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Guiding carbon farming using interdisciplinary mixed methods mapping

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Abstract

1. In recognition of the need to address complex environmental problems, some ecological studies have adopted social research methods to better understand the complexity of social-ecological systems management. The overwhelming majority of these studies stop short of fully embracing qualitative methodologies.
2. The lack of integrative social and natural science data for a topic such as soil carbon farming is problematic as theoretical carbon sequestration opportunities identified through soil mapping and process-based models can fail to deliver the sequestration levels promised when introduced on-the-ground. Such mapping needs to account for the human factors involved in delivering increased soil carbon on-farm.
3. Here, we develop a mixed methods mapping approach to explore the potential for increasing soil carbon stocks on upland farms in the UK. Our approach considers ecological and social complexity through application of soil science, ecology, participant observation, interviews and a focus group.
4. Our maps revealed landscapes that are full of carbon farming opportunity, but contain previously hidden barriers to the delivery of increased soil carbon. For example, they revealed that carbon farming can be considered by farmers to work in opposition to perceived 'good farming' practices and be correlated with increased incidents of livestock disease. We also discovered that the use of maps in research can be problematic as they can close down discussion and exclude local representation of an area.
5. Trialling an interdisciplinary mixed methods approach produced new, deeper and more richly-textured understandings about how soil carbon management is produced socially as well as ecologically on upland livestock farms. Our findings have potential to improve the success of future carbon farming initiatives by incorporating farmer knowledge and social drivers of implementation.

KEYWORDS
agri-environment, climate change, farming, interdisciplinary, local knowledge, mixed methods, qualitative mapping, soil carbon sequestration, soil carbon storage, uplands

1 | INTRODUCTION

The effectiveness of management interventions for delivering ecosystem services depends on place-specific environmental conditions. For example, the success of soil conservation measures is affected by factors such as soil type, topography and climate (Powlson et al., 2012; Smith et al., 2015). Effectiveness is also influenced by human factors, such as land managers' commitment to environmental practices along with their knowledge and skills, agency ("the ability to act (and achieve) on the basis of what one values and has reason to value"; Hicks et al., 2016, p. 39), financial circumstance, cultural practices and future plans (e.g. Blackstock, Ingram, Burton, Brown, & Slee, 2010; Burton & Paragahawewa, 2011; Morris, 2010). Consequently, there is a need to understand environmental and human factors together and explore how they interact in order to develop management interventions which optimise success in these social–ecological landscapes (Adams, 2007; De Snoo et al., 2013; Hicks et al., 2016; McCracken et al., 2015; Sandbrook, Adams, Büscher, & Vira, 2013; White, Jennings, Renwick, & Barker, 2005). This paper demonstrates, through empirical mixed methods research, why it is important that we look for, reveal and work with the complex and situated values, experiences and environments that exist alongside natural science findings.

Soil carbon loss results from environmental processes and from human–environment interactions. It has been proposed that increasing the amount of carbon in soil could be an effective means of mitigating climate change (Scharlemann, Tanner, Hiederer, & Kapos, 2014; Smith et al., 2008), while also benefiting soil fertility, given the central role of soil carbon in regulating soil physical, chemical and biological properties (Bardgett, 2016). Depleted soil carbon levels can sometimes be restored and maintained through appropriate land management techniques, which can include re-wetting via blockage of drainage systems, afforestation and adding organic matter directly to soils (Bussell, Jones, Healey, & Pullin, 2010; Ostle, Levy, Evans, & Smith, 2009). Soil carbon storage, delivered through multifunctional land management, has been of increasing scientific and policy interest (Chabbi et al., 2017; Committee on Climate Change, 2017; Defra, 2018; HM Government, 2018).

Soil "carbon farming" is an emerging approach where farmers and other land managers manage land for soil carbon storage both for agricultural productivity and climate change mitigation reasons. However, in some regions, initiatives designed to promote soil "carbon farming", such as Australia's Carbon Farming Initiative, have shown limited success (Kragt, Dumbrell, & Blackmore, 2017). Kragt et al. (2017) suggest that such initiatives should consider the range of drivers and barriers land managers consider when deciding whether to engage in and continue with carbon farming practices, as well as the information and support they require.

Within the European Union, one possible mechanism for encouraging and enabling carbon farming is to introduce it through agri-environment schemes (soon to be replaced by an environmental land management system of payments in the UK; HM Government, 2018). Agri-environment schemes have been a dominant feature of rural policy in Europe for over 30 years (Dwyer, 2014). They work alongside incremental environmental regulation of the farm sector to promote and support more environmentally sustainable agricultural landscapes (Dwyer, 2014). However, agri-environment schemes have received mixed reviews regarding how beneficial they have been for farmland biodiversity and whether they are cost-effective (Batáry, Dicks, Kleijn, & Sutherland, 2015). Boatman et al. (2008) and Dwyer (2014) suggest that management instruments are often not sufficiently sensitive to local social and ecological conditions to achieve desired environmental outcomes. Dwyer (2014, p. 6) explains that "little attention has been devoted to how they [agri-environment schemes] affect farmers' evolving relationship with their landscape", and she highlights how such schemes can even result in negative effects on long-standing relationships between farmers, their land and its stewardship. Riley (2008) highlighted the lack of space within agri-environment schemes for taking account of other ways of knowing the agricultural landscape, including experiential knowledge and how conservation management fits with day-to-day land management practice. This exclusion can lead to ineffectual or even counterproductive outcomes and a lack of long-term pro-environment management change (Burton & Paragahawewa, 2011).

