Agriculture and Environment Research Unit
School of Life Sciences

University of Hertfordshire

National Trust

A Land Carbon Management Plan for the Wallington Estate

Final Report

Agriculture and Environment Research Unit
School of Life Sciences
University of Hertfordshire
United Kingdom

&

Dept. of Earth Sciences
University of Durham
United Kingdom

Contents

Executive Summary

The National Trust aims to enter the majority of tenanted farms on the Wallington Estate into Higher Level Stewardship (HLS) agreements. The agreements aim to enhance biodiversity, the historic environment, access and landscape features however the impact on soil organic carbon (SOC) and biomass carbon (C) is also of importance. Multiple options may be available to achieve each particular aim with differing impacts on SOC and biomass C. The project will identify land management options that achieve each primary objective (enhance biodiversity, the historic environment, access and landscape features) but also maximise C without increasing emissions of other greenhouse gases (GHGs). An inventory of the potential C that may be sequestered by introduction of HLS on The Wallington Estate will be undertaken and the impact on other greenhouse gas (GHG) emissions indicated. Current SOC content measured by the University of Durham will be used as the baseline against which any predicted change in C by implementing existing or new HLS options may be compared. Using the data generated by Bell and Worrall (2009) and Defra project BD2302 (Warner et al., 2008a) this project will evaluate those HLS options most suited to each individual tenancy within the Wallington Estate and calculate their potential to enhance soil or biomass C. Those with the greatest potential will be subject to further analysis to calculate their impact after a period of 20 years. Their practicability will be further assessed taking into account other objectives (farm productivity, soil and water protection and biodiversity). A programme of monitoring will be devised to ascertain the effectiveness of selected options relative to the predicted calculations. As part of this projects function as a 'blueprint' for other land holdings step-by-step guidance will be produced to allow the method to be implemented on other National Trust estates.

1.0. Introduction

The National Trust aims to enter the majority of tenant farms on the Wallington Estate into Higher Level Stewardship (HLS). Higher Level Stewardship is a component of Environmental Stewardship (ES) in England that also includes Entry Level Stewardship (ELS) and Organic Entry Level Stewardship (OELS). Higher Level Stewardship is targeted at land that contains habitats or features deemed to be of a high priority (Defra, 2005; Natural England 2008). Further, it consists of more complex management requirements, and involves the creation, restoration or maintenance of specific habitats but may also be combined with the ELS options. The five primary objectives of Higher Level Stewardship are:

- wildlife conservation
- maintenance and enhancement of landscape quality and character
- natural resource protection
- protection of the historic environment
- and promotion of public access and understanding of the countryside.

A further two secondary objectives include flood management and the conservation of genetic resources. Each HLS option is designed to contribute to one or more of the five primary objectives and normally are suited to land of significant environmental interest. In meeting specified objectives, a further aim is to enhance the climate change mitigation potential of agriculture within England, through a reduction of greenhouse gas (GHG) emissions and maintenance of carbon (C) stores within soil or biomass.

Defra project BD2302 assessed the impact of implementing each individual ELS and HLS option on soil organic carbon (SOC) and biomass C, and the greenhouse gases carbon dioxide (CO_2), nitrous oxide (N_2O and methane (CH_4). A detailed study by Bell and Worrall (2009) has quantified the carbon (C) within soils on the Wallington Estate to a depth of 20 cm accounting for soil group, soil series, land use, management practice, pH and altitude. Using the data generated by Bell and Worrall (2009) and Defra project BD2302 (Warner *et al*., 2008a) this project has evaluated those HLS and other options most suited to each individual tenancy within the Wallington Estate and calculated their potential to enhance soil or biomass C. As an example, habitat creation options may be preferable to sequester C where there is below average SOC, habitat restoration options where SOC is below to average, and habitat maintenance options where above average SOC is identified.

Certain measures may yield immediate benefits with respect to increasing the sequestered C at Wallington, while for some the benefits may be more long term (several decades). Monitoring will be established and resourced for a 20 year period initially. Options with the greatest potential will be subject to further analysis to calculate their impact after a period of 20 years. The project has considered strategies not currently included within HLS that may offer potential, and calculated projected impacts of strategies that offer promise, but require further research.

2.0. Inventory of the impact of land management practices on carbon sequestration in soils and biomass, and CO_2 emission from soils

Carbon may be stored in soils as soil organic carbon (SOC) and as biomass in the stem, leaves and roots of plants. Soil organic carbon is present within soil organic matter (SOM), of which it comprises around 58% (IPCC, 2006). The European Parliament report "Towards a Thematic Strategy on Soil Protection" in 2002 identified a decline in SOM, soil erosion and soil compaction as among eight priority threats to soil quality. These factors also impact on the C stored within soils and biomass. The maintenance of SOM is a requirement to keep land in Good Agricultural and Environmental Condition (GAEC) (Louwagie *et al*., 2009).

Benefits of enhanced SOM include increased absorption capacity (approximately six times its weight in water), maintenance of soil fertility, enhancement of buffering capacity (protection of plants from sudden change in acidity or alkalinity), maintenance of favourable soil structure and porosity, and increased sorption capacity (water and plant nutrient retention, with positive implications for crop yields) (Louwagie et al., 2009; Mudgal and Turbé, 2010). Soil biodiversity on arable and grassland is also increased by greater SOM levels, notably populations of arbuscular mycorrhizal fungi, beneficial species that facilitate nutrient transfer between soil and plant. These species also enhance soil aggregation that improves soil structure, and mitigates the negative effects of pathogenic micro-organisms on plants. The presence of SOM reduces the potential surface water flow and run-off (and with it the transport of soil particles) and improves infiltration (Louwagie *et al*., 2009; Pimentel *et al*., 1995). Further, it reduces the vulnerability of soil to erosion and compaction, another factor detrimental to crop yield. Crucially, enhanced soil carbon increases the resilience of many soils to climate change and depletion of water resources via greater soil structural stability and productivity even when stressed by extremes of dry or wet conditions.

2.1. Land use

Land use is one of the key variables determining the quantity of SOC and biomass C, as illustrated in Table 2.1. Section 2.1 outlines the key links between land use and land carbon.

2.1.1. Priority habitats

Priority habitats high in either SOC and / or biomass C include bog, heathland (heather moorland), acid grassland and lowland woodland. Although acid grassland may form naturally it may also indicate degraded wet heathland or blanket bog communities due to over-grazing or drainage (practices detrimental to the SOC equilibrium). Marshy areas are also potentially higher in SOC while larger plant species such as trees, store large amounts of C in biomass. Plant species with deep roots offer potential to enhance SOC in the deeper soil layers. Watercourses and the immediately adjacent areas (banks) are included as priority habitat because of the potential for soil erosion and loss, and pollution of water with particulate matter.

Table 2.1. Measured SOC, and estimates of biomass C as tonnes of C per ha (t C ha^{-1}) at equilibrium for different land uses and habitats (from Carey et al., 2008; Falloon et al., 2004; IPCC, 2006; Milne & Brown, 1997; Ostle *et al*., 2009; Dawson and Smith, 2007). Carey et al. (2008) describe SOC to a depth of 15 cm based on the Countryside Survey (2007).

Land use / habitat	SOC (to 15 cm)	Biomass C	Description
Bog	[a]259.0	2.4	Unimproved wetland habitat
Dwarf shrub heath	87.6	1.7	Unimproved (partial wetland) habitat
Acid grassland	87.0	2.4	Unimproved / semi-improved grassland
Bracken	81.4	[c]3.0	Deep rooting species but may indicate degraded organic soils
Fen, marsh and swamp	75.6	2.4	Unimproved wetland habitat
Coniferous woodland	69.9	[b]70.0 – 195.0	Forestry / upland woodland
Mixed broadleaved and yew woodland	62.7	98.9 – 140.0	Lowland woodland
Hedgerow	[c]61.0	5.0	Boundary
Neutral Grassland	59.9	2.4	Unimproved / semi-improved grassland
Improved grassland	58.8	1.6	Includes temporary / improved permanent grassland
Arable and horticultural land	42.6	2.2	Cultivated land

[a] extrapolated to 50 cm; [b] rotational forestry; [c] estimate based on Falloon *et al*., 2004.

The preservation of priority habitats (with the maintenance options of HLS) will preserve the C stocks contained in them. Where priority habitats are present but degraded, or where they have been removed (e.g. small numbers of indicator species are still present in grassland), SOC tends to be lower but their restoration offers the opportunity to increase SOC. The avoidance or removal of drainage, burning and ploughing and reseeding (the cultivation of organic soils increases CO_2 release significantly (Freibauer *et al*., 2003)) is preferable. The uplands are more prone to higher wind speeds that, coupled with exposed (where overgrazing has occurred) organic soils of low bulk density results in erosion. It should be noted that priority habitat species such as those in bog or heathland are indicative of soil conditions conducive to SOC accumulation (e.g. waterlogged with low pH), rather than being solely responsible for carbon (C) accumulation themselves. In woodland by contrast, a much greater proportion of C is contained in biomass in the trees. It must also be appreciated that the presence of some species e.g. coniferous woodland or bracken may be indicative of degraded habitat on high C containing soils and that carbon dioxide (CO_2) release may be occurring. At Wallington different land uses are present on different soil series (this is covered in detail in Section 5). The land use change options in Table 2.2 are therefore limited to certain soil series (e.g. the restoration of heather moorland mainly to the series K, Hj, and Wo). Where priority habitats such as bog or heather moorland have been improved (e.g. by drainage), but support relatively small levels of production, gains in C from their restoration could be significant, coupled with limited production displacement.

With respect to future options, 'paludiculture', the growing of water tolerant plant species such as reed (*Phragmites* spp) or alder for use as biomass crops on either wet or rewetted peat soils (Wichtman and Joosten, 2007) has been suggested. The full impact on site hydrology of such a strategy would have to be assessed.

