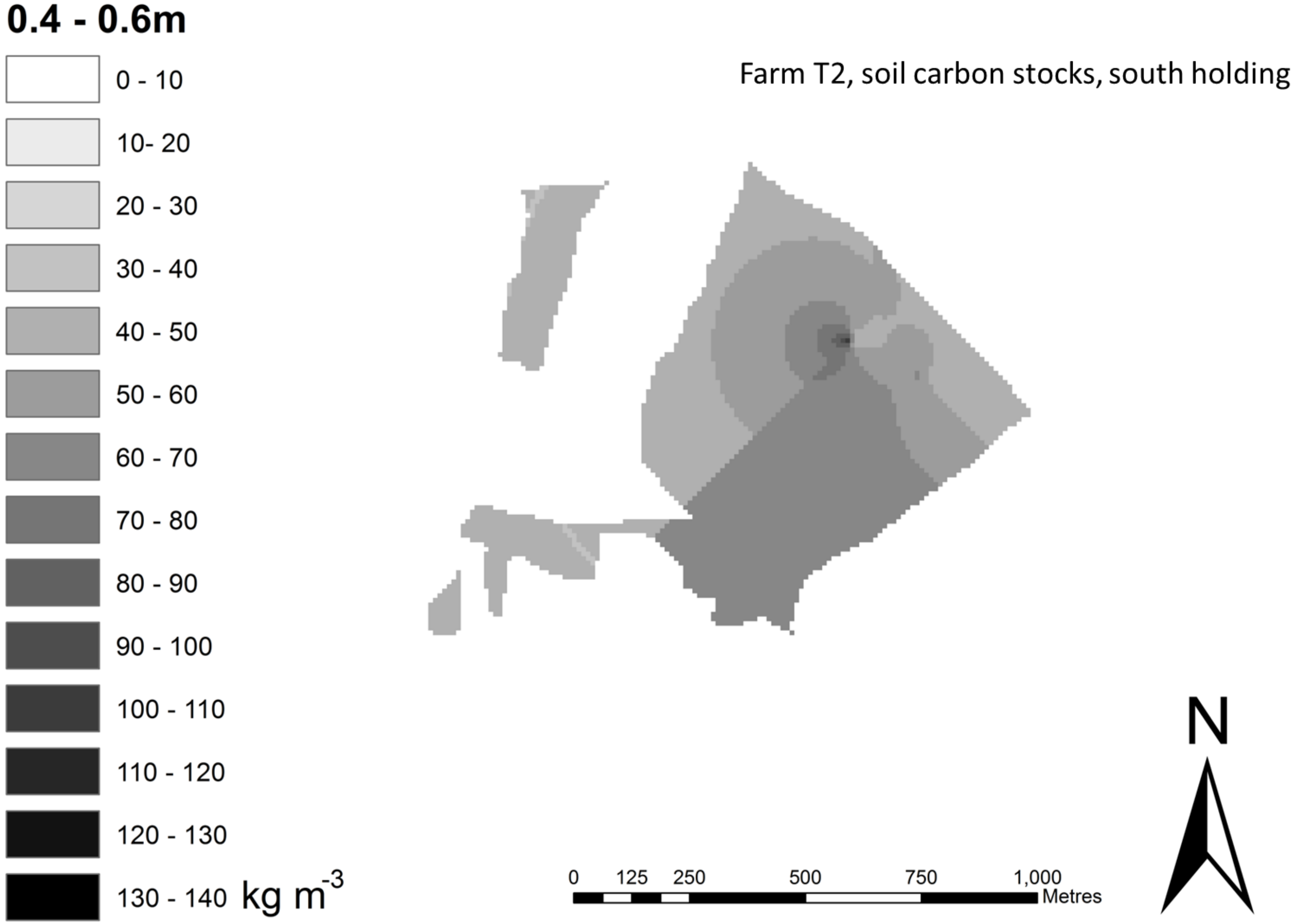
Farm T2, soil carbon stocks, north holding

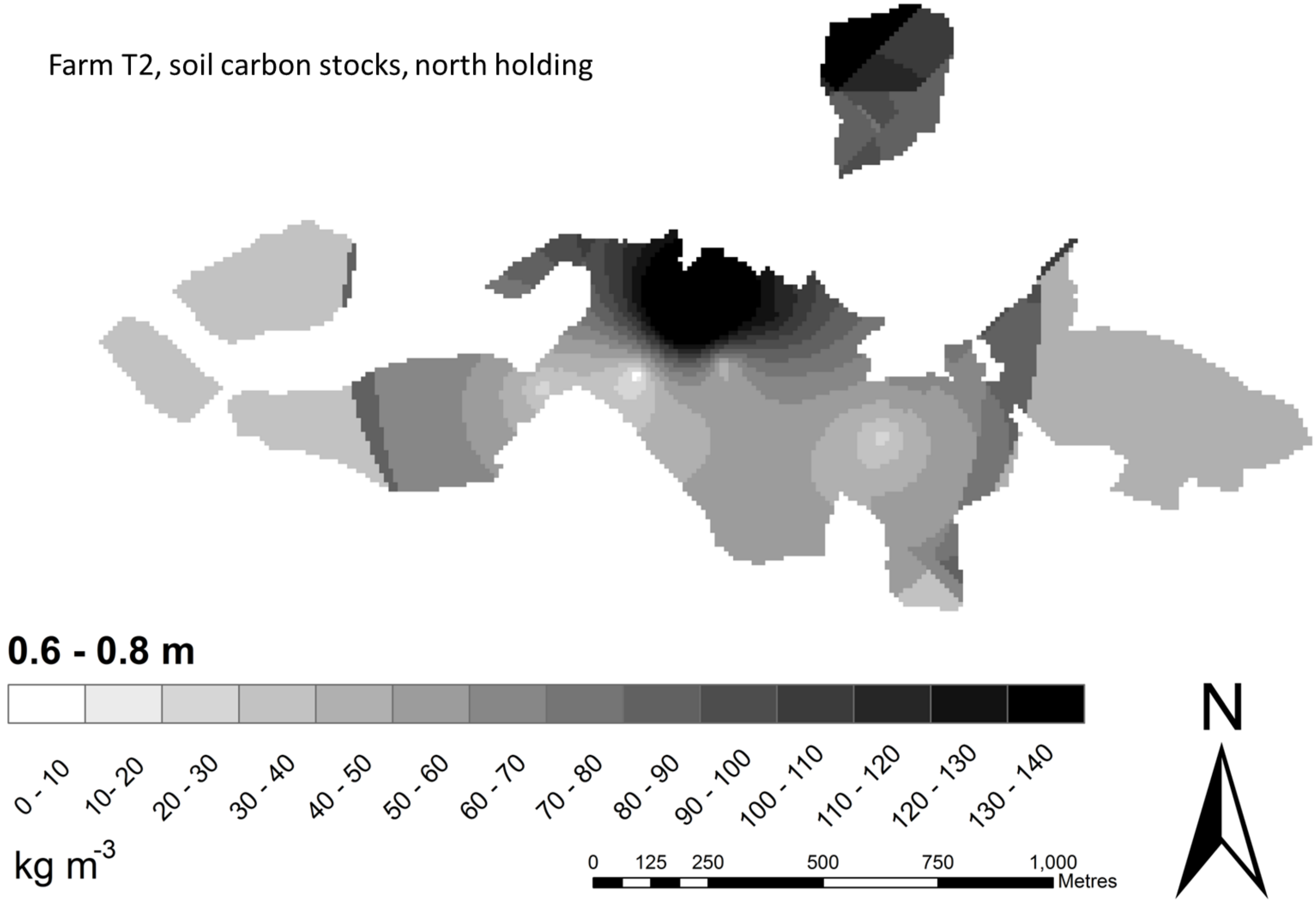


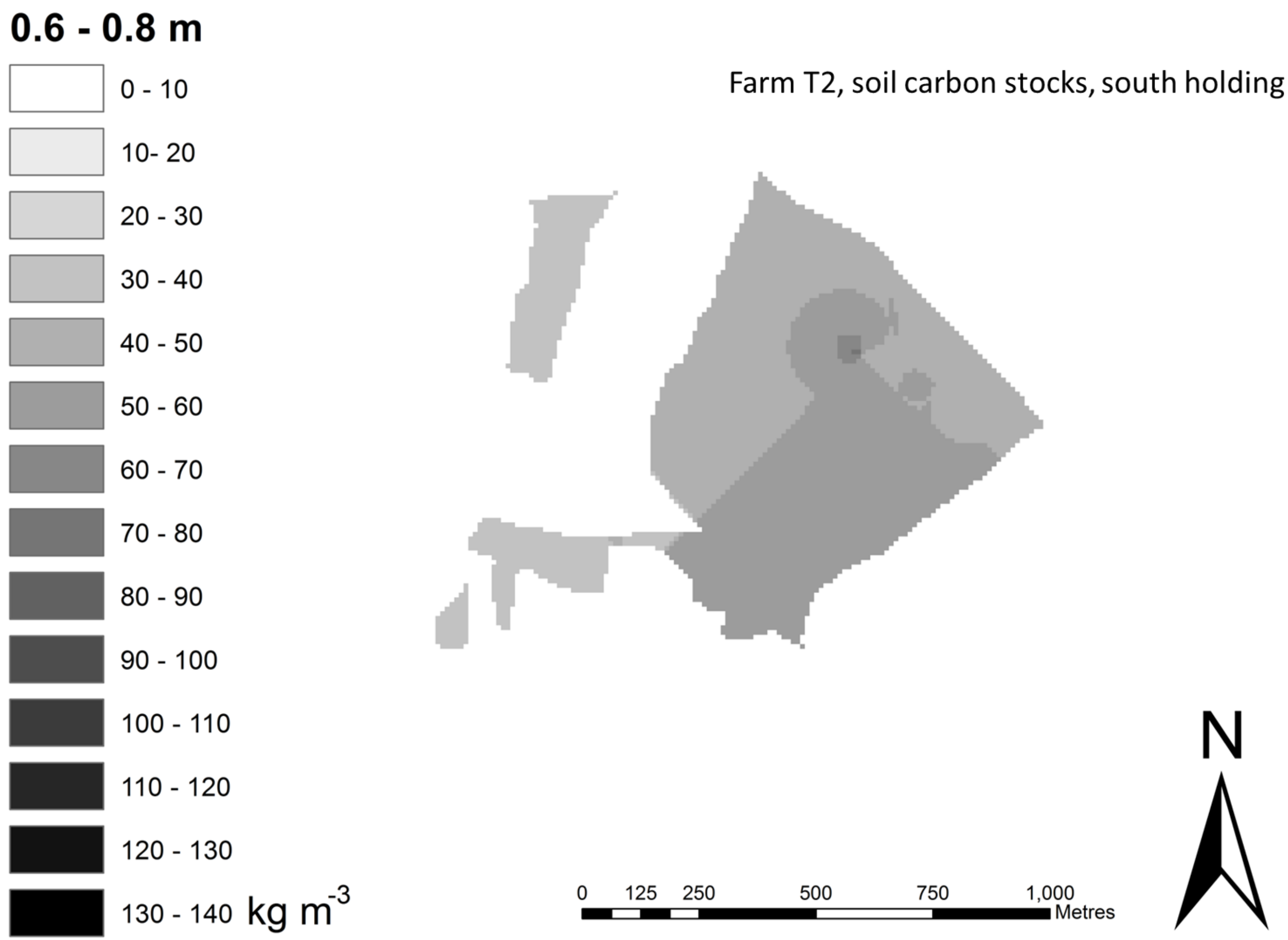
Farm T2, soil carbon stocks, south holding