Research which takes account of the complexity of the human elements of agri-environment systems, as well as ecological complexities, is needed to support improved policy design. Consideration of how study design can limit the types of knowledges included and valued is important. An interdisciplinary approach to studying the agricultural environment can provide researchers with access to different ways of knowing the land and the farmers' relationship to it (Riley, 2008). Including place-based and tacit knowledge (intuitive, largely experience-based; Polyani, 1966) within an ecological study can deliver a more complete picture of what is possible through policy interventions, including an improved understanding of what management changes are acceptable and possible for those directly involved. This cannot be captured through quantitative research methods alone: a reliance on quantifiable concepts within ecological sciences leads to key determinants of human equity and action being ignored, including the effects of broader policies and objectives on humans' ability to act to promote sustainability (Hicks et al., 2016). However, the burgeoning corpus of ecological studies that do consider human and social factors, including research on agri-environment schemes, tend to prioritise quantitative methodologies to inform management interventions and evaluate the success of those interventions (Mills, 2012).

There are an increasing number of published studies that discuss the need for interdisciplinary mixed methods research, particularly the inclusion of qualitative social research methodologies within ecological studies (Drury, Homewood, & Randall, 2011; Hicks et al., 2016; St. John, Keane, Jones, & Milner-Gulland, 2014). Hicks et al. (2016) suggested that debate about this form of interdisciplinary engagement is outpacing actual use, which hampers our capacity to develop effective sustainable management interventions. This paper directly addresses this gap in application.

Our study examined opportunities for increasing and maintaining soil carbon stocks through carbon farming in extensively managed grasslands, which form the backbone of livestock farming in upland regions of the United Kingdom. Extensively managed grasslands represent a major soil carbon pool that is both sensitive to long-term management and important for climate change mitigation (Smith, 2014; Ward et al., 2016). We demonstrate empirically how the application of interdisciplinary approaches to ecological research, through a mixed methods mapping approach, which includes quantitative soil carbon modelling, ethnographic methods and place-based interviewing, can be used to inform better soil carbon management on upland farms in the UK. In doing so, we demonstrate how the design and delivery of agri-environment schemes might be improved when the main criterion for success is increased soil carbon storage.

We follow in the footsteps of Riley (2008) in considering the production and politics of knowledge within agri-environment systems, and of critical physical geographers (Lave et al., 2014), such as Landström et al. (2011) and Lane et al. (2011) who offer new methods for "redistributing expertise between science and affected publics in relation to environmental problems" (Landström et al., 2011, p. 1617). This study is also situated in the work of feminist and other critical cartographers such as Harvey, Kwan, and Pavlovskaya (2005), Knigge and Cope (2006) and Kwan (2002) who critique and seek to subvert the exclusionary and often uncontested power and "immutable mobile" (Latour, 1987) nature of maps and other scientific models (Lane et al., 2011).

Drawing from these intellectual traditions we pose the research question: how can soil carbon storage be increased at the farm scale? In doing so, we open up the soil carbon mapping process with the intention of revealing implicit assumptions within current agri-environmental research and policy. We also explain how to harness an interdisciplinary mapping processes to work with natural and social scientific, place-based and experiential knowledge of upland soil management. We do not do so in order to promote a single, definitive agri-environment methodology for carbon farming (Tadaki, Brierley, Dickson, Heron, & Salmond, 2015), nor to simply advance debate on the significance of interdisciplinary and critical ecological studies (Hicks et al., 2016). Rather, we seek to demonstrate through a study on a selection of upland farms in northwest England how interdisciplinary mapping processes can be deployed to reveal different versions of the farm, improve the communication of information between different stakeholders and inform agri-environmental policy design.

2 | METHODS

2.1 | Study system

The study was carried out on extensively managed upland livestock farms in the Lake District National Park, Cumbria in the northwest of England. The Lake District National Park is recognised as a culturally important landscape, with upland farming playing an important social, environmental and economic role (UNESCO, 2017). There is a strong lineage of rural social science research within this region (e.g. Waterton & Tsouvalis, 2015; Wynne, 1989). The vegetation, which is dominated by semi-natural grassland and dwarf shrub heath, with pockets of broadleaved and coniferous woodland and improved pasture, is strongly influenced by steep topography and a long history of agricultural management, especially sheep grazing (Pearsall & Pennington, 1989). The soils, which are relatively acidic and carbon-rich, reflect both the cool, wet climate and the recalcitrant nature of the litter derived from the dominant vegetation (Pearsall & Pennington, 1989). As in many marginal agricultural areas, there are opportunities for increasing soil carbon storage through changes to land management (Haines-Young & Potschin, 2009; Ward et al., 2016). Many of the area's farmers have experience of participating in agri-environment schemes (Harvey, Thompson, Scott, & Hubbard, 2013). Therefore, any new intervention, such as encouraging the management of land for soil carbon storage, will occur within a history of such interventions and within a set of existing relationships and farmer experiences (Fish, Seymour, & Watkins, 2003). We used three study farms which were selected on the basis of the suitability of land with regard to sustaining carbon farming alongside other productive uses and on farmer willingness to engage in all aspects of the research. All three study farms were enrolled in an agri-environment scheme at the time of data collection. Farm and farmer information are detailed in Table 1.