2.1.2. Hedgerows

Hedgerows growing along field boundaries within grassland or cultivated land are estimated to contain SOC somewhere between that of permanent grassland and broadleaved woodland (Falloon *et al*., 2004). Additional biomass C is contained within woody species such as hawthorn, although regular cutting does restrict this somewhat.

2.1.3. Grassland

Improved grassland and neutral grassland (characteristic of neutral soils) are similar in SOC according to Carey *et al*. (2008) (Table 2.1). The classification improved grassland includes a proportion of temporary (by definition this is ploughed and reseeded every five to eight years) grassland, the cultivation of which reduces SOC, albeit not as drastically as land cultivated annually (Smith *et al*., 2000 a,b; Falloon *et al*., 2004). An unknown quantity is the area of grasslands that have been ploughed and reseeded in the past. For example, grassland reseeded 10 years previously is not strictly by definition 'temporary' but will in all probability have lower SOC than grassland that has not been reseeded previously. Neutral grassland may be subject to greater agricultural improvement than acid or calcareous grassland and includes hay meadows where biomass is cut and removed, but is permanent. Acid grassland may be indicative of degraded high C containing soils (degraded heather moorland) that have lost, or are losing, SOC and not at their maximum equilibrium. Calcareous grassland tends to be species rich.

2.1.4. Cultivated land

Agricultural (annually cultivated) land contains the smallest levels of SOC in the surface layer (Carey *et al*., 2008; Dyson *et al*., 2009) (Table 2.1). The biomass is also relatively low since cropping is annual but this may be exacerbated by the presence of fallow areas that contain negligible plant biomass.

The values displayed in Table 2.1 for grassland and cultivated land represent the mean, a range of values exist above and below these values depending on environmental factors (e.g. soil type) and management practice (Ostle *et al*., 2009).

2.2. Increasing SOC through land use change

Table 2.1 lists the SOC and biomass C of a number of land uses. Conversion from a land use of low C to one of high C (subject to practicalities e.g. the previous existence of bog habitat or heathland) will increase C stocks. Table 2.2 lists generic C accumulation rates that occur when a change in land use is implemented. These figures can be used to calculate the quantity of C accumulated after a given period e.g. 10 or 20 years.

2.2.1. Modes by which land C is increased

Land use change can either increase the rate of C accumulation from photosynthesis, or reduce the return of C from oxidation of organic matter or respiration to the atmosphere (Smith *et al*., 2000 a & b). The return of plant material to the soil enhances the levels of SOM and SOC (Schils *et al*., 2008) however soils are not able to increase in SOM and SOC indefinitely (Johnston, 2008) because decomposition of plant material within soil releases C as CO_2. An equilibrium is eventually reached when the rate of C added equals that released as CO_2. Addition of organic matter (OM) to the soil after reaching equilibrium will not continue to increase SOC levels but will however, continue to release CO_2 (Johnston, 2008). The majority of data gathered applicable to SOC tends to be within the top 30 cm, where most disturbance occurs (Bell and Worrall, 2009; Carey *et al*., 2008; Smith *et al*., 2000 a & b) although the impact on C within the subsoil is also of importance.

2.2.2. Variables influencing the level at which equilibrium is reached

The level of SOC at equilibrium depends on climate (temperature and rainfall), soil conditions (pH, soil type, water content and the prevalence of anaerobic soil conditions, compaction), land use (type of vegetation, permanent or cultivated) and soil management practices (e.g. frequency of tillage, addition of organic materials). The development of increased plant root mass and greater root depth are crucial to the enhancement of SOC equilibrium levels in habitats such as grassland. Management that increases the rate of plant growth (for example supplementary nutrients where there is an identified soil deficiency) increases the rate of SOC accumulation (IPPC, 2006). In contrast, soil conditions that hinder plant root growth, namely compacted soils, reduce the SOC at equilibrium.

2.2.3. Land use changes likely to increase SOC

The most significant process by which a change in SOC or biomass is achieved is by a permanent change in land use where the SOC established at equilibrium is greater than that of the original land use (Bradley *et al*., 2005; Milne and Mobbs, 2006). The new equilibrium is established when C emitted to the atmosphere equals the C accumulated from increased organic matter returns (King *et al*., 2004).

Soil C may be increased by conversion of cultivated land to permanent cropping (i.e. untilled land) which is either ungrazed (e.g. woodland, wildlife strips/zones) or grazed permanent grassland (Table 2.2). Cultivated land in England has been reported as containing smaller quantities of SOC compared to grassland or woodland (Bradley *et al*., 2005; Carey et al., 2008; Dyson *et al*., 2009). Conversion of arable land to grassland or woodland is likely therefore to increase the SOC at equilibrium. Woodland creation also has considerable potential to sequester additional biomass C (Falloon *et al*., 2004; King *et al*., 2004) although a period of several years is needed for trees to reach their full biomass potential. It does however remove land from production that risks displacement of that production to land elsewhere (Smith *et al*., 2010; Warner *et al*., 2008a) resulting in no net gain in SOC or biomass C. The SOC in grassland may be enhanced by replacement of temporary with permanent grassland (removal of tillage and reseeding operations) (Falloon et al., 2004). Temporary grassland however provides silage for winter feed allowing indoor overwintering of cattle.

The drainage and subsequent cultivation of organic soils is more detrimental to C stocks than drainage alone, because mineralisation (formation and emission of CO_2 from C contained within organic matter) increases rapidly in response to frequent tillage (Freibauer *et a*l., 2004). The removal of drained organic soils from arable land use is therefore deemed a priority. The drainage of organic soils is described in more detail in Section 2.3.1.

The rate of SOC accumulation may be increased in e.g. a change from cultivated land to permanent grassland by the addition of nutrients such as N (Section 2.3.). This is however dependent on soil type and applicable only to existing nutrient poor mineral soils.

2.2.3. Permanence of land use change

Although a change in land use may increase C stocks, reversion to the original method of management will reduce it (Jackson et al., 2009; King et al., 2004; Milne and Mobbs, 2006; Smith, 2005; King et al., 2005). Gains in C may easily be lost and at a rate faster than it was accumulated originally (Smith, 2004). Changes in land use or management practice that increase C must be continued indefinitely. There is opportunity for permanent land use change in the restoration or maintenance of the priority habitats.

2.2.4. Time lapsed to reach new equilibrium

The IPCC (2006) default time period to reach a new equilibrium is 20 years. In reality this depends on the existing C content of the soil at the time of management change, and the potential achievable new equilibrium. Both may be variable and depend on existing management of a given land use. The conversion of cultivated land to grassland has been reported to reach equilibrium after more than 60 years (Hopkins *et al*., 2010). Soils at Rothamsted in receipt of FYM for over 150 years continue to gradually increase in SOC (the equilibrium has yet to be reached). To quantify an exact timescale is therefore difficult.

The restoration of peat or organic soils e.g. on moorland habitats may accumulate greater quantities of SOC at equilibrium overall, and to greater depths than arable or grassland, though it may be a slower process because of smaller returns of biomass within these habitats.

Table 2.2. Examples of C accumulation (to 30 cm) in Europe and (in brackets) on UK soils, and biomass listed in the literature. SOC refers to mean accumulated per year over a given period. New land uses that specify a habitat e.g. wet heathland assume previous existence of that habitat on the existing site.

Original land use	New land use	Change in SOC (t C ha^{-1} yr^{-1})	Change in biomass (t C ha^{-1} yr^{-1}) and (N° years)
Cultivated	Temporary grassland	0.35	-0.6 (1)
	Fertilised permanent grassland	0.3–1.9 (1.2)	0.2 (1)
	Sown unfertilised grassland	0.3–1.9 (1.0)	0.2 (1)
	Sown unfertilised grass margins	0.3–1.9 (1.0)	0.2 (1)
	Natural reversion	0.3–0.6	0.2 (1)
	Hedgerow	0.95	1.0 (5)
	Scrub	0.95	1.0 (5)
	Broadleaved woodland / tree strips	0.9	2.8 (50)
	Conifer woodland	0.9	2.8 (70)
	Marshy grassland	2.2 – 4.6	0.2 (1)
Temporary grassland	Fertilised permanent grassland	0.2 – 0.5	0.8 (1)
	Unfertilised permanent grassland	0.2	0.8 (1)
	Grass margins	0.2	0.8 (1)
	Hedgerow	0.15	1.0 (5)
	Scrub	0.15	1.0 (5)
	Broadleaved woodland / tree strips	0.1	2.8 (50)
	Conifer woodland	0.1	2.8 (70)
	Marshy grassland / wet heathland / bog	0.8 – 3.9	
Existing grass boundary	Hedgerow	0	1.0 (5)
Unfertilised grassland	Marshy grassland / wet heathland / bog	0.8 – 3.9	
Unimproved wetland	Drained, cultivated organic soils	-2.2 to -5.4 (-4.1)	
	Grassland on drained organic soils	-2.73	
	Upland drainage (afforestation)	-2.0	

2.3. Land management practices

The second approach to increasing C does not change the land use, but permanently changes the land management practices to alter the SOC at equilibrium.

2.3.1. Organic soils – prevention of drainage

Of particular significance to the priority habitats described in section 2.1 is the previous draining of organic soils that results in loss of SOC as CO_2 (Dawson and Smith, 2007; Jackson *et al*., 2009). Their preservation is identified as a priority mitigation strategy both within the UK and Europe as a whole (Schils *et al*., 2008; Smith *et al*., 2008). The accumulation of SOC is enhanced under wet anaerobic conditions, for example in peat. Their maintenance also prevents the SOC contained within organic soils from decomposing and being released as carbon dioxide (CO_2).