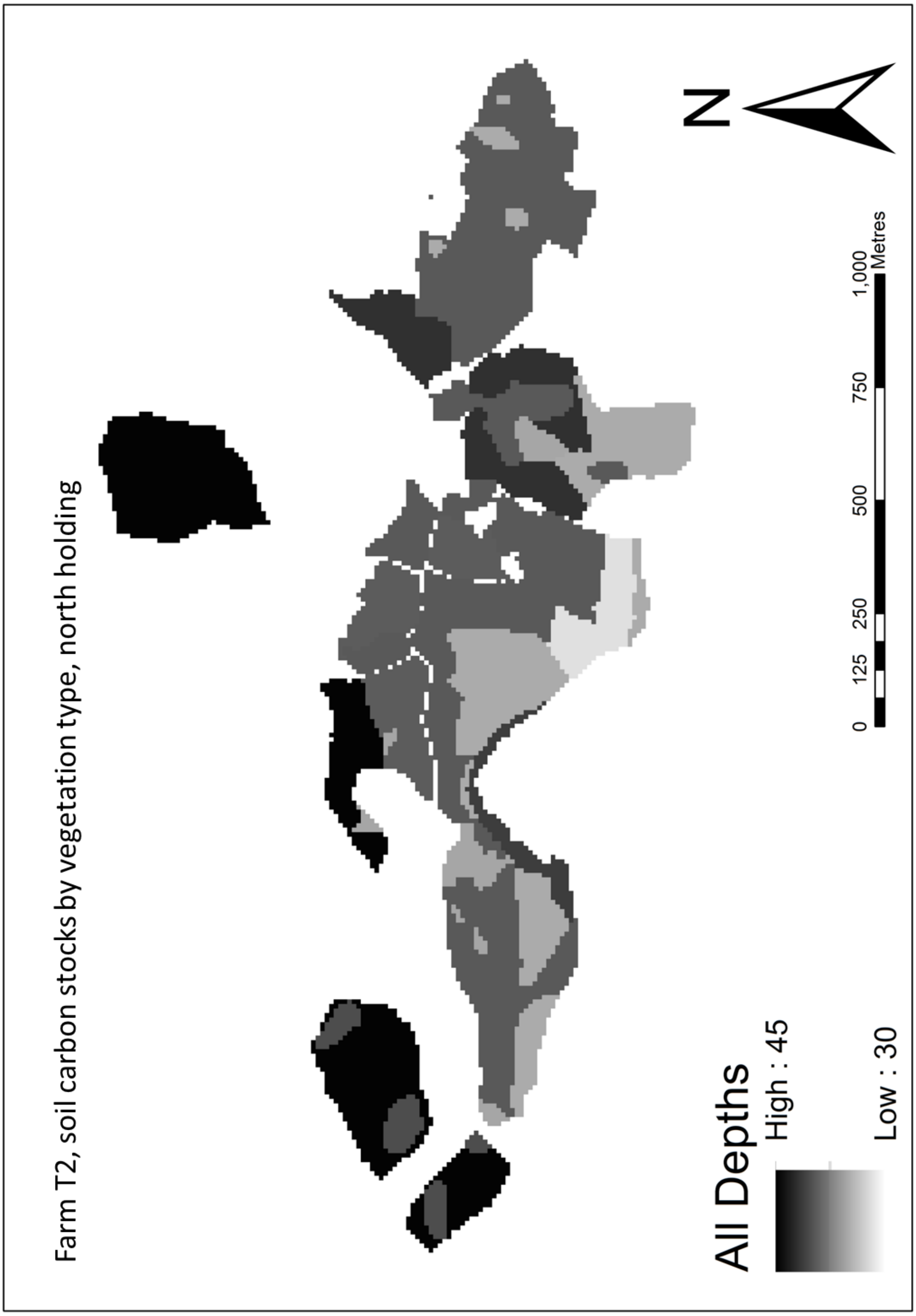


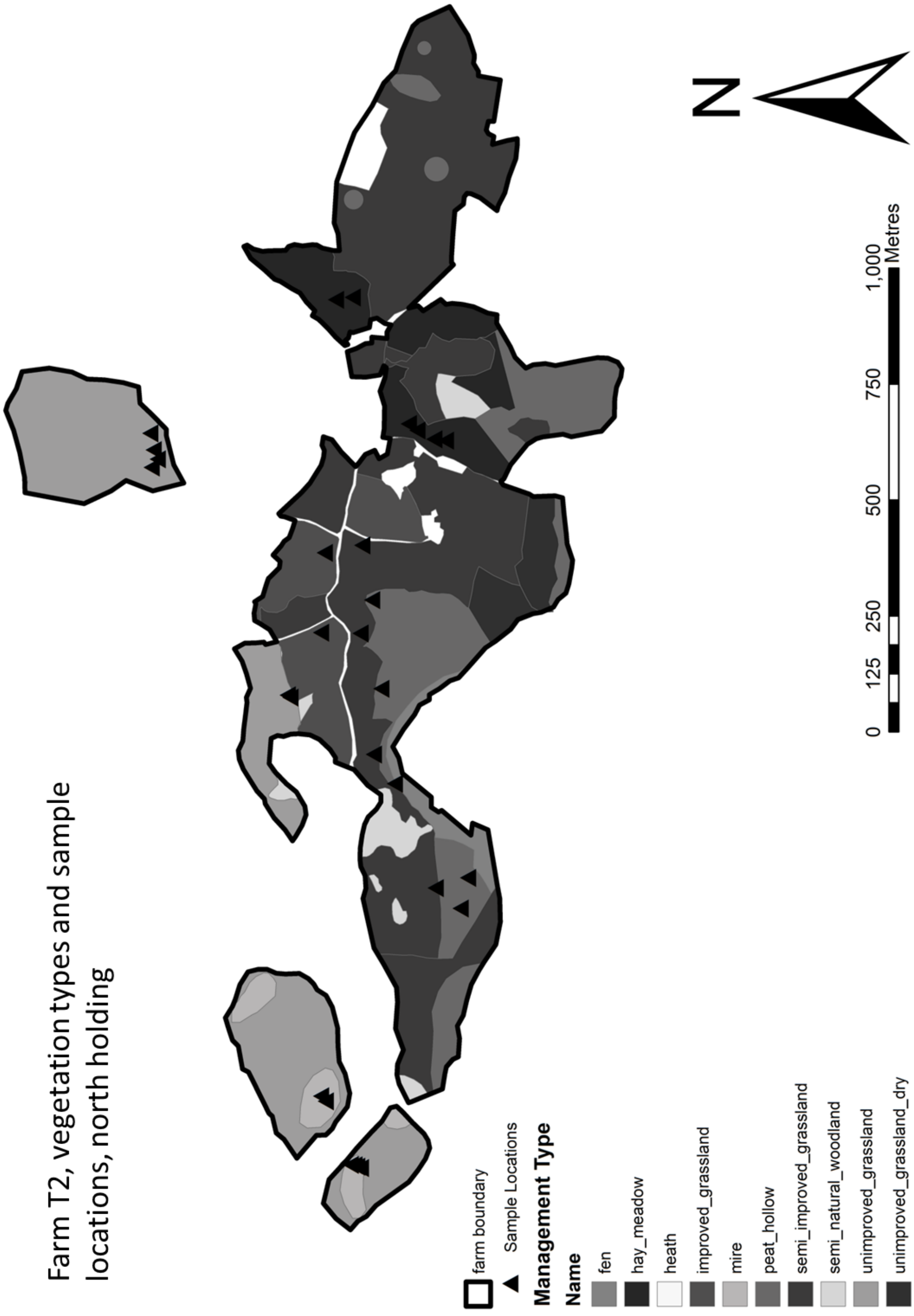

Farm T2, soil carbon stocks, north holding
0.4 - 0.6m
0 - 10
10- 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 100
100 - 110
110 - 120
120 - 130
130 - 140
kg m-3
0
125
250
500
750
1,000
Metres
N


0.4 - 0.6m
0 - 10
10- 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 100
100 - 110
110 - 120
120 - 130
130 - 140
kg m-3
Farm T2, soil carbon stocks, south holding
0
125
250
500
750
1,000
Metres
N

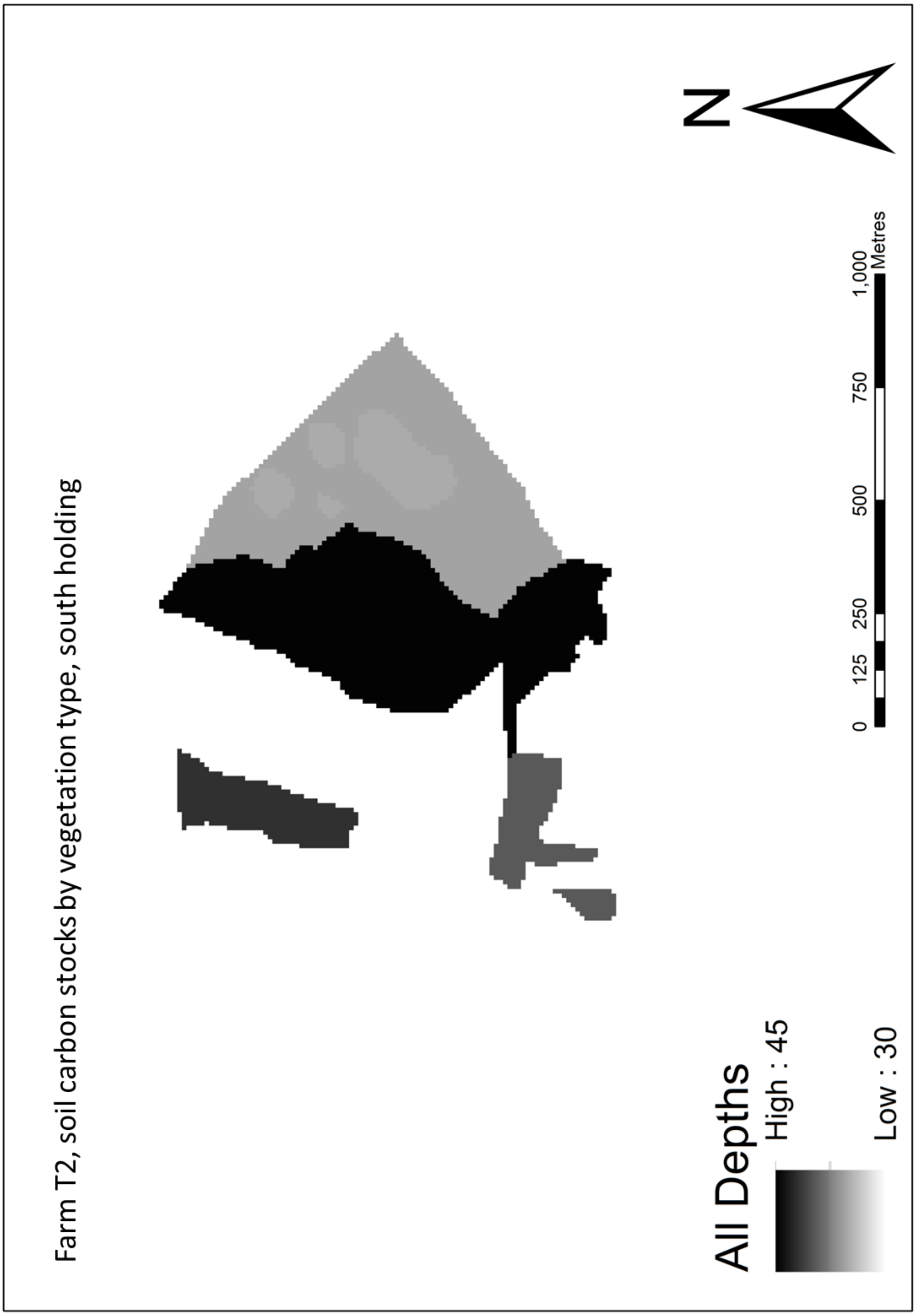

Farm T2, soil carbon stocks, north holding
0.6 - 0.8 m
0 - 10
10- 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 100
100 - 110
110 - 120
120 - 130
130 - 140
kg m-3
0
125
250
500
750
1,000
Metres
N


0.6 - 0.8 m
0 - 10
10- 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 100
100 - 110
110 - 120
120 - 130
130 - 140
kg m-3
Farm T2, soil carbon stocks, south holding
0
125
250
500
750
1,000
Metres
N


Farm T2, soil carbon stocks by vegetation type, north holding
All Depths
High : 45
Low : 30
N
0
125
250
500
750
1,000
Metres