2.2 | Interdisciplinary methods

The team consisted of an interdisciplinary lead researcher, who trained in both social and natural science, and a multidisciplinary team of two human geographers, a soil ecologist and two geographical information systems (GIS) specialists. The team used Donaldson, Ward, and Bradley's (2010) mode of interdisciplinary working, making a commitment to engage constructively with the working assumptions and methods that underpinned other members' research practices and, in doing so, to re-evaluate our own. Regular meetings included formal reflection on emergent data from the variety of disciplinary standpoints and explored whether the terms of reference and data sources were adequate to ensure both internal and external research validity (Drury et al., 2011; Kitchin, Gleeson, & Dodge, 2013). We employed Hesse-Biber's (2012) feminist approach to triangulation of data, which challenges the "deductive model of reasoning that relies on the testing of theory and values objectivity over subjectivity" (p. 138). This approach also suggests that tensions in the data or interpretation can lead to productive new strands of enquiry, rather than always indicating error or incomplete data collection (Nightingale, 2016).

TABLE 1 Study farm and farmer information

	Farm/er One	Farm/er Two	Farm/er Three
Size of holding and tenure	34 ha owned with access to approximately 150 ha of common grazing	95 ha tenanted holding with access to a 350 ha common and with an additional 60 ha rented from other land owners	Own 80 ha of inbye across two holdings, plus 200 ha of owner-occupied rough grazing (or "fell") and access to approximately 2,000 ha of common grazing
Successor identified?	Yes – son	Yes – son (transfer imminent at time of data collection)	Yes – son
Farming system	270 breeding ewes and 18 cows with calves (beef)	~700 sheep	2,800 breeding ewes in total in summer with 800 replacement "hogs" and 60 beef cattle
Who farms? *denotes main study participant	Husband* and wife team (wife also farms another holding)	Male farmer*	Father* and son team
Notes	Farm been in family for many generations. Limited inbye[a] available	Holding contains areas designated as Sites of Special Scientific Interest and a County Wildlife Site	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

[a]That part of the farm used mainly for arable and grassland production, but which is not hill and rough grazing.

The first stage of data collection (spring 2012–autumn 2013) involved simultaneous collection of qualitative and quantitative data from the three study farms; exploring what data were accessible and useful in answering the overall research question: how can soil carbon storage be increased at the farm scale? Answering this question required an understanding of where the existing soil carbon stores were on the farms and the potential for further carbon sequestration to occur at these locations. This required an understanding of how human factors interacted with carbon farming scenarios. Methods used were participant observation (Bryman, Liao, & Lewis-Beck, 2004; Watson & Till, 2010), semi-structured interviews (Galletta & Cross, 2013), and scientific soil and vegetation sampling methods (Brockett, 2016).

A detailed account of the scientific methods can be found in Brockett (2016); only a brief outline is given here. We conducted a soil carbon survey of each farm by taking soil samples and bulk density measurements at specific depths, to maximum soil depth, across different vegetation types and analysed the samples to determine total (organic and inorganic) soil carbon content. The methods used followed standard protocols for assessment of total soil carbon content, as used by Ward et al. (2016), and involved expression of carbon stock as total carbon kg C/m^3, based on bulk density assessments to maximum soil depth. Associated vegetation was recorded and vegetation samples were collected to explore the relationship between total soil carbon content and plant traits, such as leaf area. The number of samples taken was determined using a power analysis. These data enabled the production of maps identifying which areas of each farm had the most potential for soil carbon storage maintenance/enhancement and so where to focus management interventions. The mapping process is described in the next section.

During this first stage, the lead researcher spent 7 months on the three farms (May–August 2012 and June–August 2013), generally Monday to Friday 9 a.m. to 5 p.m. conducting both scientific surveys and participant observation. On a typical day, the lead researcher would arrive at the farm around 9 a.m. and would speak to the farmer about the day's farm management tasks, explain the day's scientific survey plans and ask questions of the farmer such as "Do you think that's a good place to get a representative soil pit?". Sometimes the lead researcher would accompany the farmer to a task to observe and ask questions relevant to the study. These tasks included rounding-up sheep on the common (an area where certain people hold beneficial rights to use land that they do not own; Foundation for Commonland n.d.) and moving cattle.

Discussion between farmer and lead researcher would also sometimes occur at lunch time and/or at the end of the working day or at another time when paths crossed. Given the deep-ethnographic nature of this on-farm work, it is difficult to provide a comprehensive list of all the questions and topics that were discussed. But they covered management of the farm, the scientific methods being used by the researchers, whether the methods employed and the emergent findings made sense to the farmers, the farmers' understanding of and thoughts on soil carbon and its management, current and previous engagements with environment management interventions (such as agri-environment schemes) and a number of other farming and agri-environment issues. Both the lead researcher and the farmer would initiate topics for discussion. These informal conversations and observations were documented in a field diary. The lead researcher also met and talked to other people on-farm, such as family members and contractors. Discussion notes were only recorded if the participant was fully aware of the research objectives and had agreed to participate.