Land drainage results in the loss of anaerobic conditions. The decomposition of C in the subsequent aerobic soil conditions is accompanied by the release of CO_2 (Jackson et al., 2009; Schils et al., 2008). Freibauer (2003) reports that grassland on drained organic soils releases 2.73 t C ha^{-1} (Table 2.2) although the overall amount is dependent on soil depth. The preservation of peat soils may be achieved by prevention of drainage / maintenance of the water table. Management practices that restore the water table though the blocking of drainage ditches are reported to have the potential to prevent further release of CO_2 (Freeman *et al.,* 2001; Moorby *et al.,* 2007) although this may not be immediate. The phenols that prevent SOC decomposition may be destroyed when the soil is drained, and emission of CO_2 continues after water table restoration (the 'enzyme-latch effect'). It should also be noted that re-wetting may increase the release of certain greenhouse gases. An associated increase in emission of CH_4 has also been identified in the short-term, the duration of this however has yet to be quantified.

The blocking of grips was found by Gibson et al. (2009) to significantly decrease the quantity of Dissolved Organic Carbon (DOC) exported from the soil by reducing the flow of water. It would be apparent that grip blocking reduces C loss in at least one form or another. The maintenance of the water table and avoidance of drainage is deemed a priority. The blocking of 'grips' and rewetting of heathland in upland areas are options within the HLS (Natural England, 2010), and they will be discussed further in Section 3.0.

2.3.2. Organic soils - cultivation

Where organic soils are cultivated, the release of CO_2 may be considerable, up to 4.1 t C ha-1 (Freibauer *et al*., 2003) (Table 2.2). Strategies to mitigate such releases include avoiding deep cultivations and row crops, and maintaining a shallow water table (Freibauer *et al*., 2004). The addition of N fertiliser to peat soils has been found to increase the rate of C mineralisation and CO_2 release (Kechavarzi *et al*., 2010), and therefore should be avoided. The management of heathland by burning is attributed to loss of C from the upper soil layers, and the removal of vegetation renders it exposed to erosion and the 'albedo effect' (Dawson and Smith, 2007).

2.3.3. Field boundaries

Field boundaries may consist solely of tussocky grass or there may be woody species that form part of a hedgerow. Neglected hedgerows may include large gaps. The biomass within field boundaries and the hedgerows themselves may be increased by allowing growth to a greater height, 'gapping up' where hedge species are absent, planting new hedges on boundaries where there is only grass, and allowing growth of 'standards' (single trees intermittently along the hedge line) (Warner *et al*., 2008a). An advantage of boundary management is that generally it has a negligible impact on agricultural production, and may contribute leaf litter to those arable or grassland areas immediately adjoining them. Yield loss may arise because of the invasion of pernicious weed species such as blackgrass or the presence of tree or hedge roots in the plough zone.

2.3.4. Grassland management

The overall effectiveness of management practices to increase the SOC of grassland is subject to an element of uncertainty, mainly because of differences in site specific variables between studies. Ploughing and reseeding in temporary grassland however, is generally accepted to decrease the SOC at equilibrium (Section 2.2). The main strategies on productive grassland and those reported in a number of recent high profile reviews (e.g. Dawson and Smith, 2007; Louwagie et al., 2009; Ostle et al., 2009) include optimal crop nutrition (subject to Good Agricultural Practice) to enhance plant growth and biomass accumulation, the presence of a greater diversity / improved productivity grass species, and low to moderate levels of grazing (Table 2.3). The nutrition of grassland will favour species capable of rapid growth at the expense of others and is likely to reduce species diversity, another proposed strategy. Naturally occurring species diverse grasslands include calcareous grasslands where the application of N would not be beneficial to species diversity and therefore the accumulation of SOC. Grasslands sited where N is a limiting factor but soil conditions are not conducive with natural formation of species rich grassland (for example, those outlined in the HLS guidelines on site assessment of potential for species rich grassland) benefit from intervention with supplementary nutrients. The avoidance of soil compaction is crucial since this prevents the full benefit of supplementary nutrient application on increased root biomass from being realised. It also hinders the development of species rich grassland where suitable sites exist.

2.3.5. Nitrogen and grassland

Where agricultural grassland requires supplementary nutrients ideally the N to optimise crop nutrition and enhance grass biomass production should be made available by the presence of clover, deemed to be a sufficient alternative to N fertilisation (King et al., 2004). The manufacture of inorganic N has significant greenhouse gas emissions associated with its manufacture (Bentrup and Palliere, 2008) and its use as a means to enhance SOC, a process that does not continue indefinitely (Johnston, 2008; King et al., 2004), is not advised. Dawson and Smith (2007) consider the presence of clover to be at least as effective in enhancing the SOC of agricultural grassland as supplementary fertiliser (Table 2.3).

Where FYM is the source of organic N, spreading with a chain harrow (which also spreads grazing deposition) ensures a more even spread of nutrients, while also returning C (Dawson and Smith, 2007).

The fertilisation of temporary grassland allows the more rapid re-accumulation of SOC lost during cultivation. For a grassland that is ploughed and reseeded every five years, the mean SOC over that five year cycle is greater than if amendments are not made.

2.3.6. Application of FYM and slurry to temporary grassland

Optimising the N available to the grass crop from amendments of manures or slurry increases the potential for biomass production and C accumulation. The availability of N is determined in part by the timing (winter or spring) and method of application (e.g. surface or deep injection). Surface application of slurry reduces the N available to the crop compared to deep injection where nutrients are delivered directly to the crop root zone. Deep injection avoids volatilisation (loss of N as ammonia (NH_3)) and incorporates the C contained within the slurry directly into the soil as opposed to it remaining on the soil surface, where there is greater opportunity for it to be oxidised and released to the atmosphere as CO_2. There is however no apparent quantification of its impact in the literature. Wallington uses straw based manure management (FYM). Straw contains a high proportion of C, as a consequence straw based manures such as FYM have greater quantities of C than manures from grazing deposition alone. The quantity of FYM available to spread is dependent on the number of livestock on the tenancy, and the period for which they are housed. The quantity of straw within FYM is dependent on either the production of arable crops on the tenancy, or the importing of straw from farms where arable cropping is present.

The net beneficial impact of manure as a source of N and additional C on SOC accumulation in grassland may be reduced by a reported increase in crop respiration and CO_2 emission (Rochette and Gregorich, 1998).

2.3.7. Deep rooting grass species & earthworms

Sowing and maintaining swards of grass species with deep rooting systems is another potential (but as yet unconfirmed) method to increase biomass and the rate of SOC accumulation in grasslands (Conant *et al*., 2001; Smith *et al*., 2008a). The addition of earthworms, or stimulation of increased earthworm activity (e.g. by addition of FYM and avoidance of soil compaction), is also cited as a means to improve SOC (Dawson and Smith, 2007). Cultivation (prior to reseeding) may however result in earthworm mortality (Louwagie, 2009) and activity may be expected to be reduced immediately after cultivation.

2.3.8. Grazing

The impact of grazing on grassland SOC is disputed. The presence of stock returns not only C but also N, P and K in deposition. This is of benefit to grass growth and C accumulation. Generally, the timing and intensity of grazing are key determinants of the rate of C accumulation in grassland soils (Conant *et al*., 2001; 2005; Freibauer *et al*., 2004). However, Smith *et al*. (2008a) concluded inconsistency between studies as being too significant to recommend any one practice with confidence. Agricultural production uses higher stocking rates and while presence of stock at lower densities (0.4 – 0.8 LU ha^{-1}) may be beneficial, higher rates result in topsoil damage. Over-grazing is generally perceived as being detrimental because of excessive removal of biomass, and increased risk of topsoil compaction and soil erosion from trampling (and removal of surface vegetation) by greater numbers of livestock (Conant *et al*., 2001; 2005; Freibauer *et al*., 2004; Louwagie *et al*., 2009). Soil compaction may be classed as either topsoil or subsoil and are regarded as two distinct problems (Section 2.3.10). Topsoil compaction prevents the infiltration of water that increases the risk of soil erosion (Louwagie *et al*., 2009). Topsoil compaction is also responsible for yield reductions of up to 13%, (van Camp *et al*., 2004) and is detrimental to beneficial soil organisms such as earthworms (Mudgal and Turbé, 2010). In the UK the Holnicote project (National Trust, 2010) has established sheep as significant factors in causing compaction on the in-bye grassland and the periphery of moorland. No consistent data exists to recommend exact stocking rates with confidence. Stocking rates above 0.8 LU ha^{-1} have been cited to be detrimental to SOC accumulation (Smith et al., 2008). A recent study by Marriott et al. (2010) that monitored two sites disputes this to a degree and found the SOC to be greater under more extensive grazing regimes on one site but not the other. Compaction may reduce biomass accumulation by up to 13% (Louwagie et al., 2008) and as a consequence, the SOC at equilibrium. It will also reduce the rate of SOC accumulation and the effectiveness of SOC accumulation strategies. On soils of high compaction risk (e.g. clays) lower stocking rates (0.4 LU ha^{-1}) may be necessary. Soil compaction is covered in more detail in Section 2.3.11. Where grazing is implemented on priority habitats such as heather moorland, lower stocking rates with grazing restricted to the summer months may be necessary. Rotational grazing where stock are removed for a period of time during the year, or removed altogether for a year, may alleviate some compaction where soils are capable of recovery. It allows grass to re-establish on poached areas (where the hoofs of livestock walking on wet soil has destroyed vegetation and formed compressions) or areas at risk to erosion. Soil compaction remediation techniques include soil aeration (top 10-20 cm).

Avoidance of topsoil and subsoil compaction allows deeper root penetration and increased production of root biomass. Low to moderate grazing levels are considered to increase C accumulation via organic matter contained within deposition (Dawson and Smith, 2007), while the risk of erosion and / or compaction remains low. Lower stocking rates may still cause localised topsoil compaction in the vicinity of feeding troughs (Moorby et al., 2007) although their frequent relocation reduces this risk.