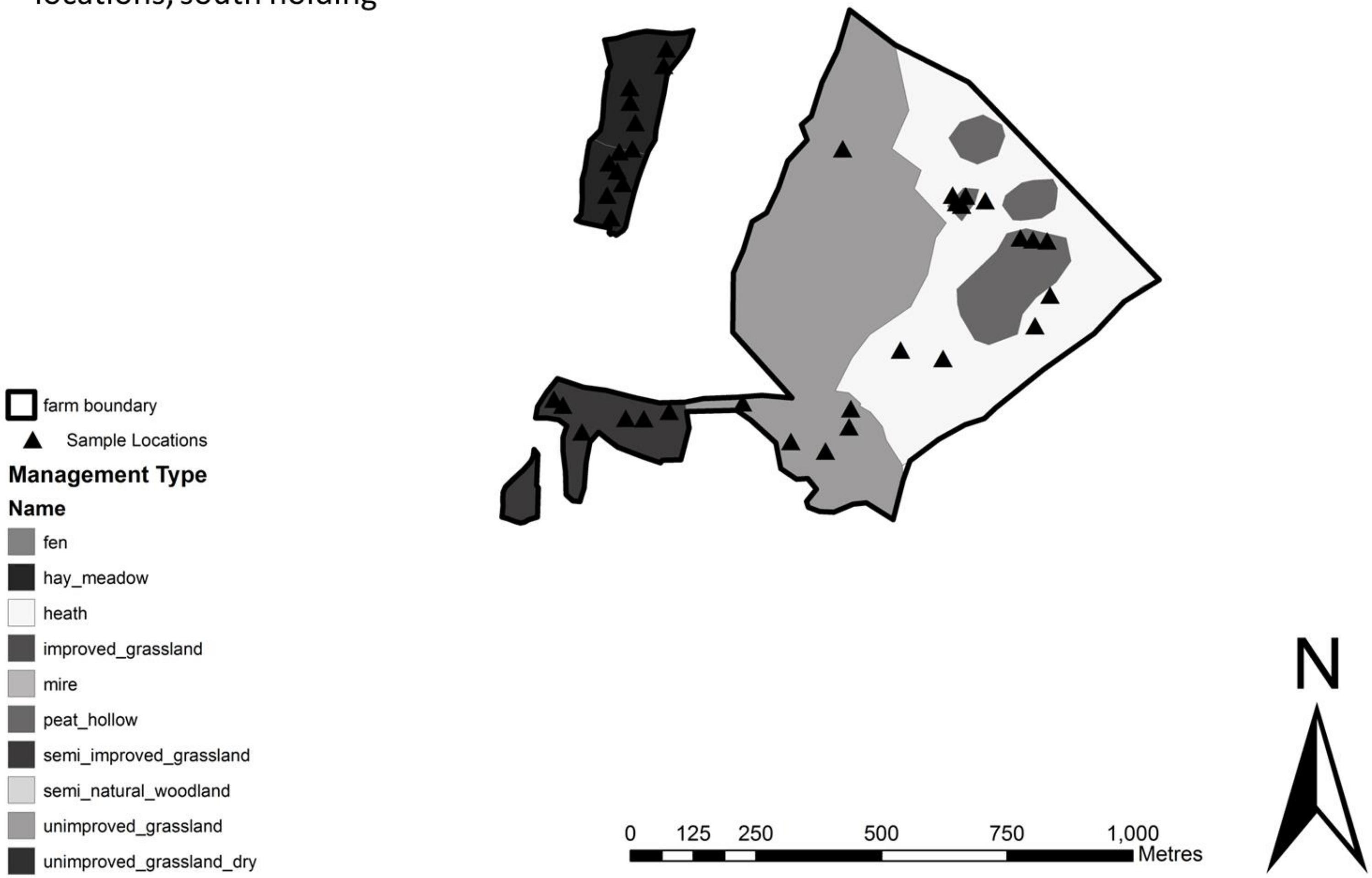


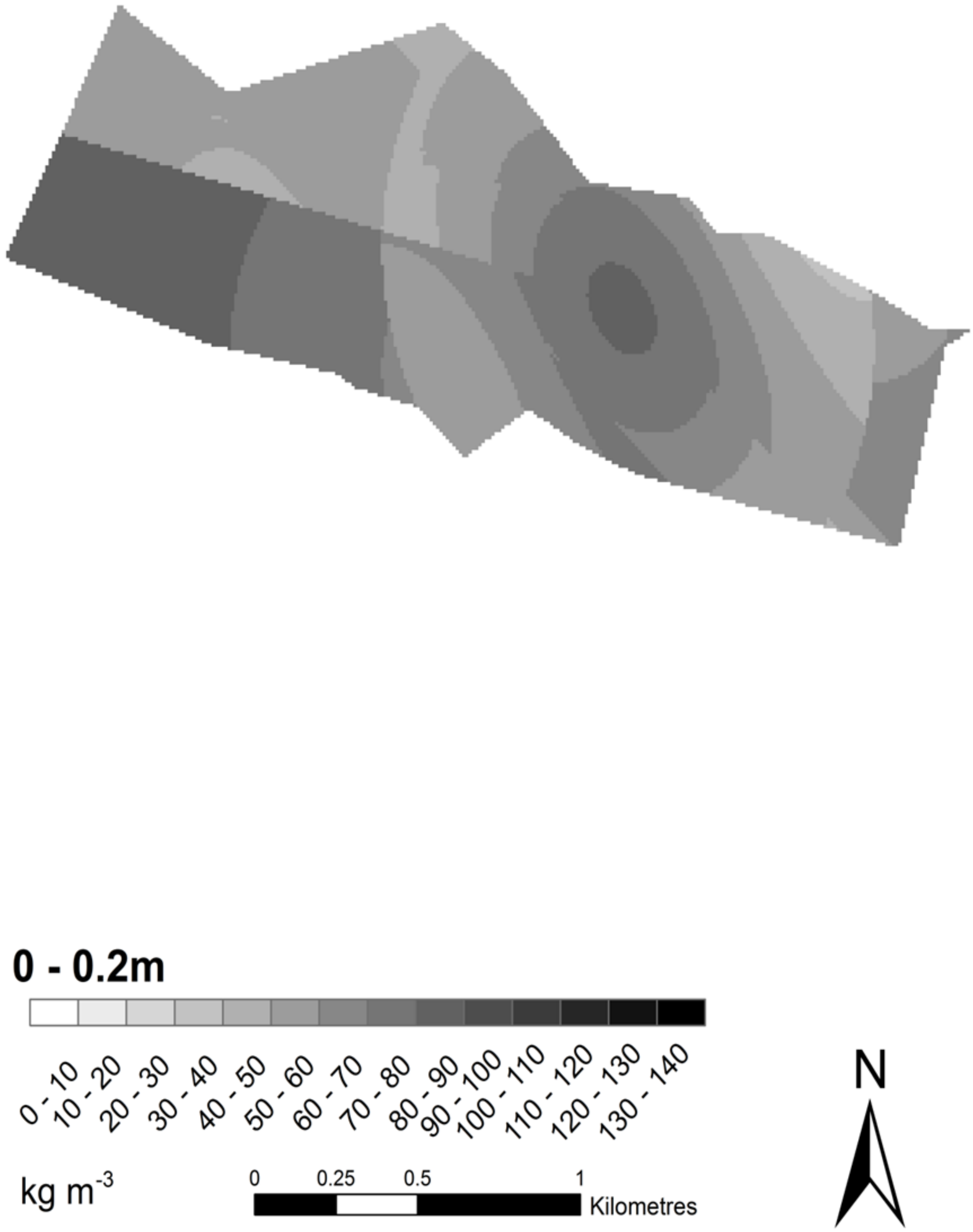
Farm T2, vegetation types and sample locations, north holding



Farm T2, soil carbon stocks by vegetation type, south holding

Farm T2, vegetation types and sample locations, south holding





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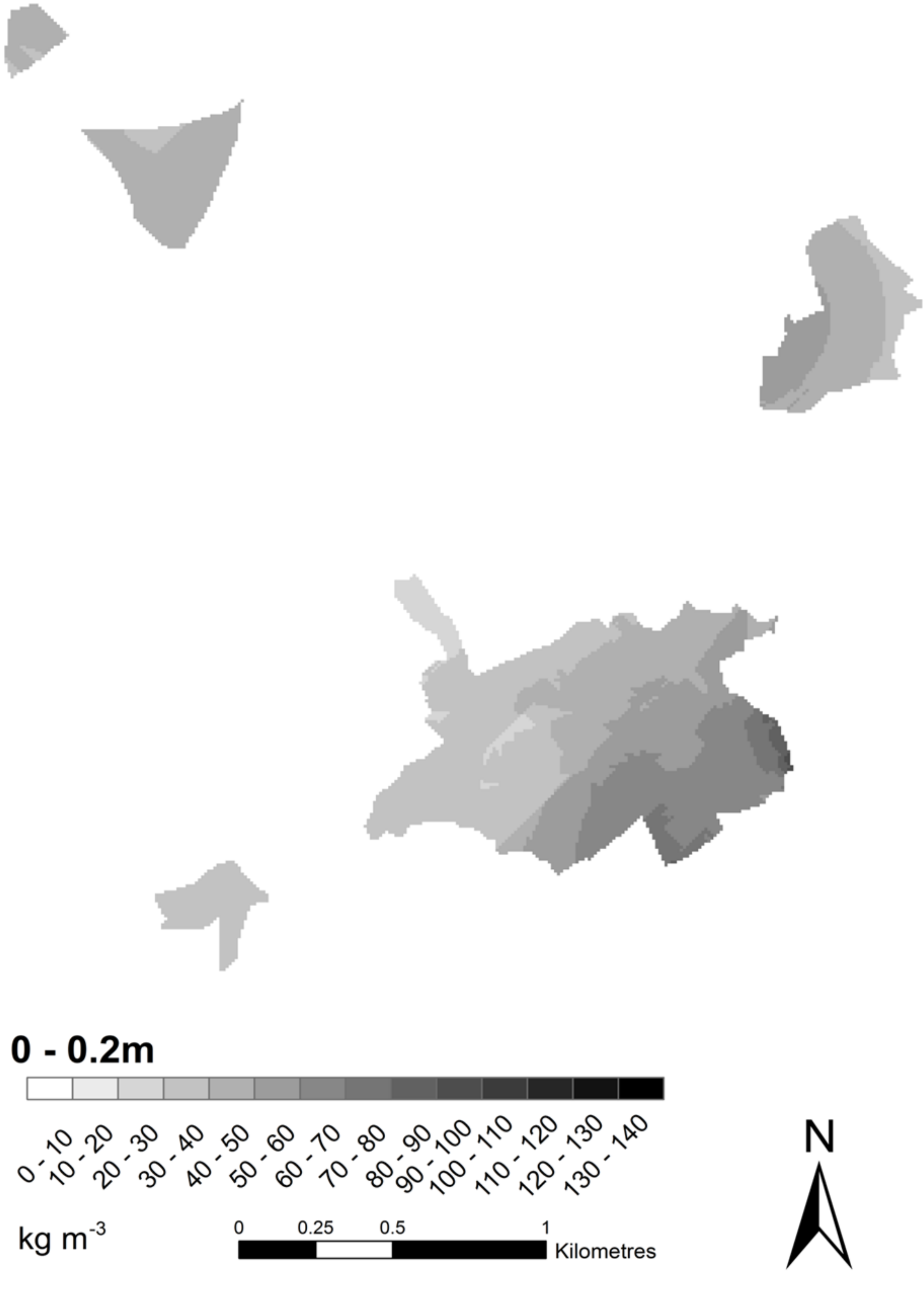

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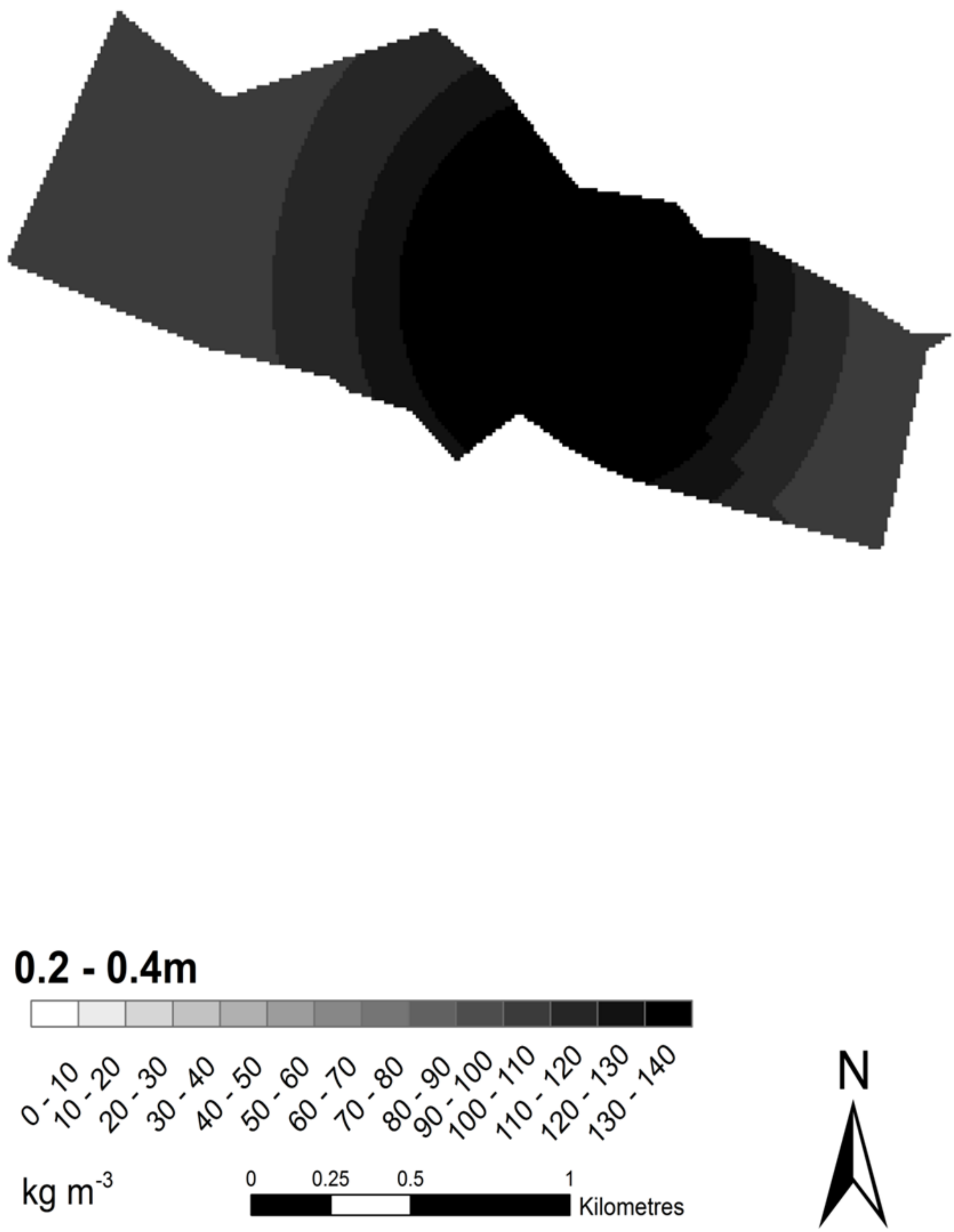