The lead researcher became a familiar presence on-farm, which improved the quality of the data collected (Jones, Andriamarovololona, Hockley, Gibbons, & Milner-Gulland, 2008) given that she was able to participate in informal and ongoing conversations about the research topics. This longitudinal perspective has proven valuable in other farmer engagement studies (Hall & Pretty, 2008). In-depth knowledge-exchange would have been difficult without the lead researcher undertaking the scientific study at the same time as it gave her legitimacy with the farmers who were accustomed to people showing an interest in soil profiles and vegetation surveys, but not explicitly having an interest in their knowledge and opinions.

At least two formal semi-structured interviews were conducted with each of the three farmers over the course of the study to prompt discussion and new insights on specific dimensions of the research questions beyond the ongoing informal discussions. The semi-structured interview questions explored: farmer's knowledge of the soil on their farms, including how they understood, experienced and managed soil carbon; their previous experience of managing land to deliver environmental outcomes; which factors could affect future management of their land for soil carbon storage; and whether they had any information which could assist in the design of the scientific study. The formal interviews were audio-recorded; basic notes were also written. All audio recordings were typed into full transcripts. The field notes and interview transcripts were manually coded by content using the software programme ATLAS.ti (version 7.1.8, 2014) using Bryman's (2012) mechanism of open, merged and final codes, and conducted between three and five times on each transcript to create a coherent set of themes (Bryman, 2012; Neuendorf, 2002).

The emergent themes identified were explored further in a focus group setting. The day-long event was held on a local farm in June 2013 with 14 farmers, nine farm environment advisers and seven researchers in attendance (Brockett & Netto, 2013). The identified themes were: carbon farming as hope for the future of upland farming; the place-based experience of carbon-rich areas of the farm, including hard work and management problems; how hard it was to know if you were storing carbon in the soil, compared to other environmental management outcomes; associations between carbon-rich soils and reduced productivity or problem land; sensory experience of carbon-rich landscapes, as compared to other environmental management outcomes; experience of engagement with agri-environment schemes, including the role farmer knowledge and monitoring; the role of maps and different spatial versions of the farm; and use of aerial imagery and "surveillance" to identify carbon farming opportunity and monitor farm management activity.

A series of "activity stations" in the morning session and a series of discussion groups in the afternoon session were designed with these themes in mind. The focus group format allowed us to probe shared meanings and values and normative responses to the themes, as well as areas of disagreement (Sim & Snell, 1996). Three activity stations were set up: two led by researchers and one by farmers. The first demonstrated how soil carbon was measured using an infra-red gas analyser and covered the characteristics of a carbon-rich upland landscape; the second centred around a soil pit (familiar to the majority of attendees) and discussed soil carbon as relates to the physical structure of soil and its management and "feel"; the third, run by two local farmers, focused on farmer monitoring of environmental outcomes. Attendees spent 20 min at each station with a short introduction led by facilitators, followed by a group discussion.

After lunch, the group split into three discussion groups focusing on: (a) the science of carbon storage and how this relates to vegetation and productivity; (b) the benefits of increased soil carbon levels for managing soil erosion and diffuse pollution; and (c) soil carbon mapping and the possible applications of remote sensing for identifying carbon farming opportunities. Each table included a member of the research team as facilitator. The facilitator did not explicitly introduce the themes but aimed to draw-out relevant points, without restricting the scope of conversation. Each discussion lasted for 30 min and each attendee participated in two discussion groups. Mobile voice recorders recorded all conversations and recordings were subsequently typed-up and coded, as described previously. A facilitator debrief session was held immediately after the event where reflections of the event were also captured for analysis.

2.3 | Creation and analysis of mixed method maps

Creation of soil carbon maps for each of the three study farms involved testing the hypothesis that easily accessible proxy measures of vegetation and soils can be used to predict soil carbon stocks at a farm scale. Full details are available in Brockett (2016). Briefly, we used linear mixed regression and regression kriging to test the utility of the following variables within a soil carbon model: vegetation type derived from Farm Environment Plan maps; soil type from soil maps; variables derived from a digital elevation model; and various soil chemical and physical properties (field data) (using the "lme" function within the "nlme" package for R; Pinheiro, Bates, DebRoy, & Sarkar, 2013 and the "gstat" and "automap" packages; Gräler, Pebesma, & Heuvelink, 2016; Pebesma, 2004 for R; R Core Team, 2015, with cross-validation carried out using the "krige.cv" function in "gstat"). Farm Environment Plans were developed to be comparable with UK's Biodiversity Action Plan priority habitat codes and are related to the UK's National Vegetation Classification system (Rodwell, 2006; D. Martin, pers. comm. Natural England, April 2015). All English farms which have applied to a Higher Level agri-environment Scheme will have had one of these maps produced (21,797 farms to April 2017; Natural England), commissioned as part of the application process. The final models included the explanatory covariables which satisfied the model assumptions and best predicted soil carbon stocks across the study farms.

The selected covariables were utilised, along with actual soil carbon values, to create a predicted soil carbon stock "surface" (which can be represented as a map) for each soil depth across the study farms using the spatial interpolation cokriging function within the Geostatistical Analyst toolkit in ArcMap (ESRI, 2011). The goal of spatial interpolation is to create a surface that is intended to best represent empirical reality, thus the model selected was assessed for accuracy and validity and error surface output or "cross-validation" statistics were calculated. Diagnostic measures (sums of squares errors, mean error and mean square deviation ratio of prediction error) were examined for each spatial model. The final predicted carbon stock surfaces, in combination with soil depth interpolation surfaces, were used to calculate average and total carbon stocks in order to produce soil carbon maps for each study farm.