2.3.9. Feed composition and manure storage

Another factor, albeit subject to the extent of anaerobic conditions in which the manure is present, is the quantity of volatile solids (VSs) within the manure (IPCC, 2006). Volatile solids are the organic matter within manure that has potential to form CH_4. The quantity of VSs within manure is dependent on the type of feed (Thomas, 2004). Under increasingly anaerobic conditions, VSs stimulate release of greater quantities of CH_4 from manure (IPCC, 2006; Thomas, 2004). Deposition onto grassland is generally under aerobic conditions, loss of CH_4 from manures therefore tends not to be such a significant factor. Where it is significant is in housed livestock, where manures are often stored in heaps, a combination of aerobic and anaerobic environments. In addition to CH_4 being a greenhouse gas, these manures will then be reapplied to the grassland minus the C contained within any CH_4 emitted. Modification to manure storage techniques may reduce atmospheric C loss as CH_4 however the impact on emission of nitrous oxide must also be taken account of (IPCC, 2006). Loss of N as N_2O reduces the value of manure as a fertiliser (in addition to its potency as a GHG) and is therefore detrimental to increased plant root growth and SOC accumulation.

The type of feed also impacts the quantity of enteric CH_4 produced. Feeds that contain greater quantities of starch (for example maize or cereals) reduce the enteric CH_4 produced by livestock (Williams et al., 2009), preserving greater quantities of C for deposition onto the grassland (Dawson and Smith, 2007). The growing of maize and cereals however requires the cultivation of land, which has lower SOC than temporary or improved grassland (Carey et al., 2008).

Modification to the livestock diet or method of manure storage may have the potential to reduce CH_4 emission from manures, particularly where stock are not grazed during the winter, a strategy to prevent soil compaction and erosion. The identification of feed mixtures (subject to not increasing the area of cultivated land) and / or implementation of manure storage strategies that minimise C loss, offer potential to recycle greater quantities of C when applied to land. More importantly, they will also prevent the emission of CH_4.

Table 2.3. Management practices for cultivated land and grassland to 30 cm (unless stated otherwise), and potential impact on SOC accumulation. Figures in parentheses represent mean UK data.

Land use	Land management practice	Change in SOC (t C ha^{-1} yr^{-1})
Cultivated	Agricultural extensification (grass leys)	0.54 (0.26)
	Straw / residue incorporation	0.69 (0.4)
	FYM / slurry / compost incorporation	0.37
	Minimum tillage	0.2 (0.1)
	Zero tillage	0.39 (0.4)
	Deep rooting crops	0.62 (0.31) (to 100 cm)
Grassland	Efficient fertilisation	0.3
	Low N fertilisation (< 50 kg N ha^{-1})	0.08
	Sward species improvement (deep rooting system / productive species)	3.04 (to 100 cm)
	Inclusion of legumes e.g. clover	0.3 – 0.75
	Increase earthworms	2.35
	Reduce topsoil compaction	0.35
	Low – moderate grazing levels (0.4 – 0.8 LU)	0.05
General	Topsoil compaction	-13% biomass
	Subsoil compaction	-35% biomass
	Erosion (clay and medium loams)	-0.22 t soil
	Erosion (upland peat)	-0.47 t soil

The application of N fertiliser or inclusion of clover benefits sown species mixtures such as perennial ryegrass, where grazing is higher or is cut for silage. Its application is generally beneficial to establish newly sown mixtures and may increase the rate of growth however this will be at the expense of species diversity. The creation of species rich grass swards is also cited to increase SOC but in the absence of clover and N fertiliser and in combination with low stocking rates. Sown mixtures may be established under most conditions, species rich grasslands are more sensitive to environmental factors and more limited in their potential distribution. It was noted that the neutral grassland on the estate (Biological Survey, 1999), a relatively species poor grassland, did not differ to rough permanent pasture in levels of SOC. Nitrogen and fertilisers are applied in response to increased stocking rates and grazing to justify the economic outlay. The application of N needs to be in conjunction with production, not solely to increase SOC. Low stocking rates reduce the risk of compaction (described in greater detail in section 2.3.11) but return ingested C via deposition. The stocking rates cited in Table 2.3 represent a balance between increased return of organic C by deposition with avoidance of hindering growth and biomass accumulation from compacted topsoil. The range in stocking rates reflects other variables such as presence during the winter (lower end of the range) and the vulnerability of the soil to compaction.

2.3.10. Soil erosion

Soil erosion results in loss of SOM and SOC (Mudgal and Turbé, 2010) and, because the soil structure is damaged, exposes remaining SOC within aggregates to oxidation that accelerates CO_2 emission. The slow formation of soils means that losses greater than 1 - 2 t ha^{-1} are considered irreversible (EC, 2005; European Environment Agency, 2010). Further, erosion can be responsible for compaction and reduced infiltration of water (Louwagie *et al*., 2009), and ultimately loss of crop yield.

The risk of soil erosion is site specific and depends on local topography, soil type and rainfall. It is exacerbated by management practices that result in exposure of bare soil to water and wind, and depleted levels of SOM (Louwagie *et al*., 2009; Mudgal and Turbé, 2010). Management practices that maintain a cover of vegetation, crop residues or green mulch on the soil surface (e.g. during the winter before sowing a spring crop) reduce the impact of rain droplets and the likelihood that topsoil is washed away (Louwagie et al., 2009; Renard *et al*., 1997; Wischmeier and Smith, 1978). Such practices are of particular relevance to arable land. They do however preserve SOC and allow arable production to continue.

Other strategies to reduce soil erosion, and those perhaps for consideration for incorporation into future ES options include ridge tillage (alternate cultivated ridges where the crop grows interspersed with furrows in which residues / green mulch are applied (Louwagie *et al*., 2009). The return of organic matter is enhanced. Contour farming is another strategy, where cultivation follows the line of field contours instead of the slope gradient (Louwagie *et al*., 2009).

2.3.11. Soil compaction

A variable not included by Bell (2010) is soil compaction, estimated to reduce topsoil biomass accumulation by up to 13%. This effectively reduces the rate of SOC accumulation and SOC at equilibrium (practices listed Table 2.3) by 13% in a 'worse case' scenario. Further, reduced compaction reduces the risk of N_2O emissions from denitrification. Soil compaction may vary significantly both within fields and between fields because it is influenced by a number of variables including soil type (or series), and movement of farm vehicles and livestock.

European Environment Agency (2010) defines the susceptibility of soil to compaction as the probability (low, medium, high and very high) that a soil becomes compacted when subject to a compaction risk (e.g. pressure exerted by livestock or farm vehicles). The properties of a soil that increases this compaction susceptibility has been the subject of analysis by a number of authors. Although agreement is not complete, a general consensus finds that clay soils (soils with the smallest particle size <0.002 mm) are most vulnerable (high risk) while larger particulate soils such as medium sand (0.2 – 0.6 mm) and coarse sand (0.6 – 2.0 mm) are low risk. Some disagreement exists for mixtures of soil texture. The European soils database (Europa, 2010) attributes susceptibility to the clay fraction within the texture and lists them (from low to high risk) as sandy < loamy sandy < sand loamy < loamy < clay loamy < loam clayey < clayey soils < clays. Sand soils contain coarser soil particles and retain pore space after compaction stress, whereas more finely textured soils do not. In an analysis of soil structural strength, van den Akker & Schjønning (2004) point out that mixtures of coarse and fine particles are also susceptible to compaction. They further include clay loam, sandy silt and silt loam as being vulnerable to compaction in addition to clay. Coarse sand and sand were considered to be least vulnerable while clay was most vulnerable. Steber *et al*. (2007) describe sand and sandy loam as low risk, clay, loam and silt loam as high risk. Silt soil particles range between 0.002 and 0.06 mm and although larger than clay, they are also high risk. On permanent habitats (e.g. grassland) that contain soils without inherent natural ability to recover (clay and silt soils) compaction must be avoided as priority since it is largely irreversible. The references described previously and the soil series description of Avery (1980) have been used to compile a risk category for the soil series found on Wallington (Table 2.4).

Louwagie et al. (2008) cite topsoil compaction as resulting in decreased biomass accumulation of up to 13%. The relevant SOC accumulation processes listed in Table 2.3 have been increased by 5% for low compaction risk soils, 9% for medium risk soils and 13% for high risk soils in calculations where topsoil compaction was modelled as being alleviated by HLS options.

Table 2.4. Soil series compaction risk

Soil series		Soil group	Compaction risk
Belmont	Bo	podzol	low
Brickfield	Br	surface-water gley soils	low-moderate
Cragside	cgs	lithomorphic soils	low
Cartington	crt	podzol	low
Dunkeswick	Dk	surface-water gley soils	low-moderate
Dunwell	dz	lithomorphic soils	low
Enborne	Eo	ground-water gley soils	low
Fladbury	Fa	ground-water gley soils	low
Freni	Fe	ground-water gley soils	low
Greyland	gJ	surface-water gley soils	low-moderate
Heapy	Hj	brown earth	low
Kielder	K	surface-water gley soils	low-moderate
	MI	brown earth	low
Nercwys	Nc	brown earth	low
Neath	nh	brown earth	low
Quorndon	qn	ground-water gley soils	low
Rivington	Rc	brown earth	low
Rothbury	Ro	podzols	low
Sulham	sj	ground-water gley soils	low
Ticknall	tL	surface-water gley soils	low-moderate
Thrunton	Tm	podzols	low
Waltham	Wa	brown earth	low
Winter Hill	wh	organic rich peat soils	low
Withnell	wm	podzols	low
Wilcocks	Wo	surface-water gley soils	low-moderate
Wigton Moor	ww	ground-water gley soils	low
Disturbed /man-made	92	man-made soils	unknown

- Brown earth: freely draining, loamy / sandy soils (low compaction risk) but may be loamy above clayey material (vulnerable to subsoil compaction but not topsoil compaction)
- Surface water gleys: topsoil may be humose or peaty above slowly permeable subsurface layer (low topsoil compaction risk but high subsoil compaction risk), stagnogley soil may have sandy or loamy topsoil (low topsoil compaction risk) or clayey topsoil (moderate-high topsoil compaction risk) may contain greater clay subsoil (moderate-high subsoil compaction risk)
- Podzols: freely draining (low risk), brown podzols well aerated (low risk), humic cryptopodzols humic topsoil (low risk), gley podzols pervious sandy or coarse loamy materials (low risk), stagnopodzols peaty topsoil (high organic content low compaction risk).
- Lithomorphic soils: humose or peaty topsoil (low risk).
- Ground-water gley soils: humose or peaty topsoil (low risk),

Soil textures with larger pore spaces or that are more freely draining tend to be more aerobic and have lower SOC at equilibrium but less risk of compaction. From the perspective of maximising SOC accumulation it would be preferable to site land uses where practicable either where SOC is at risk of being lower (e.g. arable production) or where compaction risk is higher (e.g. IpermP) on these soils. More freely draining soils have implications for increased nitrate leaching and emission of N_2O from the leachate.