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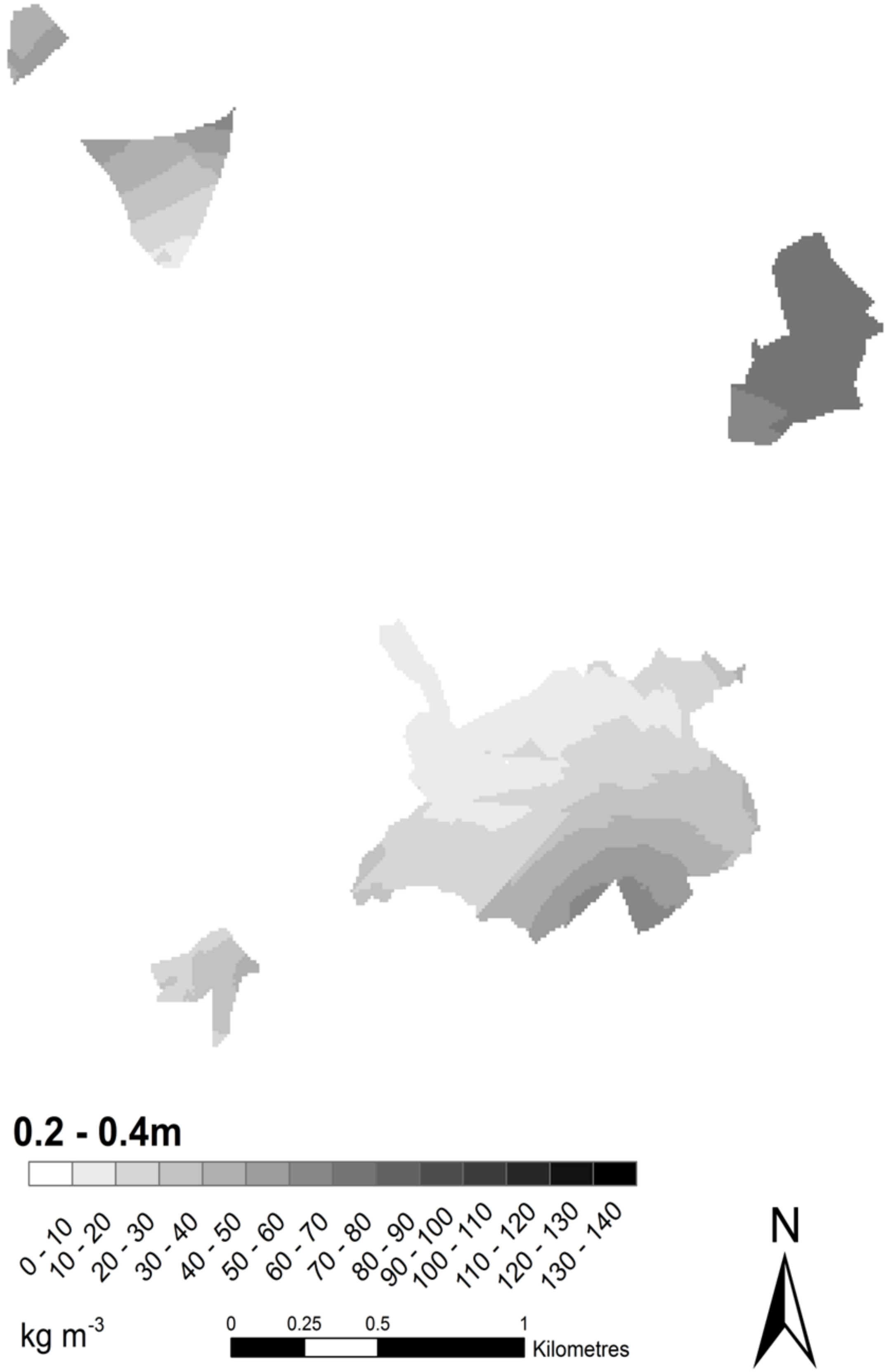

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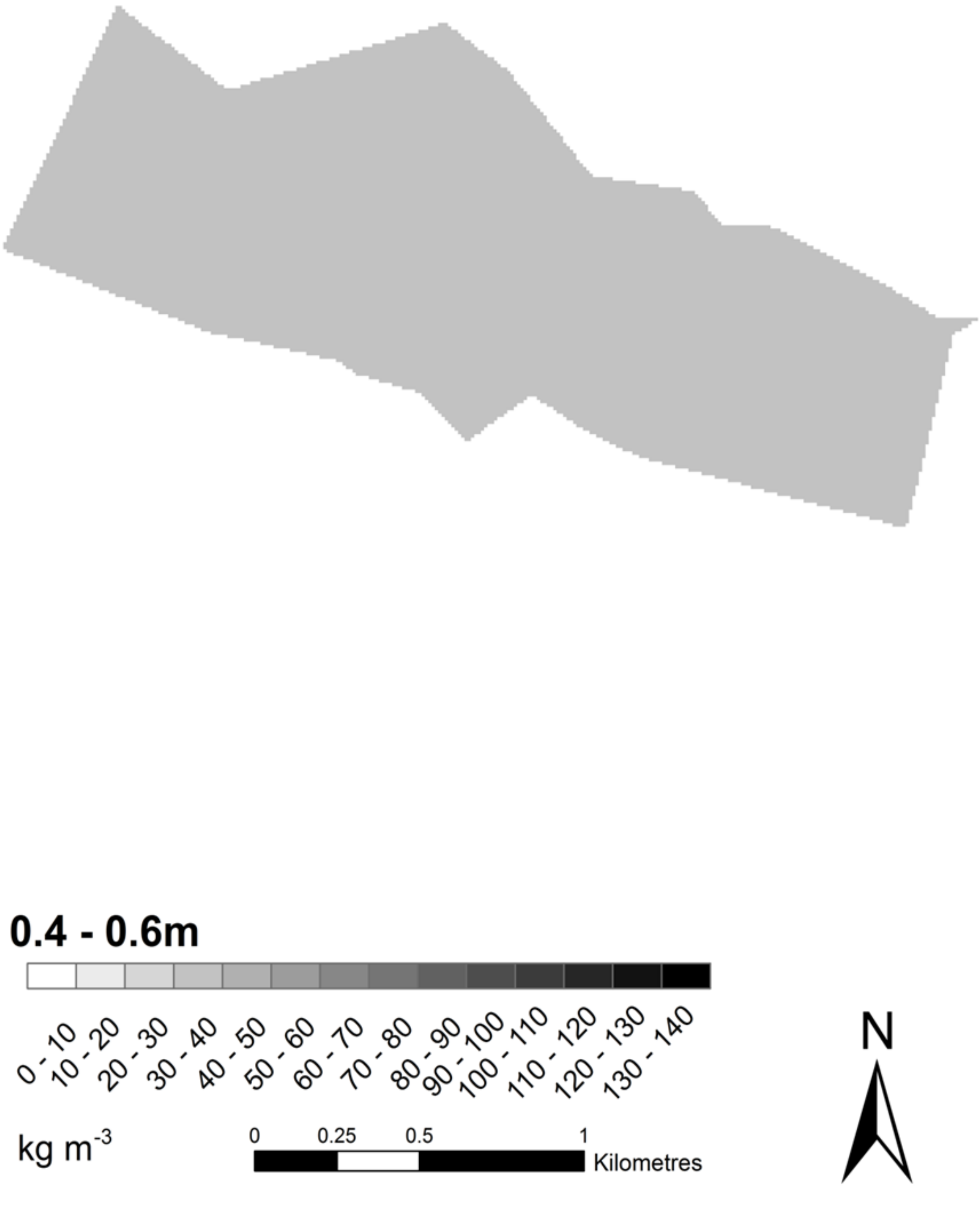

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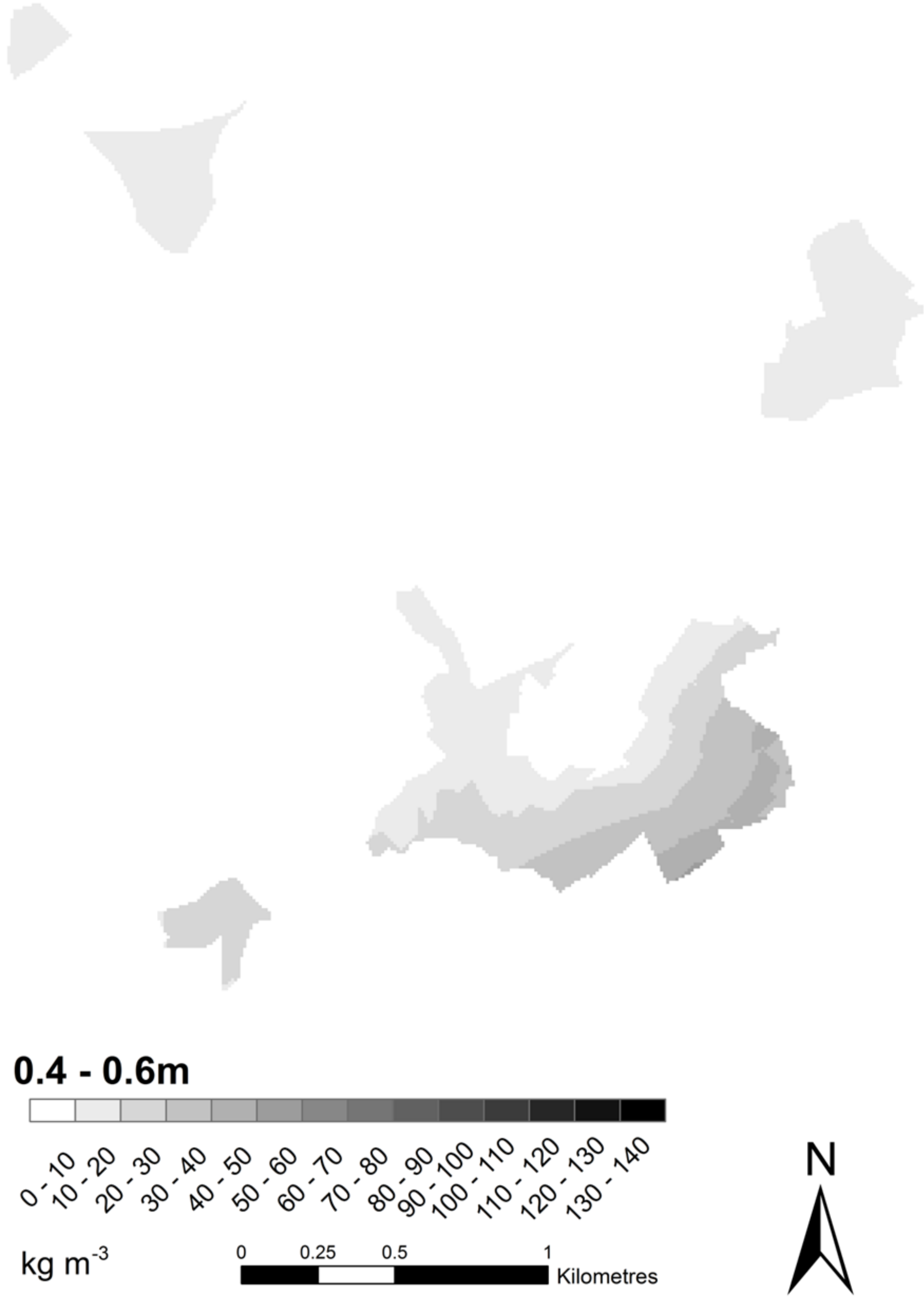

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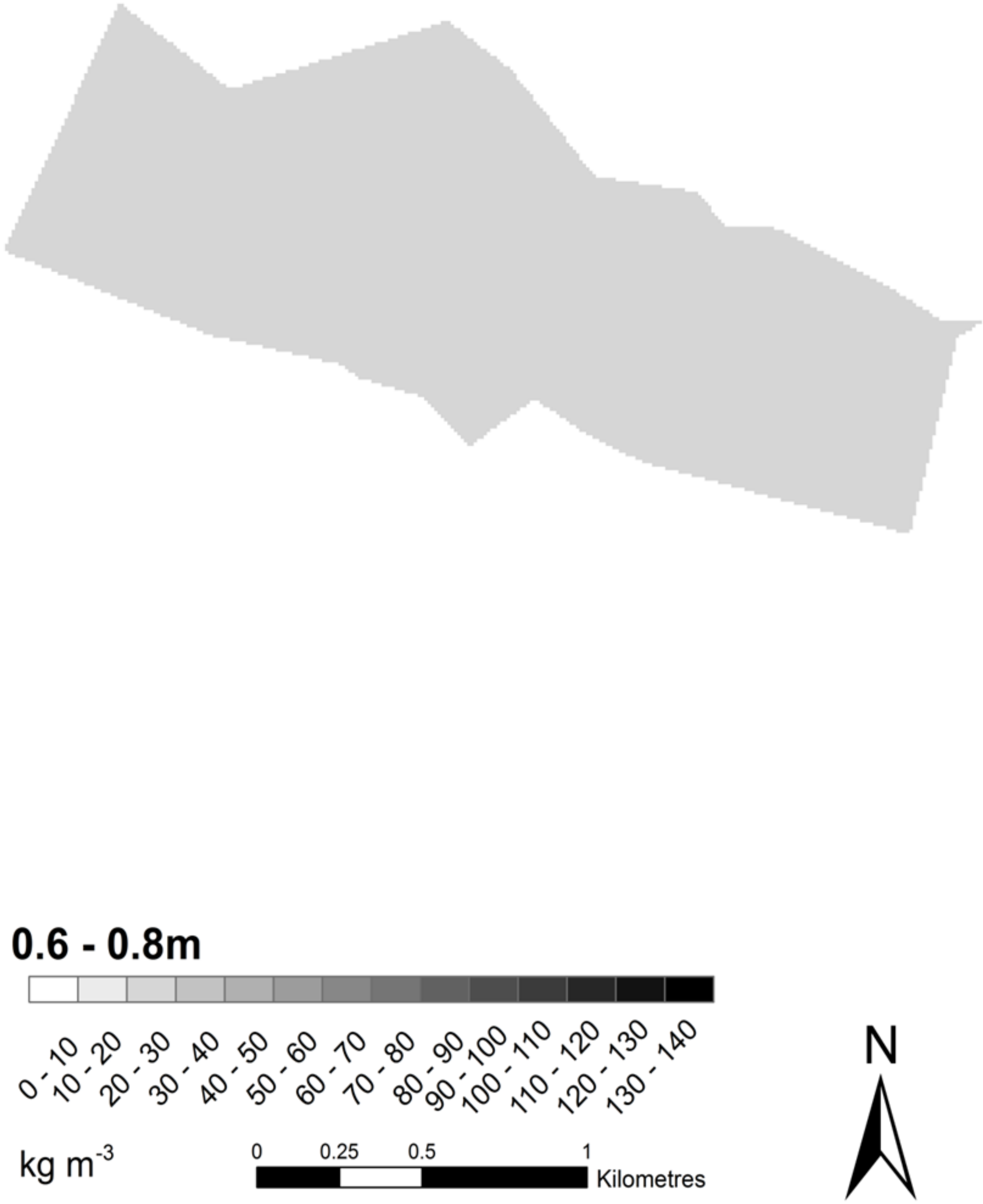