Emergent findings from the earlier stages of research indicated the importance of collecting qualitative data with attention to place. We hypothesised that collecting these data would improve our understanding of the relationships between soil carbon stocks and how farmers experience and think about soil carbon in the farmed landscape. We employed a spatial transcript method to test this hypothesis. The spatial transcript method is a walking interview where a voice recorder and a global positioning system are synched to enable the interview narrative to be geolocated within a digital map (Jones & Evans, 2012). A key advantage of this method "is that it allows the location of apparently ephemeral comments to be recorded, without the researcher having to constantly note location/time during the interview. This produces a much richer range of data that can be geolocated and thus analysed spatially, without omitting that which may have seemed trivial at the time" (Jones & Evans, 2012, p. 95). The walking interviews took between 35 min and 2 hr, starting from the farm yard with the route agreed by mutual consent to cross a number of different vegetation types (associated with varying levels of soil carbon and management practices).

The interviews explored farmers' reactions to the digital soil carbon maps and possible future scenarios for managing soil carbon on-farm, directed by the maps and reference to the Lake District National Park's "Managing Land for Carbon" booklet (Hagon et al., 2013). The progression of the walk was plotted as a route on the map and the associated narrative and coded themes were geolocated within the map's database. We also drew on the work of Jung (2009) to create "imagined grids" within the GIS to store qualitative spatial data. 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, p. 120). As such, the data are not just superimposed onto the map, but forms part of the map. The resulting "mixed methods maps" layered the predictive, quantitative soil carbon maps with the other spatially explicit information gathered during the research process (qualitative and quantitative) such as historic farm management maps, land tenure, yield information, research observations, the results of the spatial transcript interviews and other place-specific interview data.

The qualitative data were considered alongside the quantitative soil carbon maps to explore themes identified in previous stages of research. Our approach considered the "patterns of human activity and symbolic practices" within the spatial data included in a mixed methods map (Perkins, 2008, p. 152). As Perkins (2008) suggested, this can include matters as diverse as social relationships and interactions, norms, language, values and actions. For example, we considered physical experiences articulated within the map, as described during walking interviews or geographically located during static interviews. These included sensory experiences of carbon-rich landscapes and related themes, such as farmers' sensory experience of environmental management activity. We also explored motivation to engage in carbon farming in relation to identified carbon farming opportunities and considered whether alternative (non-Cartesian) spatial gradients such as land tenure, elevation, view-shed, accessibility, distance from the farm house and the farmer's emotional connection to different areas of the farm played a role.

3 | RESULTS AND DISCUSSION

3.1 | Mixed methods improved our scientific outcomes

Interviews with the study farmers provided us with unexpected information and data sources for the natural science study, which led to subsequent changes in our study design and in the research parameters. We provide two specific examples of how farmers' local knowledge informed our research on predicting farm-level soil carbon stocks and how this affected our results. First, the sampling design for developing the soil carbon models and maps was improved by including farmer knowledge of their land and its management history in the preliminary phases of our research. Discussions with farmers enabled us to explore alternative survey designs for each study farm and divide seemingly homogenous survey units based on historic management information or farmer knowledge of the soils and associated vegetation. For example, Farmer Two alerted us to the Lake District National Park's "Managing Land for Carbon" booklet (Hagon et al., 2013) and both Farmers One and Two expressed doubts as to whether the presence of bracken fern (*Pteridium aquilinum*) increased soil carbon stocks, as suggested by the booklet. We subsequently tested this and found the farmers were correct, in that we detected no association between bracken cover and soil carbon stocks on Farm One (Brockett, 2016). In another example, Farmer Three suggested that we consider the area locally known as "Frogholes" as a separate survey unit, as he thought there was a lot of carbon stored within pockets on this land. He was proven correct.

Second, through discussions with Farmer Two, we developed the idea of using the information contained in Farm Environment Plan vegetation survey maps as a proxy for vegetation type and land management history in our farm-scale assessment of soil carbon stocks. These vegetation types were retained in the final models used for predicting soil carbon stocks across the three farms, along with soil moisture, as they were a significant term in the models that best explained variance in total soil carbon stocks (Brockett, 2016). Local knowledge therefore played an integral role in proving that it is possible to predict total soil carbon stocks at a farm scale within upland agricultural landscapes by utilising simple measures of vegetation and soils derived from easily accessible information (Figure 1).

3.2 | Mixed methods can improve our understanding of complex systems and identify novel considerations for "carbon farming" initiatives

At the beginning of the project, all three case study farmers were introduced to the research concepts (they were already familiar with some