Movement by farm vehicles on grassland may be more pronounced along boundary edges. Compaction by livestock under trees may be a problem (provision of shade during the summer), close to watercourses (to drink), feeding rings, and access points (gates and gaps in boundaries or fences). Many farm tenants observed that livestock spent a greater proportion of time in areas of the field increasingly closer to the farm house. Poaching may occur where stock show a preference for particular areas of the field (Figure 2.1 centre) but elsewhere movement may also be concentrated in particular areas (Figure 2.1 left) where several stock followed the same path) compared to a single individual (Figure 2.1 right). It is recommended that compaction be measured and quantified directly using e.g. a penetrometer to derive soil strength.

Figure 2.1. Sheep tracks illustrating movement (left and right) and poaching (centre) in preferred field areas (maximum stocking rate 1.8 LU ha^{-1} grazed by sheep and cattle).

Hopkins *et al*. (2009) highlight the importance of grazing management in the prevention of soil compaction. They cite management of hay meadows where stock graze the aftermath and are present during the summer months until the autumn as a method to avoid compaction.

2.3.12. Cultivated land

Management practices recommended to increase the SOC of cultivated land without its removal from production include the incorporation of organic materials (farmyard manure, straw, crop residues), avoidance of burning, a reduction in tillage frequency, prevention of soil erosion and maintenance of the water table on peat soils (Cerri *et al*., 2004; Falloon, *et al*., 2004; Ostle *et al.*, 2009; Schils et al., 2008; Smith *et al*., 2000a,b; Smith *et al.*, 2008a). These are summarised in 2.3.

The majority of disturbance and also the potential to change the SOC of cultivated land occurs in the top soil layers (Smith *et al*., 2000 a, b). Tillage frequency may be reduced by the inclusion of a two year grass clover ley in a rotation, the growing of perennial crops and zero tillage. Minimum tillage disturbs only the top few centimetres of soil, in contrast to conventional ploughing, allowing in theory accumulation of SOC in the deeper soil layers normally subject to disturbance (Smith *et al*., 2000 a, b; King *et al*., 2004). It has yet however to be proven with confidence as a means to increase SOC.

The presence of grass strips (subject to location), incorporation of organic matter and avoidance of bare soil during the winter (e.g. cover crops) helps prevent soil erosion (Wischmeier and Smith, 1978; Renard *et al*., 1997) that also reduces loss of SOC. Soil erosion may be responsible for the loss of on average of 0.22 t soil ha^{-1} on clay soils (Table 2.3). The avoidance of bare, recently cultivated soil during the winter e.g. by growing a cover crop reduces the risk of soil erosion. Cover crops also utilise surplus nitrate from the previous crop Where grass buffer strips are sown, there is the opportunity to use specialist species mixes e.g. deep rooting species or shade tolerant species, depending on location. Such mixtures offer potential for inclusion within ES. Modification of crop rotations to include greater numbers of deep rooting crop species (on mineral soils) or the use of intercropping, where two crops are grown in alternate strips, are potential strategies that could be considered for future ES options.

Strategies that are currently unquantified include the incorporation of biochar, a material produced by the pyrolysis (heating in the absence of oxygen) of organic materials has been cited as a potential means to increase soil carbon since decomposition in soil is thought to be between 10 and 1000 times slower than soil organic matter (SOM) providing a potential C sink (Verheijen et al., 2009). It also enhances nutrient retention and reduces bulk density and compaction risk. Research is currently at a preliminary stage and its widespread use not recommended as a mitigation strategy although it does show promise. Until its benefits have been established with confidence it has not as yet been included within the recommendations for Wallington but it is acknowledged that it may be in the future.

2.3.13. Soil water content

Soil water content was also not included by Bell (2010), but is difficult to measure because of fluctuation during the year. The dominant vegetation cover is one indicator although on permanent pasture and temporary pasture vegetation cover cannot be used, rather position of sampling site e.g. at the base of a slope or within an area of localised depression where rainwater has potential to collect and remain for longer periods. The Wallington Estate is bisected by several watercourses. They require particular attention due to drinking (and associated soil erosion) by livestock and their importance for biodiversity on the estate. The allowance of raised waterlevels on parts of the adjacent agricultural land has implications for the alleviation of flooding further downstream.

2.3.14. Burning

The burning of vegetation often oxidises C on the soil surface that, on organic soils in particular, results in loss of SOC. Burning also forms aerosols in smoke which is considered to have a positive contribution to atmospheric warming (Smith *et al*., 2008a). Burning is typically used in heathland management to stimulate the regeneration of *Calluna*. Alternatives include mowing but this is restricted by there being sufficient access for machinery which themselves, can cause compaction to the detriment of SOC accumulation. Ash or burnt material could be incorporated into the soil however on organic soils, this practice would not be advisable.

2.3.15. Albedo effect

The removal of vegetation (e.g. by erosion from excessive stocking levels) causes the soil surface to be darker in colour and more capable of absorbing greater quantities of short-wave sunlight radiation (Ostle *et al*., 2009). This renders it more prone to warming and on high C containing peat soils accelerate drying out, the rate of CO_2 release and loss of SOC.

2.3.16. Imported sources of carbon

Sources of C produced off-farm include compost. The Wallington Estate has areas of forestry from which woodchip may be derived and used for livestock bedding during housing periods. If composted such material can be incorporated into cultivated land or applied to temporary grassland. Opportunity exists to pilot use of this material and monitor its impact on SOC.

3.0. Overview of HLS Options

Table 3.1 summarises the HLS options (and ELS options available under HLS) relevant to those C accumulation practices listed in Tables 2 and 3. They are divided by priority habitats (those with existing high SOC or biomass that should be preserved, or potential to achieve high SOC or biomass where restored or created on land where they previously existed) described in Section 2.1.

3.1. Priority habitats

The HLS options of pertinence to preserving, restoring or creating (subject to their presence previously) the priority habitats bog, wet heathland and marshy grassland (Table 1) are summarised in Table 3.1. The preservation of existing marshy grassland would avoid potential CO_2 loss on drainage and potential increase in CH_4 upon rewetting. Organic soils were not noted as present in samples taken by Bell (2010) on cultivated land or improved temporary pasture.

Table 3.1. HLS and ELS options permitted under HLS of relevance to maintenance, restoration or creation of priority habitats (Warner *et al*., 2008).

Code	Option	Management specifications of relevance to C	GHGs	£/ha
HL9	Maintenance of moorland	Maintenance of high SOC	[a]-2	£40
HL7	Maintenance of rough grazing for birds	Maintenance of high SOC, wet heathland, blanket bog	[a]-2	£80
HL13	Moorland rewetting supplement	Restoration of water table, arrest degradation of high SOC	-2	£10
HL10	Restoration of moorland	Arrest degradation of high SOC, restoration of water table	-2	£40
HL11	Creation of moorland	Creation of conditions to accumulate high SOC, restoration of water table, arrest degradation of SOC	-2	£60
HL8	Restoration of rough grazing for birds	Arrest degradation of high SOC, restoration of water table	-2	£80
HL5	Enclosed rough grazing	Maintenance of high SOC	[a]-2	£35
HL6	Unenclosed moorland rough grazing	Maintenance of high SOC	[a]-2	£35
HK15	Maintenance of grassland for target features	Maintenance of high SOC e.g. where applicable to unimproved acid grassland	[a]-2	
HL4	Management of rush pastures in SDAs	Maintenance of marshy grassland	[a]-2	£60
HC7	Maintenance of woodland	Maintenance of SOC and tree biomass	0	£100
HC8	Restoration of woodland	Additional tree biomass where new planting; increased SOC	0	£100

HC9	Creation of woodland inside the SDAs	Additional tree biomass where new planting; increased SOC on non-organic soils	-2	£200
HC10	Creation of woodland outside the SDAs	Additional tree biomass where new planting; increased SOC on non-organic soils	-2	£315
HQ6	Maintenance of fen	Maintenance of high SOC	[a]-2	£60
HQ7	Restoration of fen	Arrest degradation of high SOC, restoration of water table	-2	£60
HQ8	Creation of fen	Creation of conditions to accumulate high SOC, restoration of water table, arrest degradation of SOC	-2	£380

[a] including loss of CO_2 if habitat becomes degraded and initial release of CH_4 when first rewetted (no net gain in CO_2e)

-2 equivalent decrease in other GHG emissions greater than SOC accumulated within 10 years
-1 equivalent decrease in other GHG emissions lower than SOC accumulated within 10 years
0 no increase or reduction in other GHG emissions
+1 equivalent increase in other GHG emissions lower than SOC accumulated within 10 years
+2 equivalent increase in other GHG emissions greater than SOC accumulated within 10 years

The maintenance options do not require a change in land use (low production displacement risk). Restoration may require a removal of stock or change of some management practices (low to moderate production displacement risk), while creation will require a change in land use and loss of associated agricultural production (high production displacement risk). The maintenance, restoration or creation of habitats indicative of soil conditions conducive with accumulation of high levels of SOC e.g. bogs or moorland are restricted to specific locations where environmental conditions are suitable. They cannot be created anywhere and therefore should be preserved as priority.