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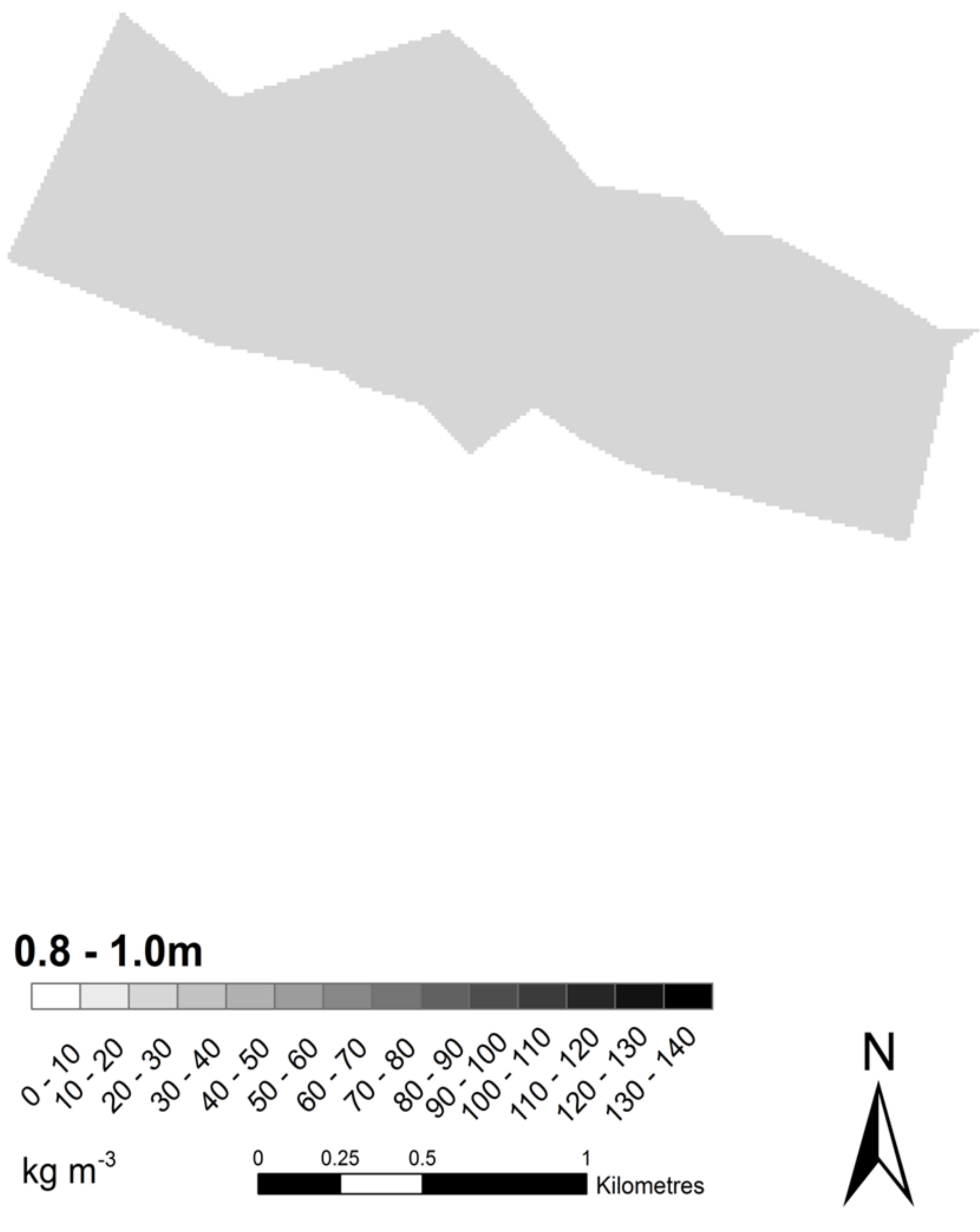

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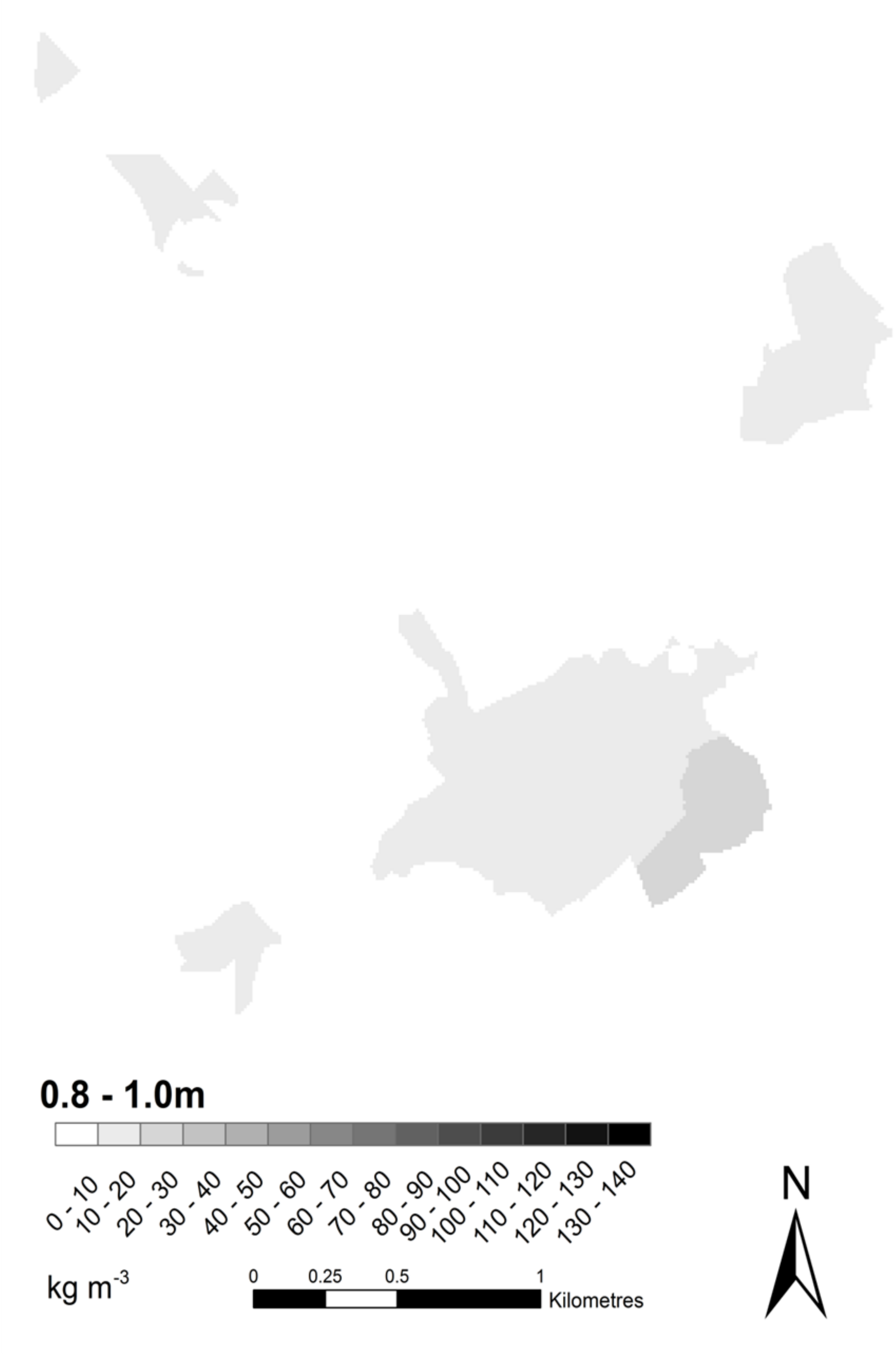

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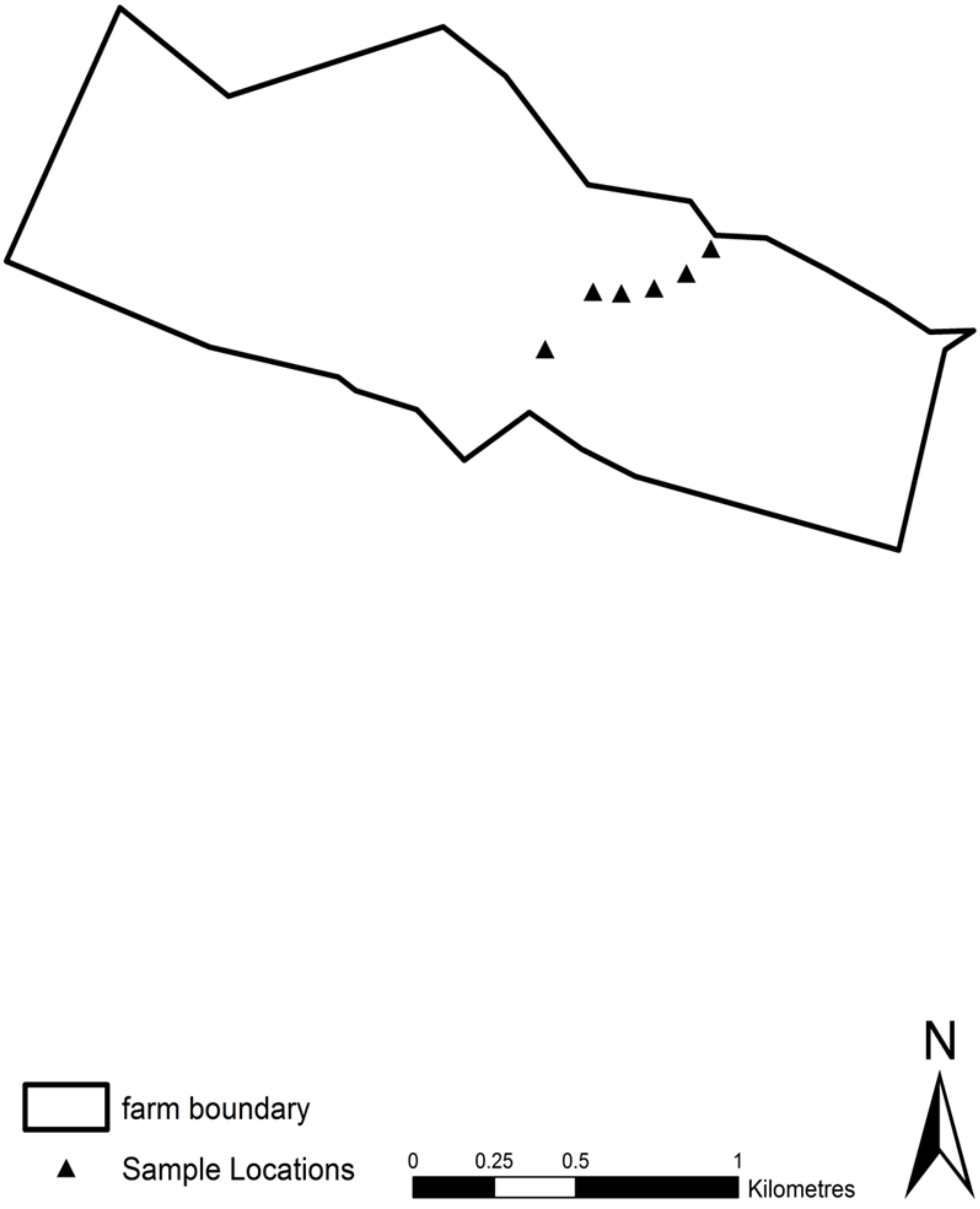
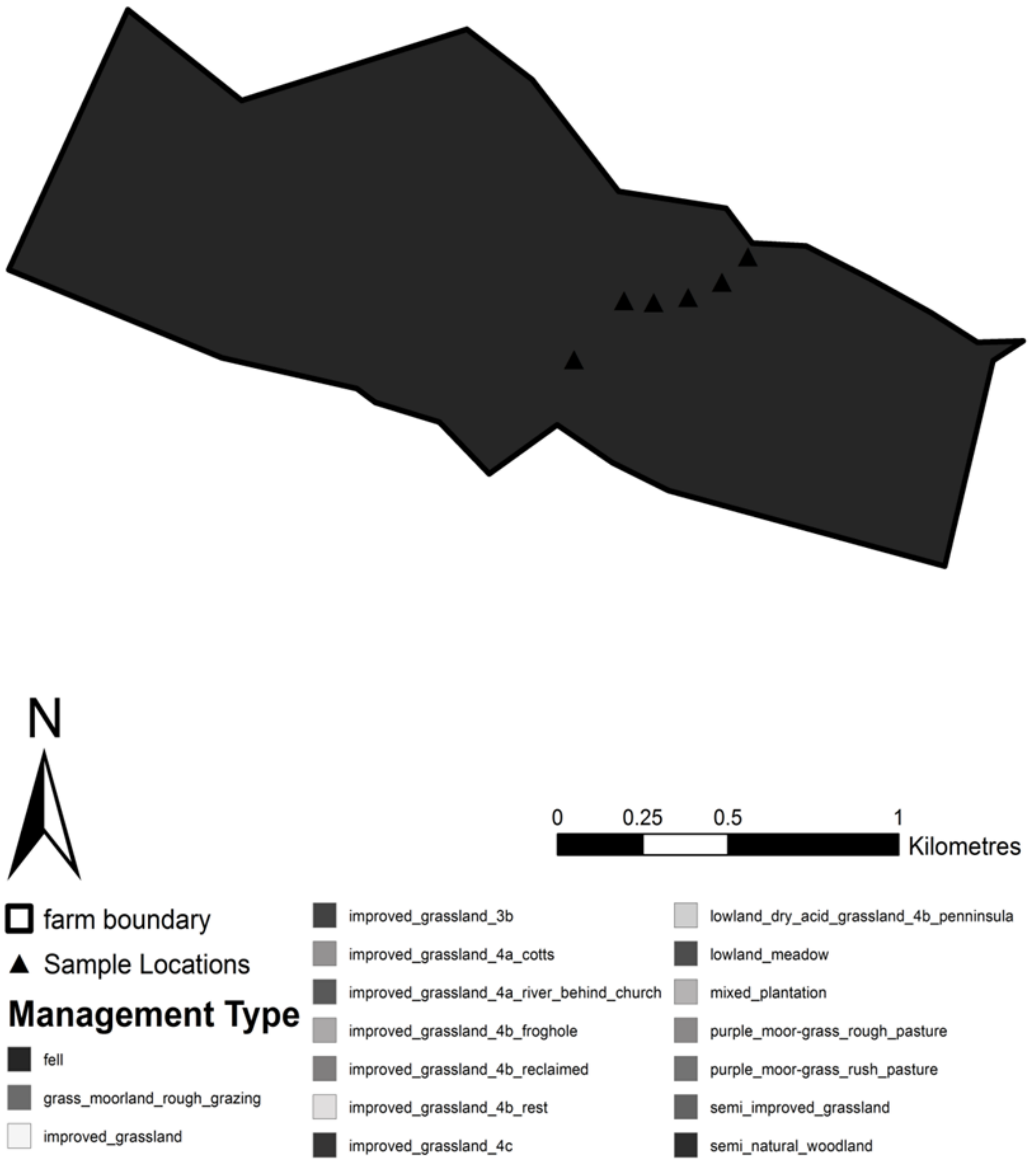