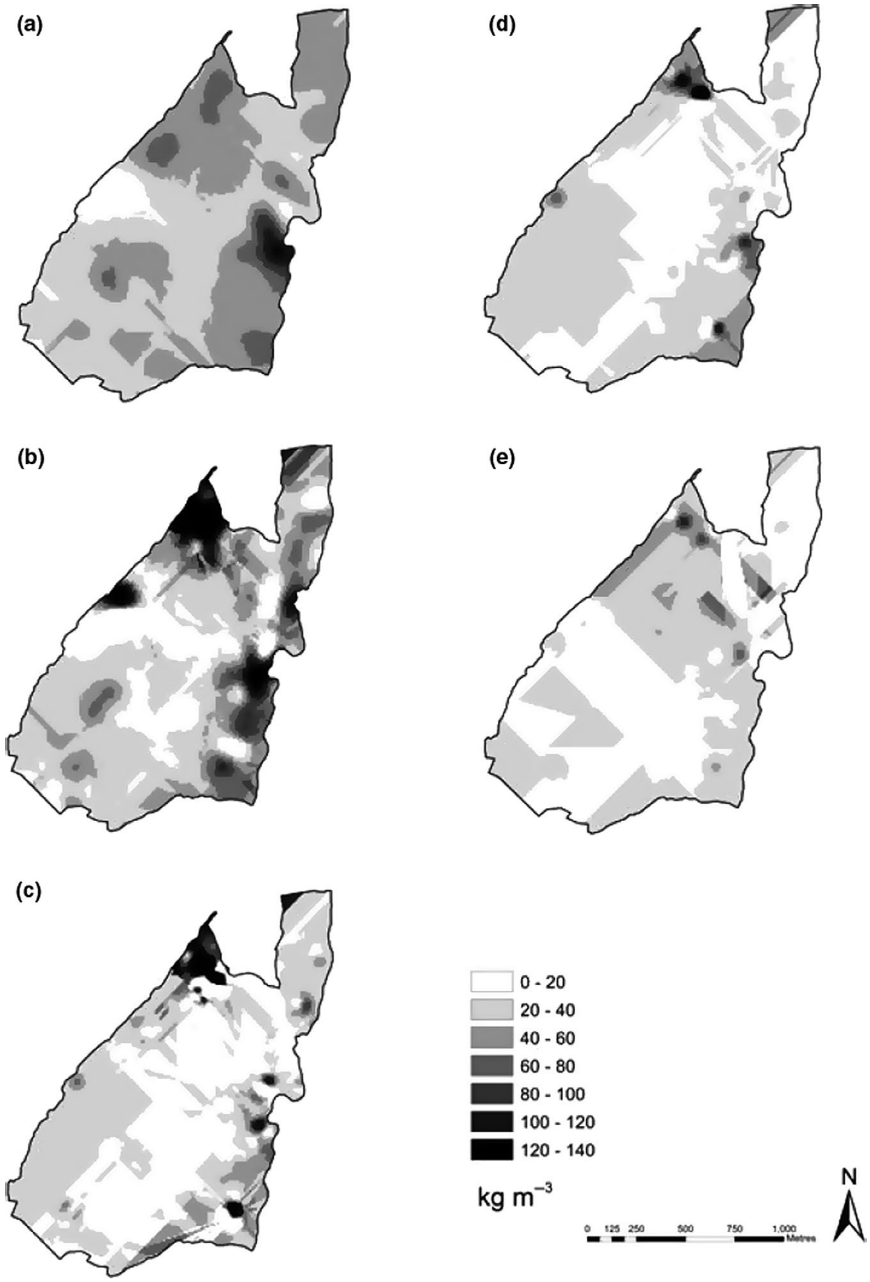

FIGURE 1 Interpolations of predicted total soil carbon stocks (kg/m^3) for each sample depth increment on Farm One: (a) 0–7.5 cm, (b) 7.5–20 cm, (c) 20–40 cm, (d) 40–60 cm and (e) 60–80 cm. Created using soil moisture and vegetation data using the spatial interpolation cokriging function within the Geostatistical Analyst toolkit in ArcMap (ESRI, 2011)

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 One). It was explained that the exchange of information between farmer and researcher was important to the project's development. Farmer Three embraced this aspect from the start, but the other two farmers were less certain of what they could contribute and Farmer One initially expressed scepticism that he could contribute. Their contributions proved essential to the development of the research and its findings, leading to an open dialogue about different ways of understanding the world (McLafferty, 1995).

We discovered, both through research with farmers from the study farms and via the focus group, that maps do not play a day-to-day role for the farmers questioned. As one participant (an academic researcher and team member) reflected after 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". (Focus group facilitators debrief)

During the focus group discussions, we identified related farmer concerns about the use of spatial data collected via remote sensing, such as could be used to identify areas of carbon farming potential (Ballabio, Fava, & Rosenmund, 2012). As one farm advisor stated during the group discussion: “I know that some of the farmers I talk to would feel that they are being spied on by satellites”.

However, data indicated the (recent) historic importance of ecological maps of the farms in the relationship between the State and farmer. Agri-environment maps, such as the Farm Environment Plan maps, were often viewed by the farmers as unrecognised or unexplained versions of their farm. Farmers did not feel able to contest the Farm Environment Plan maps, so these maps became symbols of prematurely foreclosed discussions and the dominance of external ways of representing their farms, to the exclusion of other representations. Contrary to our expectation, referring to a soil carbon map in interview discussions and scenario development closed-down conversation. For example, when a soil carbon prediction map was first introduced into conversation with Farmer One and its assumptions explained, including possibilities for altering the parameters to show a farm which stored more or less carbon, he commented on how easy it was to be "Fiddling with it" (Farmer One) and exhibited polite scepticism about the scientific process. When we probed this further, we found that the authority, finality and technical presentation of soil carbon maps precluded farmers from questioning them; as such, any future management scenarios consequently became limited and fixed by the maps.