Where significant C is present in biomass e.g. woodland such restrictions are fewer and areas for creation more flexible. Under HLS small parcels of woodland are permitted that if sited on marginal areas will have minimal impact on production.

3.2. Change in land use

The removal from cultivation of organic soils and creation of appropriate habitats e.g. wet heathland and restoration of water levels are deemed a priority. Conversion of cultivated land or temporary grassland on mineral soils to permanent grassland or woodland is also cited as a strategy on marginal productive land (Dawson and Smith, 2007). The sowing of grass strips should be undertaken ideally where additional benefits such as resource protection (e.g. prevention of run-off entering watercourses or prevention of soil erosion) or protection of sensitive habitat features are achieved in addition to the accumulation of SOC through removal from tillage. Where grassland or grass strips are sown, the seed mixture should preferably include legumes such as clover to provide benefits equivalent to the fertilisation of grassland.

Table 3.2. HLS and ELS options permitted under HLS of relevance to accumulation of C where a change in land use is required.

Code	Option	Management specifications of relevance to C	GHGs	£/ha
Arable				
HC14	Creation of wood pasture	Removal from cultivation, additional tree biomass where new planting (approx 10% woodland equivalent)	-1	£180
HD7	Arable reversion by natural regeneration	Reversion to permanent grassland, potentially slower C accumulation rate due to zero fertiliser	0	£500
HD8	Maintaining high water levels to protect archaeology	Maintenance of anaerobic soil conditions	0	£240
HJ3	Arable reversion to unfertilised grassland to prevent erosion or run-off	Conversion to permanent grassland, potentially slower C accumulation rate due to zero fertiliser but not if legumes present	-1 to 0	£280
HJ4	Arable reversion to grassland with low fertiliser input to prevent erosion or run-off	Conversion to permanent grassland, addition of fertiliser increases rate of SOC accumulation	-1 to 0	£210
HK8	Creation of species-rich, semi-natural grassland	Conversion to permanent grassland	-1 to 0	£280
HK17	Creation of grassland for target features	Conversion to permanent grassland	-1 to 0	£210
Improved temporary pasture				
HC14	Creation of wood pasture	Additional tree biomass where new planting (approx 10% woodland equivalent)	-1	£180
HK8	Creation of species-rich, semi-natural grassland	Conversion to permanent grassland	-1 to 0	£280
HK18	Haymaking supplement	Increased grass species diversity	0	£75
HK1	Take field corners out of management (outside SDAs)	Conversion to permanent grassland	-1 to 0	£400
HK2	Permanent grassland with low inputs (outside SDAs)	Conversion to permanent grassland, addition of fertiliser increases rate of SOC accumulation	-1 to 0	£85
HK3	Permanent grassland with very low inputs (outside SDAs)	Conversion to permanent grassland, addition of fertiliser increases rate of SOC accumulation	-1 to 0	£150
HO4	Creation of lowland heathland from improved grassland	Conversion to dwarf shrub community	-1	£150
Improved permanent pasture				
HC13	Restoration of wood pasture and parkland	Maintenance of existing tree biomass, additional tree planting (approx 5% woodland equivalent)	0	£180
HC14	Creation of wood pasture	Additional tree biomass where new planting (approx 10% woodland	-2	£180

		equivalent)		
HK7	Restoration of species-rich, semi-natural grassland	May reduce higher stocking rates and the risk of erosion and topsoil compaction	-1	£200
HL2	Permanent grassland with low inputs in SDAs	May reduce higher stocking rates and the risk of erosion and topsoil compaction	-1	£35
HL3	Permanent grassland with very low inputs in SDAs	May reduce higher stocking rates and the risk of erosion and topsoil compaction	-1	£60
HO4	Creation of lowland heathland from improved grassland	Conversion to dwarf shrub community	-2	£450
Rough permanent pasture				
HC13	Restoration of wood pasture and parkland	Maintenance of existing tree biomass, additional tree planting (approx 5% woodland equivalent)	-1	£180
HC14	Creation of wood pasture	Additional tree biomass where new planting (approx 10% woodland equivalent)	-1	£180

-2 equivalent decrease in other GHG emissions greater than SOC accumulated within 10 years
-1 equivalent decrease in other GHG emissions lower than SOC accumulated within 10 years
0 no increase or reduction in other GHG emissions
+1 equivalent increase in other GHG emissions lower than SOC accumulated within 10 years
+2 equivalent increase in other GHG emissions greater than SOC accumulated within 10 years

The options HC16 and HC17 specify the restoration or creation of successional areas and scrub respectively. From the perspective of C accumulation, such areas would be better planted as broadleaved woodland because the land would be removed from production anyway. The value of options for permanent improved pasture depend on existing stocking rates (i.e. where they are higher, a reduction may reduce the risk of erosion and compaction, this requires clarification from farm visits).

3.3. Change in / maintenance of management practice

The following options do not change the overall land use classification because they either maintain existing production, or remove a proportion of an individual field e.g. buffer strips but maintain the overall land use within its original classification. The requirement of some options may not differ greatly to existing land management practices (e.g. areas of rough permanent pasture with low inputs already exist on some tenancies).

Table 3.3. HLS and ELS options permitted under HLS of relevance to accumulation of C where a change in management practice or small area of land use is required.

Code	Option	Management specifications of relevance to C	GHGs	£/ha
Arable				
HC4	Maintenance of woodland edges	Removal from cultivation, biomass in woody vegetation; potential for growth of deep rooted species such as bracken and thistle	-2	£380
HC5	Ancient trees in arable fields	Removal of 15 m radius from cultivation, maintenance of tree biomass	-2	£25 / tree
HD6	Crop establishment by direct drilling (non-rotational)	Minimum or zero tillage	-1	£70
HE10	Floristically enhanced grass buffer strips (non-rotational)	Removal from cultivation	-2	£485
HF12	Enhanced wild bird seed mix plots (non-rotational)	Removal from cultivation	-2	£475
HF12	Enhanced wild bird seed mix plots (rotational)	Reduced frequency of cultivation, increased return of plant residues on re-establishment	-2	£475
HF14	Unharvested, fertiliser-free conservation headland	Reduced risk of soil erosion, increased return of plant residues on re-establishment	-1	£440
HD2	Take archaeological features currently on cultivated land out of cultivation	Removal from cultivation	-2	£460
HD3	Reduce cultivation depth on land where there are archaeological features	Minimum tillage	-1	£60
HE1	2 m buffer strips on cultivated land	Removal from cultivation, reduced risk of erosion and run-off where appropriately sited	-2	£300
HE2	4 m buffer strips on cultivated land	Removal from cultivation, reduced risk of erosion and run-off where appropriately sited	-2	£400
HE3	6 m buffer strips on cultivated land	Removal from cultivation, reduced risk of erosion and run-off where appropriately sited	-2	£400
HE8	Buffering in-field ponds in arable land	Removal from cultivation	-2	£400
HF1	Field corner management	Removal from cultivation	-2	£400
HF7	Beetle banks	Removal from cultivation, reduced risk of erosion and run-off where appropriately sited	-2	£580
HG1	Under sown spring cereals	Increased return of plant residues (clover biomass)	-1	£200
HJ5	In-field grass areas to prevent erosion and run-off	Removal from cultivation, reduced risk of erosion and run-off	-2	£350
HJ9	12 m buffer strips for watercourses on	Removal from cultivation, reduced risk of run-off and soil entering	-2	£400

	cultivated land	watercourse		
HJ13	Winter cover crops	Reduced risk of erosion and run-off however may require additional tillage operation	0 to 1	£65
Improved temporary pasture				
HC2	Protection of in-field trees - grassland	Removal of radius from ploughing and reseeding, maintenance of tree biomass	-2	£11
HC4	Maintenance of woodland edges	Removal from ploughing and reseeding, biomass in woody vegetation; potential for growth of deep rooted species such as bracken and thistle	-2	£380
HC6	Ancient trees in intensively managed grass fields	Removal of 15m radius from ploughing and reseeding, maintenance of tree biomass	-2	£25
HC14	Creation of wood pasture	Additional tree biomass where new planting (approx 10% woodland equivalent)	-1	£180
HD5	Management of archaeological features on grassland	Removal from ploughing and reseeding	-2	£16
HE4	2 m buffer strips on intensive grassland	Removal from ploughing and reseeding	-2	£300
HE5	4 m buffer strips on intensive grassland	Removal from ploughing and reseeding	-2	£400
HE6	6 m buffer strips on intensive grassland	Removal from ploughing and reseeding	-2	£400
HE10	6 m buffer strips on intensive grassland next to a water course	Removal from ploughing and reseeding	-2	£485
HE11	Enhanced strips for target species on intensive grassland	Removal from ploughing and reseeding	-2	£590
HJ11	Maintenance of watercourse fencing	Reduced risk of erosion by livestock	-2	£4 / 100m
HJ6	Preventing erosion or run-off from intensively managed improved grassland	Removal of topsoil compaction (e.g. feeding areas), reduced erosion	0	£280
HJ7	Seasonal livestock removal on grassland with no input restriction	Reduced risk of erosion and topsoil compaction	-1 to 0	£40
Improved permanent pasture				
HC14	Creation of wood pasture	Additional tree biomass where new planting (approx 10% woodland equivalent)	-1 to 0	£180
HJ7	Seasonal livestock removal on grassland with no input restriction	Reduced risk of erosion and topsoil compaction	-1 to 0	£40
Rough permanent pasture				
HJ7	Seasonal livestock removal on grassland with no input restriction	Reduced risk of erosion and topsoil compaction	-1 to 0	£40

HL15	Seasonal livestock exclusion supplement	Reduced risk of erosion and topsoil compaction	-1 to 0	£10
HL2	Permanent grassland with low inputs in SDAs	Maintenance of permanent grassland with low stocking rates	0	£35
HL3	Permanent grassland with very low inputs in SDAs	Maintenance of permanent grassland with low stocking rates	0	£60
HL4	Management of rush pastures (outside SDAs)	Maintenance of marshy grassland	0	£60

-2 equivalent decrease in other GHG emissions greater than SOC accumulated within 10 years
-1 equivalent decrease in other GHG emissions lower than SOC accumulated within 10 years
0 no increase or reduction in other GHG emissions
+1 equivalent increase in other GHG emissions lower than SOC accumulated within 10 years
+2 equivalent increase in other GHG emissions greater than SOC accumulated within 10 years

Options HL2 and HL3 may not change SOC compared to the existing management (subject to individual tenancy and stocking rates) however they maintain permanent grassland without high stocking rates.