Farm T3, sample locations, east holding

Farm T3, sample locations, east holding



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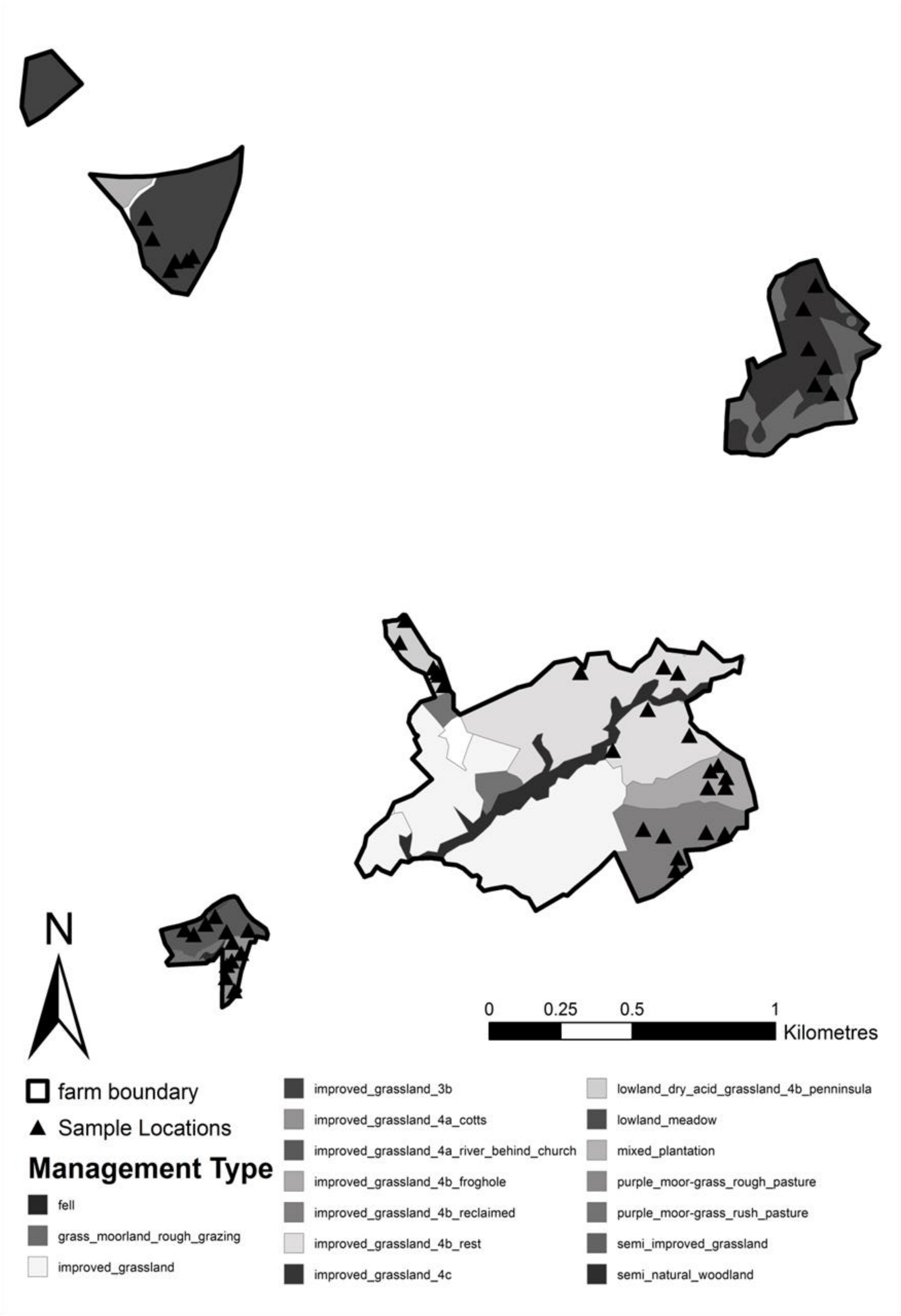

Farm T3, vegetation type and sample locations, west holding

Appendix V – 'Emissions from Crops' POSTnote

HOUSES OF PARLIAMENT
PARLIAMENTARY OFFICE OF SCIENCE & TECHNOLOGY

POSTNOTE

Number 486 January 2015

Emissions from Crops

Agriculture contributes 9% of the UK's greenhouse-gas (GHG) emissions burden and 10-12% globally.[7,8] Although there is a long-term declining trend from UK agriculture,[9] the sector may account for a larger share of overall emissions in the future as other sectors reduce emissions.[10] This POSTnote focuses on reducing GHG emissions from growing and storing arable and horticultural crops.

Overview

- Climate change mitigation and food security present challenges to agricultural systems.
- Nitrogen management has the greatest potential for reducing greenhouse-gas emissions from farming crops.
- Research suggests increasing stocks of carbon in soil can reduce emissions and improve soil fertility,[1-4] but other studies indicate that the UK's capacity to increase soil carbon stocks through cropland management may be limited.[5,6]
- Mitigation options need to be evaluated as part of the global food system in order to avoid exchanging one form of pollution for another.
- Improving farm efficiency alone will not be enough to ensure reductions in greenhouse-gas emissions and food security; diet change and food waste reduction will also need to be considered.

Agricultural Emissions and Sources

The 2008 Climate Change Act aims to reduce the UK's GHG emissions by at least 80% (from 1990 levels) by 2050. For agriculture in England, a reduction objective of 3 million tonnes of carbon dioxide equivalent ($MtCO_2e$) per annum is set for the period 2018-2022, an 11% reduction on 2008 emissions levels. Similar reductions are required for Scotland (1.3), Wales (0.6) and Northern Ireland (0.276).

Nitrous oxide (N_2O) contributes more to global warming than any other gas emitted from agriculture (Table 1). Soils are the main source of agricultural nitrous oxide emissions (90%);[9] which arise from microbial activity following application of man-made nitrogen fertilisers, farmyard manures and slurries and re-deposition of airborne nitrogen pollution to land (POSTnote 458). Nitrous oxide is also emitted from nitrogen leached into water bodies (POSTnote 478). The main sources of agricultural CO_2 emissions are on-farm energy use and crop storage. The majority of methane (CH_4) emitted from agriculture is from fermentation by livestock digestive systems (POSTnote 453) and the anaerobic break-down of stored farmyard manures and slurries (POSTnote 387). Methane is also produced as a by-product of the decomposition of organic matter in low oxygen environments, such as flooded rice paddies and wet grassland.[8,11]

Globally, agricultural expansion is a major driver of land use change and associated GHG emissions. Livestock farming and cultivating soya for animal feed are the main drivers (POSTnote 466).[12] The sector emits 30% of global GHG emissions, when all agricultural and land use change emissions are included,[13] and it is estimated that deforestation and forest degradation are responsible for 11% of these emissions.[16] Palm oil and pulpwood

Table 1. UK Agricultural GHG Emissions

GHG	Global Warming Potential (GWP)[a]	MtCO2e[14,b]	% agriculture's contribution to emissions[14]
N_2O	310	30.3	84
CH_4	21	22.3	44
CO_2	1	6.6	1

[a] GHGs vary in the extent to which they contribute to the greenhouse warming effect. GWPs assigned relative to CO2 are expressed over a period of 100 years (POSTnote 428).
[b] CO2e is calculated by multiplying the weight of gas emitted by the gas's GWP. There is uncertainty in calculating emissions (Box 1).

Box 1. Agricultural GHGs and Emissions Reporting
The UK is obligated to provide an inventory of its GHG emissions to the United Nations Framework Convention on Climate Change (UNFCCC) and the European Monitoring Mechanism (EUMM). Defra and the Devolved Administrations are funding a £12.6 million project which will enable the UK to submit agricultural emissions figures with reduced levels of uncertainty.[15] A major outcome will be refined emissions factors for nitrous oxide and methane from the range of agricultural sources. An emission factor is the rate of GHG emission per unit of activity, output or input. For example, the emission of nitrous oxide is expressed as a percentage of nitrogen input to the soil. The factors will be region-specific and will take into account different nitrogen sources (fertiliser type, livestock slurries and manures, and urine and dung deposition by outdoor livestock), as well as soil type and weather conditions. These refined factors will be used with improved regional farm practice data in a new reporting tool.

production is another major driver; in recent decades over 10 million hectares of peat swamp-forest in South East Asia has been drained for agriculture, leading to rapid peat degradation and large CO_2 emissions.[17]

Mitigation Options

This POSTnote focuses on mitigating GHG emissions from growing and storing crops through improved ‘emissions efficiency’ (minimising GHG emissions produced per unit of agricultural output). The following key issues are dealt with:

- improving nitrogen management
- soil carbon storage
- water and crop residue management for flooded rice
- improvements in on-farm energy efficiency (Box 2).

Options for emissions mitigation need to be considered with food security and adaptation to climate change in mind.[18] Climate change is predicted to have profound effects on global food production via temperature change, altered water availability, and changing patterns in crop pests and diseases, among other things.

Mitigating Nitrous Oxide Emissions

On-Farm Nitrogen Management
The addition of synthetic nitrogen fertiliser to land leads to increases in crop yield but also to large amounts of reactive nitrogen being added to soils (Box 4). Under most conditions, the more nitrogen added to soil the greater the nitrous oxide emissions.[19] A desired balance is to supply adequate nitrogen to maximise crop yield while reducing the release of excess nitrogen into the surrounding environment (nitrogen pollution). However, in England, 40% of farms have no nitrogen management plan (accounting for 26% of the farmed area) and Scotland reports similar figures.[20,21] Defra provides guidance on application levels for different crops under a range of conditions,[22] but the Agriculture and Horticultural Development Board is concerned that much of this information is out of date.[23,24]

Good nitrogen management requires the farmer to know how much nitrogen is in the soil and other relevant soil properties, such as pH, as well as the quantity of farmyard manure and slurry (FYMS) available for addition to land and how much nitrogen it contains. Weather conditions play an important role, as nitrous oxide emissions tend to be associated with warm and wet top soils (as well as with

Box 2. On-Farm Energy Management
Some examples of on-farm energy-efficiency measures:

- The Potato Council has identified energy costs associated with potato storage as a sector focus and has launched the Storage 2020 project to assist growers.[25]
- In horticulture, use of LEDs, improved design, and consideration of alternative energy sources for lighting and heating can improve greenhouse energy-efficiency.
- The UK tomato industry uses atmospheric CO_2-enrichment to improve yields. Using waste-CO_2 improves energy efficiency, for example Cornerways Nursery uses waste-CO_2 from British Sugar.[26]

high soil nitrogen levels).[27] Careful timing of fertiliser applications, on the basis of medium-range weather forecasting and crop requirement, can reduce both direct emissions of nitrous oxide and leaching of nitrogen into water bodies.[11] Appropriate FYMS application techniques, storage capacity and management will also help to minimise nitrogen pollution (POSTnote 453). Managing land to reduce levels of nitrogen in water bodies also has the benefit of reducing nitrous oxide emissions.

Precision Farming to Optimise Nitrogen Management
Precision farming uses technology, agricultural engineering and data to help farmers apply treatments efficiently through the 4Rs: “right intervention, right time, right place, and right amount” (Box 3). In 2012, 22% of English farms used Global Positioning Systems and 20% used soil mapping to optimise treatments. Larger farms are more likely to take up the technology with almost half of farmers who do not use any precision farming techniques stating that they are not cost effective or the initial setup costs are too high.[28] The recently launched £160 million Agricultural Technology Strategy, co-funded with industry, includes funding for the translation of precision farming research.