Uncovering the problematic role of maps and other spatial representation of participants' farms led to us to reconsider how we used maps within our study. To ensure that we took account of the implicit meaning and power inherent in mapping as well as the explicit meaning (Harley, 1989), we sought to open up the process by making our scientific and mapping assumptions and process as transparent as possible during interactions with participants. We included explanations of our assumptions and level of confidence in our scientific mapping process during the walking interviews and encouraged interviewees to question the maps as part of the discussion. Only after such a discussion did Farmer One feel able to question the findings and place them within his own understanding of the land.

As well as providing a novel way of collecting, representing and analysing qualitative spatial data alongside quantitative spatial data, the spatial transcript method provided access to farmer knowledge that was not accessed through static interviews. For example, Farmer One 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 talked about how root depth might affect the amount of 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 … the depth of the roots isn't that deep". (Farmer One)

This quote shows that the farmer has an understanding that root depth can be correlated with soil carbon content. Root biomass and traits have shown to be strongly correlated with several soil properties, particularly the biomass of bacteria relative to fungi in soil, soil carbon accumulation and other measures relating to soil carbon cycling (Fornara & Tilman, 2008; Orwin et al., 2010). Knowing the farmer has this level of understanding, even if they are unable to articulate it using scientific terms, is important because it is often stated that farmers do not understand enough about the science to engage fully in planning for environmental management (Feliciano, Hunter, Slee, & Smith, 2014). This is an opinion with which we would have concurred had we considered only the data from static interviews. This new understanding provided us with a different starting place for conversations with this farmer regarding soil carbon management on his farm.

It is seductive to consider that data collected using different methods, including mixed methods, should somehow triangulate, i.e. converge with the goal of validation (Hesse-Biber, 2012). However, we found that tensions or apparent inconsistencies between qualitative and quantitative findings led to new insights about the storage and management of soil carbon in farming landscapes. For example, we found that some of the areas identified as having high potential for carbon sequestration, based on our quantitative soil carbon maps, were rejected as areas of soil carbon management opportunity by the farmers. Specifically, using the spatial transcript methodology, we found that proposed enhancement of soil carbon sequestration in wetter areas of the farms was associated by two of the farmers with animal health concerns.

Farmers were concerned that carbon farming interventions in wetter parts of their farms would lead to the spread of *Narthecium ossifragum* (Bog Asphodel), which is toxic to sheep and cattle (Strugnell, 2014). In another example, Farmer Two would only consider reducing liming on organic soils as a way of increasing soil carbon (Moore, Ouimet, & Duchesne, 2012) where his sheep had not experienced trace-element deficiency, "which if you don't catch it in time can be deadly". Whether these are seen as "valid" concerns or not by policy makers and scientists, they will continue to be a factor in how some farmers decide to manage their land. This is an example of how a tension in different accounts of the farm can be identified and therefore further explored and addressed using mixed methods. It is worth noting that these animal health concerns were not vocalised in any of the static interviews and were only drawn out through use of spatial transcripts and by studying qualitative responses to carbon management scenarios using the mixed methods mapping process.

Exploration of alternative spatial gradients proved illustrative in explaining some of the "inconsistencies" regarding farmer attitudes to managing their land for soil carbon storage. Tenure of land, as expected, was a factor in whether farmers would be willing to consider carbon farming. However, we discovered that some areas of farm land may appear to have the same ownership status or physical properties as surrounding land but they will not be considered or will be considered differently in discussions about changing management practice. For example, our findings suggest that distance from farm house and historical relationship to land are two alternative spatial gradients worth exploring in future research.

We found that in initial discussions all farmers interviewed would cite financial incentives as the main and often only reason to stay engaged in agri-environment schemes or other environmental management interventions. However, with further in-depth discussion, it emerged that direct experience of positive outcomes, linked to a sense of success, was often an over-riding factor in decisions as to whether to engage in new schemes or continue engagement in existing schemes. Statutory bodies and researchers occasionally communicate to farmers the success, or not, of environmental management interventions. But knowledge of success was found to be most often derived from farmers' themselves through their observations, their sensory and practical experience of the environmental outcomes and their scientific understanding of the environmental goals. This finding is supported by Riley (2008) who studied the management of hay meadows in another area of the English uplands through participant observation.

Farmer One had originally explained to us that his only interest in managing for agri-environment scheme outcomes was financial "like most farmers". 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'; because of this success he stated that he would continue managing for species-rich hay meadows. It was sensory experience in particular that was repeatedly referred to within our interview texts. The sensory experience of upland hay meadows was very important for Farmer One: 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 One alluded-to when discussing whether it was "worth" him continuing with their management. In another example, Farmer Three 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'". (Discussion with Farmer Three, field notes)

Both of these examples contrast with descriptions of carbon-rich parts of the farm. Carbon-rich areas were described as problematic and "nuisance bits" of land (Farmer One). Soil carbon is not visible in the same way as hay meadows and weasels; it reflects vastly different embodied, material and affective entanglements. In contrast to the positive sensory experiences farmers talked about in relation to environmental management goals, such as observing increasing biodiversity of hay meadows and the building of stone walls, we found that farming soil carbon has the potential to conflict strongly with upland farmers' concepts of a productive landscape and with their strong self-identity as producers of food (see Burton & Wilson, 2006 for further discussion of farmer identity). In the focus group and during interviews, a number of farmers talked about machinery getting stuck in peaty, boggy, carbon-rich areas and such areas as places of increased labour within the landscape.