3.4. Boundary features

The HLS options relevant to boundary features have negligible impact on production, with the exception of HC24 and HC25. Where existing boundaries are managed as grass, or where there are poorly maintained hedgerows, there is the opportunity for the addition of biomass.

Table 3.4. HLS and ELS options permitted under HLS of relevance to C on existing field boundaries.

Code	Option	Management specifications of relevance to C	GHGs	£/ha
HB11	Management of hedgerows of very high environmental value (both sides)	Maintenance of existing hedge biomass	0	£54 / 100 m
HB12	Management of hedgerows of very high environmental value (one side)	Maintenance of existing hedge biomass	0	£27 / 100 m
HB14	Management of ditches of very high environmental value	Removal of area adjacent from cultivation	-2	£36 / 100 m
HC24	Hedgerow tree buffer strips on cultivated land	Removal of area adjacent to hedgerow from cultivation	-2	£400
HC25	Hedgerow tree buffer strips on grassland	Removal of area adjacent to hedgerow from ploughing and reseeding	-2	£400
HR	Hedgerow restoration including laying, coppicing and gapping up	Additional biomass where gaps replanted, laying allows additional stem length and biomass	0	£5 / m

PH	Hedgerow planting – new hedges	Additional biomass where planted on existing grass boundaries	0	£5 / m

-2 equivalent decrease in other GHG emissions greater than SOC accumulated within 10 years
-1 equivalent decrease in other GHG emissions lower than SOC accumulated within 10 years
0 no increase or reduction in other GHG emissions
+1 equivalent increase in other GHG emissions lower than SOC accumulated within 10 years
+2 equivalent increase in other GHG emissions greater than SOC accumulated within 10 years

3.5. Potential strategies not within current HLS options

On grassland grown for silage the maintenance of a desirable grass species mix e.g. a ryegrass / clover sward tends to come at a cost, since it is eventually outcompeted by other less palatable grass species, and requires intermittent ploughing and reseeding. Such sward mixtures are usually a component of temporary grassland, the cultivation of which lowers the SOC relative to permanent grassland. If viable alternatives to ploughing and reseeding were available, a loss of C from soil may be reduced while maintaining adequate silage yield. Attempts to reseed by direct drill have been made on the Wallington Estate however they were not successful because the sown species mix was outcompeted by the existing grass species. The tenant suggested close grazing, burning or herbicide prior to drilling as a possible solution. If these methods were at an increased cost, the cost could be met by payment from ES. Strategies on permanent grassland may include specialist grass species mixes, for specific conditions e.g. shaded areas under trees or along woodland edges / in combination with boundary tree strips, or species capable of producing additional biomass below ground in the roots (deeper rooting species such as bracken).

On cultivated land, deeper rooting crop species or intercropping have been suggested as a means to increase SOC (Freibauer *et al*., 2004). Also methods to reduce soil erosion, where applicable, such as ridge tillage or contour farming (Louwagie et al., 2009) are possibilities.

Silvipasture has been piloted in Scotland and combines permanent grassland with trees planted at rates not sufficient to be classed as woodland. It would be a promising strategy to pilot on permanent grassland at risk to soil compaction where SOC tends to be lower already, namely IpermP. The conversion of grassland to woodland may have negligible impact on SOC initially (an estimated 0.05 t C ha^{-1} $year^{-1}$ based on the figures in Table 2.2) however the biomass C will increase. For an assumed planting density 50% of woodland this equates to 1.4 t C ha^{-1} $year^{-1}$. On The biomass within hedgerows could also be increased from incorporation of additional tree biomass by planting tree strips.

Paludiculture grows water tolerant plant species such as reed (*Phragmites* spp), willow or alder for use as biomass crops on either wet or rewetted peat soils (Wichtman and Joosten, 2007). The numerous areas of marshy ground on lower priority soil series on the Wallington Estate means such species need not be limited to peat soils. As mentioned previously, such strategies require a full evaluation of the impact on site hydrology, and would have to be assessed. Willow produces an estimated 4.1 t C ha^{-1} $year^{-1}$ as biomass C (Smith *et al*., 2000) but is harvested approximately every 10 years, equilibrium would therefore be reached after an equivalent 5 years. A further 2.8 t C ha^{-1} $year^{-1}$ is estimated as 'energy substitution potential' (substitution of C otherwise released from the burning of fossil fuel) for as long as the biomass is used as fuel (Smith *et al*., 2000). Bell (2010) however noted increased soil respiration and emission of CO_2 with increased age of stand, the overall balance is therefore probably lower.

The use of bracken as biofuel would utilise bracken plants already growing and not seek to increase its distribution further deliberately on the estate. For an assumed rate of growth of 1.5 t C ha^{-1} $year^{-1}$ (not additional biomass C since it is already present) the potential energy substitution would be approximately 0.75 t C ha^{-1} $year^{-1}$. Bracken is a deep rooting species and so has potential benefit for the accumulation of SOC in deeper soil layers. It may also be composted and applied as a soil amendment, where it confers the additional benefit of being high in the nutrient potassium (K) (*P. Muto, pers comm.*).

Hedgerows have the opportunity to include single trees (standard trees), or tree strips provide an alternative to or could be used in conjunction with existing hedgerows.

4.0. Wallington soil C data

4.1. Baseline soil C

The data has been disaggregated (based on the method in Ravindranath and Ostwald, 2008 page 118) into land use (with modifications to RpermP land use classification) in order to provide baseline land use / habitat types with which the feasibility of particular HLS options could be established. The data has been disaggregated further by soil series on account of vulnerability of different soil series to compaction and erosion, and potential to reach different SOC equilibriums, variables potentially influenced by choice of option (e.g. a reduction of stocking rates). Finally, the data was disaggregated to tenancy in order to establish the mean baseline SOC for each, and highlight where the SOC of individual sample sites is lower than the mean and to be considered as priority.

4.1.1. Land use

4.1.1.1. Revision of land use classifications for rough pasture

Bell (2010) uses six land use classifications, based the National Trust's biological survey for Wallington with additional information from the tenant farmers (Table 4.1). Bell and Worrall (2009) found that the most significant variation in SOC between farms, when all other variables considered were constant, was for the land use rough permanent pasture. The current report revises the land use category of rough permanent pasture, further dividing it into the categories listed in Table 4.1 using the Biological Survey (1999).

4.1.1.2. Use of fieldwork and the Biological Survey to establish baseline conditions

The Biological Survey (1999) habitat maps for each tenancy have been overlaid onto an Ordnance Survey map (2010) of the area, and then overlaid with the geo-referenced sample points of Bell (2010) to establish on which habitats they are present. Subsequent farm visits aim to verify that the Biological Survey (1999) is still relevant and if any change in land use has occurred since. All sample locations on permanent rough pasture were listed by Bell (2010) as having been in that land use for 28 years (since at least 1980) i.e. the land use had not changed since the biological survey of 1999. Where land use within other categories had changed within the past 10 years (Bell, 2010) the Biological Survey (1999) was used as a guide to previous land use. The Biological Survey (1999) habitat maps were used to:

1. Revise original land use classifications of rough permanent pasture (verified by farm visits) and identify additional variables that may impact SOC (e.g. marshy grassland indicates a higher soil water content)
2. Identify areas likely to be devoid of agricultural improvement where management practices are not undertaken (e.g. areas within the same field where livestock prefer not to graze, and where e.g. fertiliser application or farm operations such as chain harrowing have not occurred).
3. Identify areas where specific HLS options may be implemented (e.g. habitat creation, restoration or maintenance).
4. Identify areas where the soil C monitoring plan may require particular focus (e.g. where grips are blocked to restore habitats such as bogs or upland heathland).

Table 4.1. Land use classifications and revised land use classifications.

Countryside Survey (2008)	Wallington (Bell, 2010)	Wallington revised (incorporating Biological Survey, 1999)
Crops/weeds	arable	arable
Fertile grassland	improved temporary pasture (ItempP)	improved temporary pasture
Fertile grassland	improved permanent pasture (IpermP)	improved permanent pasture
Infertile grassland / heath / bog / moorland grass / mosaic / tall grassland / herb	rough permanent pasture (RpermP)	Marshy grassland / unimproved acid grassland / semi-improved acid grassland / unimproved neutral grassland / semi-improved neutral grassland / blanket bog / wet heath / flush / grassland G3 / grassland G3-G4 / grassland G4
Lowland wooded	woodland	woodland
Upland wooded	forestry plantation	forestry plantation

4.1.1.3. Additional rough permanent pasture classifications

The Biological Survey (1999) uses the classification 'Improved grassland'. This is further subdivided by G3, G3-G4, G4, cut and reseeded. Table 4.2 refers to increased species diversity as a method to increase SOC. The grassland classifications G3, G3-G4 and G4 are indicative of species diversity within the grass sward where G4 represents lower species diversity. The descriptors suggest where improvements have been made (e.g. by fertilisation and where grazing may be more intense, and identify the parts of fields where the management practices identified in Section 4.1.2. are applicable), although still remaining within the classification of RpermP. It was noted during farm visits that a proportion of sample sites classed as rough permanent pasture but within areas of G3, G3-G4 or G4 grassland (Biological Survey, 1999) were actually present in marshy rush dominated areas or in low lying parts of the field (at the base of slopes with localised depression) where drainage water collected and the soil was wetter. There is evidence that rush infested pastures may indicate ploughed land from several decades previously, and where the soil structure is damaged and 'gleyed', with impeded subsoil drainage, exacerbated by over-grazing and poor pasture management subsequently (R. Jarman, *pers comm*). This would be indicative of potential topsoil compaction. Where drainage is impeded, the soil water content tends to be higher. Further, sheep do not tend to graze rushes unless under duress, such areas therefore are presently avoided by stock. The soil series 92 is classed as man-made but may indicate previous deep cultivation of organic soils. Areas of rough permanent pasture are located on this series at Wallington and this is discussed in more detail for the Rothley West Shield tenancy.