Plant Breeding to Optimise Nitrogen Management
Most commercial plant breeding focuses on maximising crop yields under optimal plant growth conditions. Focusing breeding programmes on optimising yields under lower nitrogen conditions would take account of the link between soil nitrogen levels and pollution.[29] A large body of research highlights the importance of plant root and soil interactions in affecting plant growth and GHG emissions from soils.[30-33] Plants are influenced by the soil environment but they can, in turn, affect the communities of soil microbes that produce GHG emissions (Box 4).

Agroecology to Optimise Nitrogen Management
Agroecology emphasises ecological principles in the design and management of agriculture and explicitly integrates the protection of natural resources into food production.[34] For example, organic farms rely on biological nitrogen fixation by legumes, such as clover, to supply nitrogen, instead of artificial fertiliser (Box 4). These farms avoid GHG emissions from fertiliser manufacture and some studies have shown less nitrous oxide emissions from soil per unit of land.[35,36] However, there are often lower yields which offset these reductions.[35,36] Some studies have found the cropping system and site characteristics are more important than any organic/non-organic distinction.[37-39] For example, many non-

Box 3. Precision Farming and The Internet of Things
Fertilisers are usually applied at uniform rates across a field. However, using a precision farming approach creates soil property and crop growth maps through manual sampling, in-field or vehicle-mounted sensors or by aerial or satellite imaging. Software then predicts the level of inputs for each part of the field that will produce the greatest yield increases with the lowest costs. As machinery passes through the field, variable-rate application devices automatically adjust the delivery of seeds, fertiliser or plant-protecting chemicals to distribute them optimally.

The Internet of Things (POSTnote 423) connects devices, such as in-field sensors with previously isolated data sets, such as farm fertiliser records and meteorological information; this enables better management decisions based on more comprehensive information.

organic farms are also making use of legumes within crop rotations to supply nitrogen to the system.[40]

Agroforestry is an agroecological land-use system that integrates trees and shrubs with crops and/or livestock production. It is used in the production of global commodities such as coconut, coffee, tea, cocoa, rubber and gum.[41] Agroforestry systems require less fertiliser inputs as less nitrogen leaches out of the soil and recycled nitrogen from leaf litter provides a source for adjacent crops.[42] It is not clear how nitrous oxide emissions from soil are affected.[43] Increasing tree cover on agricultural lands reduces atmospheric carbon by increasing terrestrial carbon storage. A review of tropical agricultural systems highlights the potential of agroforestry to mitigate GHG emissions.[44] Agroforestry's potential for mitigating GHG emissions in temperate systems has been less well studied.[43,45]

Improving Global Use of Fertiliser
Large parts of the world – and sub-Saharan Africa in particular – suffer from low production efficiencies due to poor soils and low fertiliser application rates. The Alliance for a Green Revolution in Africa (AGRA) has enrolled 1.75 million small-holder farmers in a programme to increase yields through monitoring soil health and providing access to fertiliser, legume seeds and microfinance. AGRA farmers now use 10-50 kg of fertiliser per hectare, and although just a tenth of what farmers use in richer countries, this has helped contribute to an average doubling of yields.[46] Proponents of an agroecological approach highlight the potential for adopting alternative management practices sensitive to local conditions, such as optimising planting and weeding dates, erosion control and water harvesting.[47,48] As the largest producer and consumer of nitrogen fertiliser, China's participation is critical to global efforts to reduce nitrogen-related GHG emissions. The use of nitrogen fertiliser has helped double crop yields in China during the past three decades. However, recent studies have highlighted gross over-application with a nationwide application rate of 30-60% above optimum.[49,50]

Mitigating Carbon Dioxide Emissions
Maintaining Soil Organic Carbon Stocks
Soil contains organic material, some of which is carbon. Soil organic material is composed of soil microbes, decaying plant and animal tissues, faecal material and products formed from their decomposition. Soil microbes can make

Box 4. Potential Nitrogen Management Biotechnology Solutions
Nitrogen is an essential element for life. It occurs predominantly as an unreactive gas in air; which means that only a few organisms can utilise it directly. This ability is only available to a select group of plants, including legumes (e.g. alfalfa and clover). These plants form a mutually-beneficial association with bacteria which can convert unreactive nitrogen from the air into a reactive form of nitrogen which is available to the plant. Scientists at the John Innes Centre in Norwich are in the early stages of a project that aims to transfer this capability into cereal crops.[51,52]

Industrial-fixation of nitrogen from the air creates reactive nitrogen (synthetic fertiliser) which can be added to soils in a form available to plants. The large amount of synthetic fertiliser added to agricultural systems has led to nitrogen cycles dominated by processes called nitrification and denitrification. These processes lead to enhanced nitrous oxide production by soil microbes; which reduces the amount of nitrogen in the soil available to plants. To address this issue there has been research conducted into the inhibition of these processes:
- Chemical nitrification inhibitors have shown potential in arable and grassland trials, however cost-effectiveness remains uncertain.
- Some varieties of crop plants naturally inhibit nitrification and reduce nitrous oxide release from denitrification: 'biological inhibition'. Research carried out at the James Hutton Institute in Dundee has highlighted the potential of high-yielding spring barley varieties to limit nitrogen losses. It is thought that varieties from other crop species may hold the same potential.[53]

carbon and nitrogen available to plants, immobilize carbon and nitrogen in soil, and also decompose organic material to CO_2. Soil organic carbon is in a dynamic balance between the addition of carbon via routes such as manure inputs, returning crop residues (such as straw) into the soil, root growth and root exudates and emissions of CO_2 via decomposition of organic matter by soil microbes.

Modification of agricultural practices is a recognized method of carbon sequestration, as soil can act as a carbon store.[1,2] It has previously been proposed that no- and reduced-tillage (ploughing) practices increase organic carbon stocks. However, evidence published in 2014 suggests that this is not the case and stocks remain the same but are distributed differently in the soil profile.[54] Long-term studies have shown that increasing manure inputs and the amount of crop residue left in the soil can increase total soil organic carbon stocks.[55,56] A review examining datasets from 74 studies in (mainly temperate) climatic zones across the globe found higher carbon stocks on organically-managed farms.[57] Soil organic carbon accumulation will not occur indefinitely: evidence from modelling studies demonstrates that the amount accumulated will reduce (and eventually stop) as a new steady-state is reached[3,5] and accumulation may be reversed if land management practices change.[58]

Defra's interpretation of the available evidence is that soil carbon storage is not an effective mitigation option in the UK.[5,6] Benefits of storage may be insignificant or outweighed by increases in nitrous oxide emissions, the risk of nitrogen run-off into water and short-term elevated CO_2 emissions.[59]

Maintaining carbon stocks in cultivated soils is important for sustaining yields and preventing soil degradation.[3,4] Soil degradation can lead directly to GHG emissions (Box 5).

There has been an overall loss of soil carbon from the UK's intensively-managed agricultural soils since the 1970s.[60]

Mitigating Methane Emissions from Rice Cropping

Rice feeds almost half of humanity.[61] Flooded rice contributes approximately 10% of global agricultural GHG emissions, with methane as the primary GHG emitted.[62] There is evidence that including a dry period leads to an average 48% reduction in methane emissions, without yield reductions. Approximately 40% of rice farmers in China and more than 80% in north-western India and Japan are applying a dry rotation as part of water-saving practices.[62] Composting rice straw before incorporating it back into the soil reduces methane emissions, as the act of composting reduces available carbon for the methane-emitting soil microbes.[63,64]

Using Policy to Reduce GHG Emissions

In the UK there is no specific legislation addressing agricultural emissions reductions. Instead, a voluntary industry-led approach has been adopted. Organisations from the sector in England have developed the Agricultural Industry GHG Action Plan[65] and the cereals and oilseed industry has a 'Roadmap' to assist with emissions reduction.[66] In the UK, cereals cover 51% of croppable land, with oilseeds and other arable making up 20%. Horticulture and potatoes cover 5% by area.[67] The Government is also supporting scientific and technological advances in 'sustainable intensification'; whereby yields are increased without damaging the environment including the cultivation of additional land.[68] In 2016, the Government plans to bring forward legislation for the Fifth Carbon Budget (which covers the period 2028-2032). The Committee on Climate Change (CCC) has recommended that Government ensures the agricultural sector monitors the effectiveness of the Industry Action Plan. They highlighted the need for quantifiable targets and evidence of buy-in from farmers, to allow effective evaluation in the Government's 2016 review.

The Scottish Government has developed the Farming for a Better Climate website which is designed to encourage voluntary uptake through the provision of information on win-win actions in five key areas, one of which is optimal application of fertilisers and manures.[69] It plans to introduce regulation if sufficient progress is not made to increase nitrogen use efficiency.

The Welsh and Northern Ireland Administrations have also established plans to consider how agriculture can reduce emissions.[70,71] One of the aims of the 'greening' component in the latest set of Common Agricultural Policy reforms is to support climate-beneficial agricultural practices.[72] However, the CCC has stated they are unlikely to reduce GHG emissions significantly.[9]

What Works Where

To establish which mitigation mechanisms are most effective they need to be considered as part of a wider system. Systems assessments can take into account all inputs (e.g. imported feed and synthetic fertiliser) and outputs (e.g. pollutants and crop yields) and costs that fall outside farming, such as additional drinking water treatment.

Box 5. Soil Degradation in England

Areas of lowland peat, such as the Fens and the Lancashire Coastal Plain produce 40% of the vegetables grown in England.[73] Once wetlands, these areas were drained for agriculture. Drainage of carbon-rich soils leads to soil degradation as microbes decompose the organic material and CO_2 is emitted. The top soil has disappeared completely in some areas and climate change could lead to complete loss from remaining areas in 30 to 60 years.[74]

The Natural Environment White Paper sets out the Government's responsibility to manage lowland peat soils in a way that supports efforts to tackle climate change. Suggestions to prevent the continued loss of these soils include re-wetting areas for low-intensity livestock grazing on wet grassland, wet agriculture (such as sphagnum moss farming and reed bed creation) and restoration of wetland habitats. (Some of these options take the land out of food production). These mitigation options can support other benefits such as water quality, flood management and biodiversity improvements.

Applying this approach when evaluating options helps avoid:

- 'pollution-swapping' (when a mitigation option introduced to reduce one pollutant results in an increase in another)
- 'exporting emissions' (e.g. domestic GHG emission reductions being offset by increased emissions abroad).

Such assessments can use production efficiency calculations, such as how much GHG is emitted relative to a unit of agricultural production. There are different ways of calculating this, such as emissions per dry weight of crop, per area of land cultivated or per nutrient consumed, or other assessment approaches based on economics and pollution-swapping modelled using nitrogen budgets.[75] Debates continue over appropriate models and metrics, relevant time-frames, inputs and outputs.[76-79]

Recent studies predict that efficiency measures alone will not ensure environmentally-sustainable food security.[13,80-84] The food system is global: the UK imports 40% of total food consumed,[85] so international agricultural emissions need to be included through systems assessments. Demand-restraint measures, which focus on dietary change (e.g. eating less livestock products) and reducing food waste (POSTnote 453), need to be considered alongside issues such as affordability and access to adequate nutrition that are affected by social and cultural factors.[76,86-90]

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POST is an office of both Houses of Parliament, charged with providing independent and balanced analysis of policy issues that have a basis in science and technology. POST is grateful to Beth Brockett for researching this briefing, to the British Ecological Society for funding her parliamentary fellowship, and to all contributors and reviewers. For further information on this subject, please contact the co-author, Jonathan Wentworth.

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Appendix VI – Planet Earth Online article

The science behind the schemes

Planet Earth Online
http://planetearth.nerc.ac.uk/features/story.aspx?id=1513&cookieConsent=A

6 September 2013

Farmers and scientists can learn a lot from each other - but they don't typically socialise. Beth Brockett and Gareth Netto describe a recent event that definitely got the two groups talking.

The idea came about when Beth was talking to Will Rawling, Chair of the Cumbrian Farmer Network, about her planned research on the carbon and nitrogen content of the soil at Will's farm, Hollins. Will commented that he had been to several events on the importance of soil carbon storage, but nobody had ever told him about the science behind it.

So Beth did her best to explain, and in return Will shared some knowledge about how farmers make silage. They both got so much out of the conversation that they began to plan an event specifically to bring farmers and scientists together to talk about something they were both deeply interested in – soil.

Just a few months later Hollins hosted a group of more than 30 researchers, farmers and farming advisors, who gathered together on different parts of the farm to share their knowledge.

One group of researchers described their work on soil compaction in the Eden Valley, and how compaction and intense rainfall combined can lead to flooding. This is a familiar problem for many farmers in the area, and the group talked about things they could do differently to reduce the risk – such as reducing stock levels and farm traffic, or introducing species-rich pasture to improve soil structure.

The researchers were able to give farmers a better insight into the whole scientific process, explaining how carbon and nitrogen emissions are measured both in the field and in the lab (a length of drainpipe hammered into the ground being particularly helpful for the latter). Processes like photosynthesis and respiration occur above and below ground with soil microbes playing a huge role, and much of the discussion focused on the significance of nitrogen and carbon storage and leaching on things like soil quality, grassland productivity and resilience to drought.

They also talked about how plant traits, such as root length and leaf size, affect carbon and nitrogen retention underground, and how this links to the activities of soil microbes. Beth's own research looks at the potential for using satellite images to analyse vegetation and estimate below-ground processes.

It turned out that fieldwork wasn't just the preserve of the scientists; one farmer described an experiment he is running on his dairy farm comparing how quickly silage fields and sheep pasture absorb water. Local farmers Duncan Ellwood and Sam Rawling talked about a monitoring scheme on nearby Kinnerside Common – a collaboration with Natural England – which aims to increase vegetation diversity on the common. Farmers are trained in plant identification and surveying – with the aid of a GPS, good eyes and a handbook – and paid for submitting information regularly.