Another consideration for carbon farming and other agri-environment initiatives, related to farmers' identity as producers of food, was revealed when discussing how grazing intensity can affect soil carbon stocks. All three case study farmers suggested that there was a herd number or a stocking density below which they would cease to feel like "good" farmers. This number cannot be obtained through scientific methods, as it is not the same number as would be derived from farm business planning processes or by calculating ecological carrying capacity, for example. It is deeply held and represents rarely articulated feelings around what it means to be a "good farmer" (Burton, 2004), but its importance is clear with regard to future management scenarios: management interventions which suggest reducing stock numbers below this threshold will be strongly resisted.

4 | CONCLUSIONS AND POLICY RECOMMENDATIONS

Here, we show how an interdisciplinary mixed methods mapping approach can be useful in obtaining a holistic view of a social–ecological landscape, contribute to ecological research through improving scientific research design, and produce new, deeper and more richly textured understandings about how soil carbon management is produced socially as well as ecologically.

In the UK, there is new government interest in working with land managers to utilise their local farming expertise, judgement and knowledge to improve environmental outcomes from agri-environment schemes (Defra, 2018). This interest is situated in the context of a long-standing academic commentary that particular scientific and policy knowledge have been privileged in discussions of management intervention in the English uplands, and that the "fuller social dimension[s]" underpinning such interventions is often ignored (Waterton et al., 2015; Wynne, 1989, p. 12). This study illustrates how utilising a mixed methods approach can help account for such histories.

We also demonstrate that ethnographic methods can be invaluable in accessing tacit knowledge, such as relate to previous experience of delivering agri-environment schemes, which can be missed using less in-depth methods. These and other social science methodologies, such as the walking interview, enabled a fuller exploration of farmer knowledge as embodied and practiced in the farm landscape. In our study, walking interviews proved to be crucial in accessing place-based knowledge and attitudes towards carbon farming not identified through static methods.

Our study also demonstrates that farmer and other local knowledge of an area can contribute to ecological research through improving scientific research design and identifying important social-ecological considerations, which add depth to understanding. Farmer knowledge contributed to our discovery that soil carbon can be predicted at the farm scale using accessible vegetation maps and soil moisture data. We suggest that local knowledge, where accessible, should not be discounted even in "purely" ecological studies.

Through mixed methods mapping we revealed landscapes that were both full of carbon farming opportunity and contained barriers to carbon farming. Mapping is a process, tool and a way of communicating information between different stakeholders and representing different versions of the farm. The use of maps in research and in agri-environmental schemes should be carefully managed because maps have a problematic history on farms and, as our findings show, using them can close-down or limit discussion, and so opportunity.

Specifically, with regard to designing and implementing carbon farming schemes in upland agricultural areas, it is particularly important to build in frequent feedback mechanisms so farmers can follow the progress of any soil carbon management intervention. We found that, for farmers, success in farming soil carbon is more intangible than success in, for example, management of a biodiverse hay meadow or repairing a stone wall. Soil carbon is often associated with negative landscape attributes, such as poor animal health and hard labour. In addition, we should not assume that farmer attitudes, motivations and knowledge are fixed and static. These factors can change over time and with a range of factors (such as land tenure and relationship to land) and identifying them depends on the methods used. Future research into carbon farming initiatives could benefit from analysis which considers the potential utility of alternative spatial gradients in understanding drivers and barriers to engagement.

The project also led to a series of reflections about critical, interdisciplinary ecological research. Insights emerged through the research team taking the time and being open to learning about and engaging with different ways of knowing the study system and the tensions and opportunities of using a mixed methods approach. Within an interdisciplinary research project, there will inevitably be tensions between disciplinary research cultures and conventions. We believe that it is imperative to work across these boundaries because improved research outcomes can be the result, if concerns are thoughtfully considered. To improve and encourage the application of mixed methods interdisciplinary research we should be training truly interdisciplinary researchers; researchers who are familiar with different research paradigms and who can facilitate and encourage better understanding and improved working across disciplines.

We are not suggesting that all ecological research should be interdisciplinary or mixed methods, nor that such qualitative methods, which can be time-consuming, should be applied to all land management decision-making processes. Rather, our results demonstrate that such approaches can identify novel considerations, especially for complex social-ecological systems as studied here. Our contention is that interdisciplinary mixed methods mapping can help improve the design and delivery of agri-environment schemes where the criterion for success is improved soil carbon storage.

DETAILS OF ETHICAL APPROVAL AND CONSENT TO PARTICIPATE

This paper followed the ethical guidance of Research Councils UK and underwent ethical review at Lancaster University. Informed consent was obtained from all participants.

CONFLICT OF INTEREST

Nothing to declare.

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AUTHORS' CONTRIBUTIONS

B.F.T.B. conceived the ideas and designed methodology with assistance from A.L.B., R.D.B., N.W. and G.A.B.; B.F.T.B. collected the data; B.F.T.B., A.B. and M.W. analysed the data; B.F.T.B. and A.L.B. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY

Where storage will not compromise the anonymity of research participants, data have been deposited in the Dryad repository https://doi.org/10.5061/dryad.5p489m3 (Brockett et al., 2019). Data will be under a 1-year embargo after publication date due to ongoing publishing activity.

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