'It is really important that farmers have a better understanding of how soils and everything that is stored in them work,' said host Will. 'Much of what was discussed at the meeting was actually about good farming practice, and if it helps to reduce damage to the planet then we all win.'

Farmers say it takes too long for scientific understanding to filter through to them, and many rely on advisors, who also feel they have limited access to useful information. Most believe that stronger bonds between farmers, advisors, scientists and policy-makers can only be a good thing – and this kind of event is definitely a step in the right direction.

More information

Beth Brockett is a PhD candidate at Lancaster Environment Centre, from which Gareth Netto is a recent graduate. Email: b.brockett@lancaster.ac.uk and g.netto1@lancaster.ac.uk

The event was supported by the Cumbrian Farmer Network, NERC, Lancaster University and the University of Manchester, and sponsored by the Ecosystems Knowledge Network and the Agricultural Ecology Group from the British Ecological Society.

Keywords: Adaptation & mitigation, Biodiversity, Farming, Pollution,

Post a comment

11346 You say most believe that stronger bonds between farmers, advisors, scientists and policy-makers can only be a good thing - and this kind of event is definitely a step in the right direction. My colleagues and I do agree with you.

It is possible to be more direct, moving forward faster. If you are interested do contact me. Ian

Dr Ian Priban, United Kingdom

Monday, 9 September 2013 - 09:33

Thank you for your comment Ian. I can't access your contact details, so please send me an email (b.brockett@lancaster.ac.uk) as I'd be interested in hearing more about your work. Beth

Beth Brockett, Lancaster University

Tuesday, 10 September 2013 - 13:39

Appendix VII – Landbridge blog article

landbridge:
A knowledge exchange network for rural professionals

Friday, 5 July 2013

The science behind the schemes

PhD student Beth Brockett shares her experience of a knowledge exchange event that brought research scientists together with the people at the practical end of land management

The idea for a knowledge exchange event came about while I was having a chat with Chair of the Cumbrian Farmer Network, Will Rawling, over tea and cake in his kitchen. I was preparing to carry out fieldwork on Will's farm to estimate soil carbon storage and nitrogen retention and he commented that, although he had attended many events about the importance of greenhouse gas mitigation and agriculture, no one had ever explained the science behind the process of soil carbon storage to him. I did my best to remedy this, and in return Will talked me through the processes involved in silage fermentation. It struck us both that it was a shame farmers and scientists didn't talk like this more often and in June of this year twelve farmers, ten farm environment advisors and nine academics met at Will's farm to discuss a range of scientific topics pertinent to livestock farming in the northwest.

The event started outside with three different activities. In one part of a field, academics gathered participants around a soil pit to explain research into soil compaction and how, when combined with intense rainfall, compaction can lead to flooding – a familiar problem for many farmers in the area. The group discussed how reducing stocking levels and farm traffic could help prevent this and recent research into how species-rich swards can improve soil structure. The discussion moved onto how hammering a length of drainpipe into the ground lets researchers "take the field into the lab" to measure the nitrogen which leaches from the soil during rainfall and how these measurements relate to the soil biota and grassland productivity.

Nearby, other scientists gathered farmers and advisors around what looked like an astronaut's helmet (and was in fact an Infra-Red Gas Analyser) to explain the basics of soil photosynthesis and respiration, and how carbon and nitrogen emissions are measured in the field. After a brief explanation the Analyser started to measure the amount of photosynthesis occurring under the slightly grey conditions. The scientists then described new research into how plant traits, such as root length and leaf size, affect carbon and nitrogen retention underground and how this links to the activities of soil microbes. Did you know that there are more bacterial cells in a handful of soil than there are people on Earth?

The flow of knowledge travelled both ways and over in the farm yard, local farmers introduced the monitoring scheme on nearby Kinnerside Common. A collaboration between the commoners and Natural England, it aims to increase vegetation diversity on the common. The farmers are trained in plant identification and surveying "with the aid of a GPS, good eyes and a handbook" and paid for submitting information regularly.

Back in the farm workshop after coffee, discussion around use of satellite images to analyse vegetation and estimate below-ground processes led to lively debate, which continued over lunch.

After the event 94 per cent of attendees said they had found it worthwhile, with a number subsequently getting in touch for further information about the research. With reform of the EU Common Agricultural Policy and changes to the UK's agri-environment schemes likely to consider managing farmland to deliver ecosystem services like absorbing greenhouse gases, these conversations benefit all parties:

"This kind of event enables scientists to understand how scientific outputs are interpreted on-the-ground and stimulates ideas and collaborations." Catherine Baxendale from Lancaster University.

"Much of what was discussed at the meeting was actually about good farming practice and if it helps to reduce damage to the planet then we all win. I think more events focusing on how sustainable food production can work alongside genuine environmental management systems, would be well received and valued by everyone, it gets us working together and sharing knowledge." Chair of the Cumbrian Farmer Network and host Will Rawling

"Thoroughly enjoyed today. Personally, I would like a whole day on each topic." Farmer Glenis Postlethwaite.

The event was sponsored by the Agricultural Ecology Group of the British Ecological Society and the Ecosystems Knowledge Network and was supported by the Cumbrian Farmer Network, NERC and Lancaster and Manchester Universities. For more information email: b.brockett@lancaster.ac.uk

Appendix VIII - Ecosystems Knowledge Network article

- Finding innovative ways of increasing engagement with local communities, including working with schools initiatives and increased volunteer time given to projects; the Humberhead Levels CONNECT Project has resulted in more than 2,500 additional visitors to Gateway sites and more than 5,000 hours of volunteer time.
- Joint working between NIAs and local universities and research organisations to develop understanding of innovative approaches to natural environment project delivery and assessment, such as ecosystem services.

For more information about NIAs and to see the progress report, visit **http://www.naturalengland.org.uk/ourwork/conservation/biodiversity/funding/nia/monitoringandevaluation.aspx**

The science behind the schemes

In June 2013, the Ecosystems Knowledge Network co-sponsored an event to increase understanding between farmers, land managers and scientists. The 'Science behind the Schemes' workshop was held at a farm in Ennerdale, Cumbria, and was the idea of Beth Brockett, a researcher at Lancaster University.

Participants discussing the 'science behind the schemes' © Anita Sedgewick, Ecosystems Knowledge Network

The workshop followed on from a conversation Beth had in the Cumbrian hills with a sheep farmer about the time it took for scientific understanding to filter through to them. The farmer pointed out how people like him often rely on advisors who may also have limited access to the appropriate scientific knowledge.

During the workshop, researchers from Lancaster University and the University of Manchester explained the science behind their work in a number of areas, such as soil compaction and how to mitigate it through reduced stocking levels and creating species-rich types of grassland. They also noted how soil microbiota help soils to be resilient in the face of climate change, how nitrogen leaching relates to soil biota and grassland productivity, and how carbon and nitrogen emissions are measured in the field.

One of the key aims of the event was for knowledge to flow both ways. One of the farmers described an experiment he is running on his dairy farm to compare how quickly silage fields and sheep pasture absorb water. A collaboration is also taking place between farmers and Natural England, to improve the vegetation diversity on Kinnerside Common in West Cumbria, with farmers paid to survey plant species and submit information regularly.

A scientist explaining how samples of soil are taken back to the lab for analysis © Anita Sedgewick, Ecosystems Knowledge Network

All the participants agreed that it was crucial for scientists to understand how their outputs are interpreted on the ground, and also that farmers need to understand new research into how soils work. To help achieve this, Beth is using a participatory approach with her research – working with farmers to create a dynamic map of their land for farm environment planning, which is able to integrate both quantitative and qualitative information.

It was also agreed that everyone would benefit from more events focusing on how sustainable food production can work alongside ecosystem management.

The Ecosystems Knowledge Network co-sponsored the event along with the Agricultural Ecology group of the British Ecological Society. The Cumbrian Farmer Network, the Natural Environment Research Council, Lancaster University and the University of Manchester all provided support.

For more information, please contact Beth Brockett by email at **b.brockett@lancaster.ac.uk**

Appendix IX – Participant consent form and Introductory letter

The Lancaster Environment Centre

LANCASTER UNIVERSITY

Incorporating farmer knowledge into ecosystem service delivery models at the farm scale – PhD project field work

Participant Consent Form

We need to ask you to complete this form to make sure that you're happy to take part in the '**Incorporating farmer knowledge**' project. Before you complete it, you should have read the information letter (ask Beth if you have any queries about this). It is possible to be involved in the project on a number of levels so please delete as appropriate below each statement to indicate whether you are happy to take part in this element of the project:

1. I am happy for Beth Brockett and members of her project team ('the project team') to access my farm land in order to conduct vegetation surveying and sampling, soil sampling and to install grazing exclusion cages (the number and location to be agreed in advance): **Yes / No**
2. I am happy for Beth to interview me about my farm. It will be very useful if she can record the interviews, but this is optional. I understand that the information, including quotes from these interviews, may be used anonymously within publications and reports: **Yes / No**
3. I understand that the project will ensure any commercially sensitive and personally private information is kept confidential. Such data will be stored on password protected devices: **Yes / No**
4. I understand that maps will be created as part of the output of this project and will be used in publications (both academic and professional) and I understand that farm and local geographical names will not be used. Grid references will be used to identify the area to a regional level only: **Yes / No**

Please remember that, if you want any further information or you wish to withdraw from the project at any time you can do so by contacting Beth Brockett (b.brockett@lancaster.ac.uk or 07525854380) or her supervisors Professor Richard Bardgett (r.bardgett@lancaster.ac.uk) or Dr Alison Browne (a.browne@lancaster.ac.uk).

Signature……………………………

Date ……..………………………………

This project has been approved by the Lancaster University Ethics Committee

The Lancaster
Environment Centre

LANCASTER
UNIVERSITY

Beth Brockett, PhD Student
Lancaster Environment Centre
Lancaster University
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Dear Sir/Madam

I am a PhD student from Lancaster University conducting research into extensive farming in the North West. With reform of the Common Agricultural Policy (CAP) imminent, I am investigating the opportunities for new agri-environment schemes where payments can be made to farmers for 'ecosystem services' such as water quality and carbon storage in soil. I will also examine how this might work in practice.

Production of food and other marketable goods is also an ecosystem service and it is important that it is considered as a priority.

I would like to map the potential for these services on your farm and use your farm as a case-study to help develop recommendations for new schemes. I am keen for this research to be of benefit to farmers. When I have finished you will have maps of all these 'services' and a report about your farm.

The work will take me several months over the summer (I'll be working on a number of farms during this period) and will not cause you any disruption. I will need to take non-destructive vegetation and soil samples, but if there are areas of the farm where you would not welcome access, I can avoid these.

I believe that your knowledge about your farm is valuable and I would appreciate the chance to have an informal chat with you about farming and a farm walk-over with you. I can be flexible with timings and I would pay you for any time taken out of your day for this.

This is a two–year study and after this summer we would discuss whether you wanted to stay involved into the second year and what that would involve.

I am happy to answer any questions you may have and I would be very grateful if you would let me know whether you are interested in participating by email, telephone or post.

Yours sincerely,

Beth Brockett

Appendix X – List of presentations given related to thesis

List of presentations given related to the thesis

'The implications of using remote sensing to map delivery of ecosystem services at the farm unit scale'**,** Interdisciplinary Seminar, Lancaster Environment Centre, Lancaster University, Feb 2013

'Applying mixed methods to mapping soil & vegetation on sheep farms', Soil Ecology Lab/Centre for Ecology and Hydrology seminar, Lancaster University, Nov 2013

'Mixed Methods Mapping for a New Approach to Agri-Environment Schemes', Society and Environment Research Group seminar, Lancaster Environment Centre, Lancaster University, Dec 2013

'The implications of using remote sensing technology to map ecosystem services for farm land management planning', Tyndall Centre, Manchester University, Mar 2013

'Sheep and trails and puppy dog tales: Mixed methods mapping for a new era in agri-environment schemes', Biodiversity and Ecosystem Change Research Group, Lancaster Environment Centre, Lancaster University, Oct 2014

'Mixed methods mapping for a new era in agri-environment decision making', Royal Geographical Society International Conference, London, Aug 2014

'Mixed Methods Mapping for a New Approach to Agri-Environment Schemes', Soil Ecology Lab Group, Manchester University, Jun 2014

'Mixed Methods Mapping for a New Era in Agri-Environment Decision-Making', Countryside and Community Research Institute, Dec 2014

'Dirt and Westminster', Soil Carbon Conference, Plant and Soil Ecology Group Conference, British Ecological Society, Manchester University, Oct 2014

'Using geospatial statistics for soil carbon model selection', Lancaster Environment Centre Geospatial research group, Feb 2015

'Predicting Soil Carbon and Nitrogen Stocks on Upland Farms', Soil Ecology Lab Group, Manchester University, Mar 2015

'My Fellowship at the UK Parliamentary Office of Science and Technology (POST)', Lancaster University, May 2015

'Mixed methods mapping for agri-environment decision-making', European Society for Rural Sociology XXVI Congress, Aberdeen, Aug 2015

'Mapping the invisible: representing soil carbon in a farm landscape', presentation in session 'Mixed Methods, Qualitative and Feminist Geographical Information Systems/Science (GIS)' co-convened at the Royal Geographical Society International Conference, Exeter, Sep 2015

'Mapping soil carbon on upland farms', British Ecological Society Agro-Ecology Group AGM, 2012

'Soil carbon on upland farms', British Ecological Society, 'Aboveground-belowground interactions: technologies and new approaches', 2012