4.1.1.4. Further considerations for grassland classification

Cooper (1997) categorises improved grassland as MG7 (*Lolium perenne* leys and related grasslands) and potentially MG6 (*L. Perenne-Cynosurus cristatus* grassland). MG6 is described as being permanent pasture, derived from the agricultural improvement (fertilisation and / or drainage) of habitats such as unimproved calcicolous and calcifugous grasslands and drained blanket bog. It is likely that much of the rough permanent pasture categorised as G3-G4 lies within this classification. Improvement of high SOC habitats such as blanket bog (Table 2.1) are likely to provide high SOC that could be attributed to the current land use or land management practice, when in reality, it is the result of the previous habitat. The high SOC of rough permanent pasture in these areas may not be the product of sympathetic management currently, but the opposite, a priority habitat that is degrading and in need of restoration. The previous land use history of 30 years may not identify all these areas. It could be concluded incorrectly that the category G3-G4 demonstrated optimal management of RpermP when in reality it is indicative of a degraded habitat.

MG7, described as often being sown specifically for high productivity swards (and therefore ploughed and reseeded) may be further subdivided depending on sward composition. MG7a is described as being generally sown as part of an arable / ley rotation (often ploughed and reseeded biennially) while MG7b is regarded as a being more permanent (equivalent to improved temporary pasture, ploughed and reseed every five to eight years). MG7 grassland may also develop naturally where grazing intensity is high. The NVC definition of improved grassland therefore does not necessarily mean it has been ploughed and reseeded.

4.1.1.5. Calculation of % SOC for revised land use classifications

The %SOC derived by Bell (2010) were converted to t C ha^{-1} using the method described in Ravindranath and Ostwald (2008) (*Equation 1*):

Equation 1:

*SOC (t ha^{-1}) = [soil mass * SOC concentration (%)] / 100*

*Where soil mass = area (10,000 m^{2} ha^{-1}) * depth (0.2 m) * bulk density (t m^{-3})*

Bulk density measurements were taken either by Bell (2010) or supplemented with NSRI values for each soil group (from the dataset provided by Bell, 2010). The mean SOC (t C ha^{-1}) for each revised land use category and each soil series is summarised in Figure 1.

4.1.1.6. Tenant interviews

Each tenant was shown a map with SOC levels marked by shaded circles (displayed in Section 5)) and a brief explanation given. Importantly, discussion with the tenant while viewing maps of SOC highlighted that management practice was often unique on individual fields despite being within a single land use classification and on the same tenancy (e.g. for the land use ItempP different fields on the same tenancy may be reseeded during different years so that a greater period had lapsed, the IpermP on different fields within the same tenancy may receive additional stock at different times of the year and at different equivalent rates, individual fields may have been grazed heavily for short periods to remove a weed problem). The interviews established different layers of detail gradually (1 to 4 in ascending level of detail).

1. General management practices (yes or no) (e.g. application of NPK, organic manures, use of particular type of machinery, herbicides), how did management of IpermP differ to RpermP.
2. Timing (when applied or grazed, sown, reseeded) or duration (e.g. time since last reseed).
3. Stocking rates, depth of tillage on arable or reseeded grassland, seed mix.
4. Application rates (NPK, FYM, herbicides).

Stocking rates varied throughout the year on IpermP and ItempP as stock were moved between land uses (e.g. removed from ItempP and added to IpermP when cut for silage, or added to IpermP if removed from RpermP during the winter), the maximum stocking rate at a given time of year was requested. Answers to point 4 were often estimated, either because it had been undertaken by a contractor (as was typical for the application of FYM), it depended on the proximity of a particular field (e.g. the FYM was applied in sequence until it was all used with some fields receiving more than others or variable quantities between years) or the data was not at hand to the tenant when interviewed (e.g. inorganic fertiliser, stocking rates). The interviews were supplemented with observations of grass species / clover mix while on farm visits and counts of stock in the fields at the time of the visit.

4.1.1.7. SOC of revised land uses

The largest SOC is found in habitats classed as blanket bog and wet heath (albeit from relatively small numbers of samples) (Figure 4.1). The SOC of marshy grassland was, for most soil series, larger than RpermP. It also highlights soil series where there is potential for high SOC, namely cgs, K, Tm, Wm and Wo. The series wh is a peat which also has potential for high SOC. Where these soil series are present on multiple habitats (e.g. K and Wo) it can be observed generally that their presence on agriculturally improved habitats such as RpermP results in lower SOC relative to where present on a priority habitat. It also raises the caveat when interpreting the impact of management practice that higher SOC may not be because of effective management of that land use, but that it is present on previously high SOC that has since degraded, or still doing so.

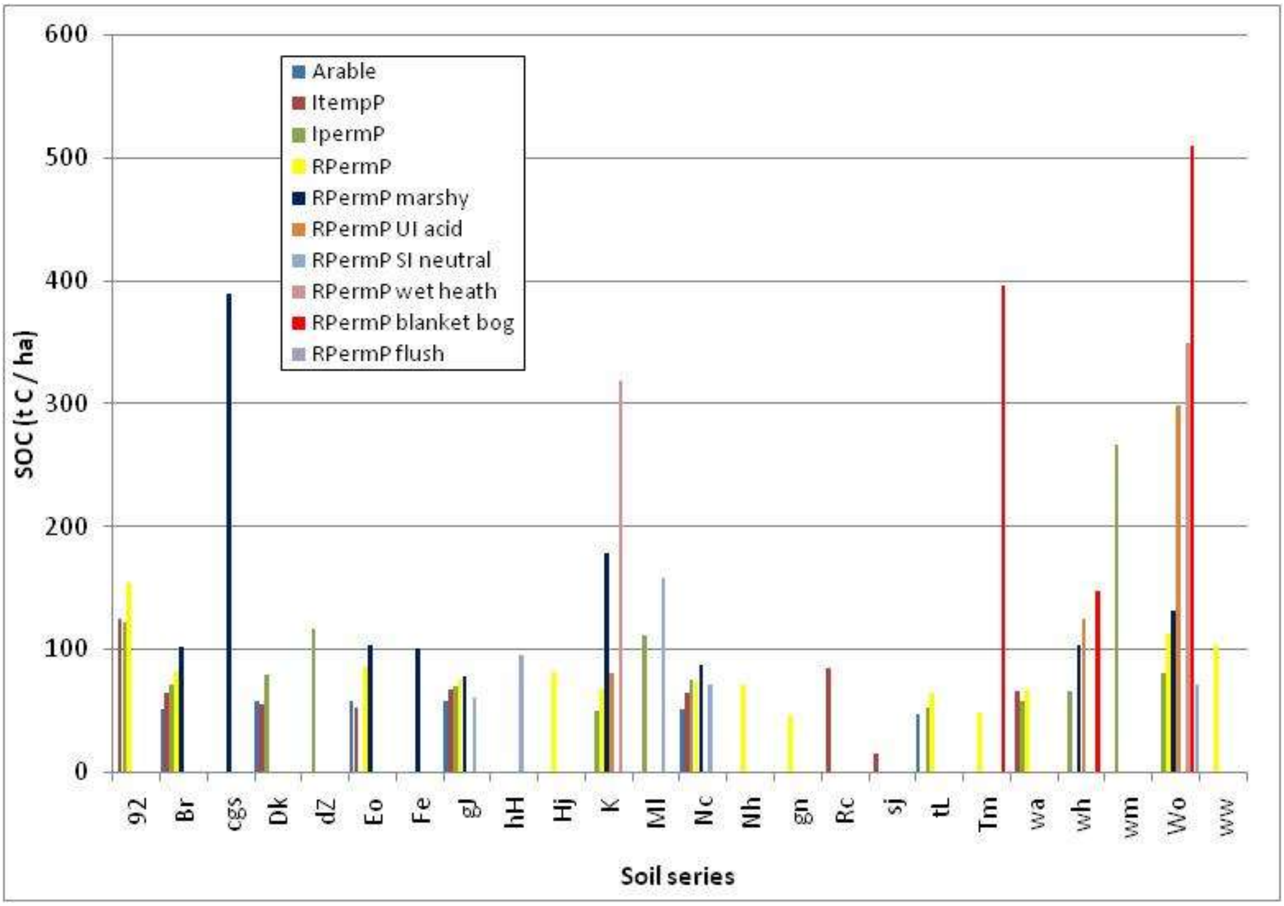


Figure 4.1. Mean SOC (t C ha^{-1}) for the revised habitats on rough permanent pasture for each soil series.

Bell and Worrall (2009) found that SOC was not related to clay content, slope angle or the number of years in current land use, and inferred that SOC had stabilised and was not changing. By this rationale these SOC values could be assumed to be at equilibrium and that the difference is because of the current land management, not because some areas are still undergoing accumulation or loss of SOC. Water content was not measured by Bell (2010), those habitats representative of wet soil conditions (e.g. marshy grassland) allow an estimate to be made, although it is acknowledged that precise measurements have not been taken.

Figure 4.2 focuses on the main soil series present at Wallington across multiple land use categories to allow a comparison. It shows increasingly greater SOC by land use in the sequence: arable < ItempP < IPermP < RPermP < marshy grassland / UI acid grassland < wet heath / blanket bog.

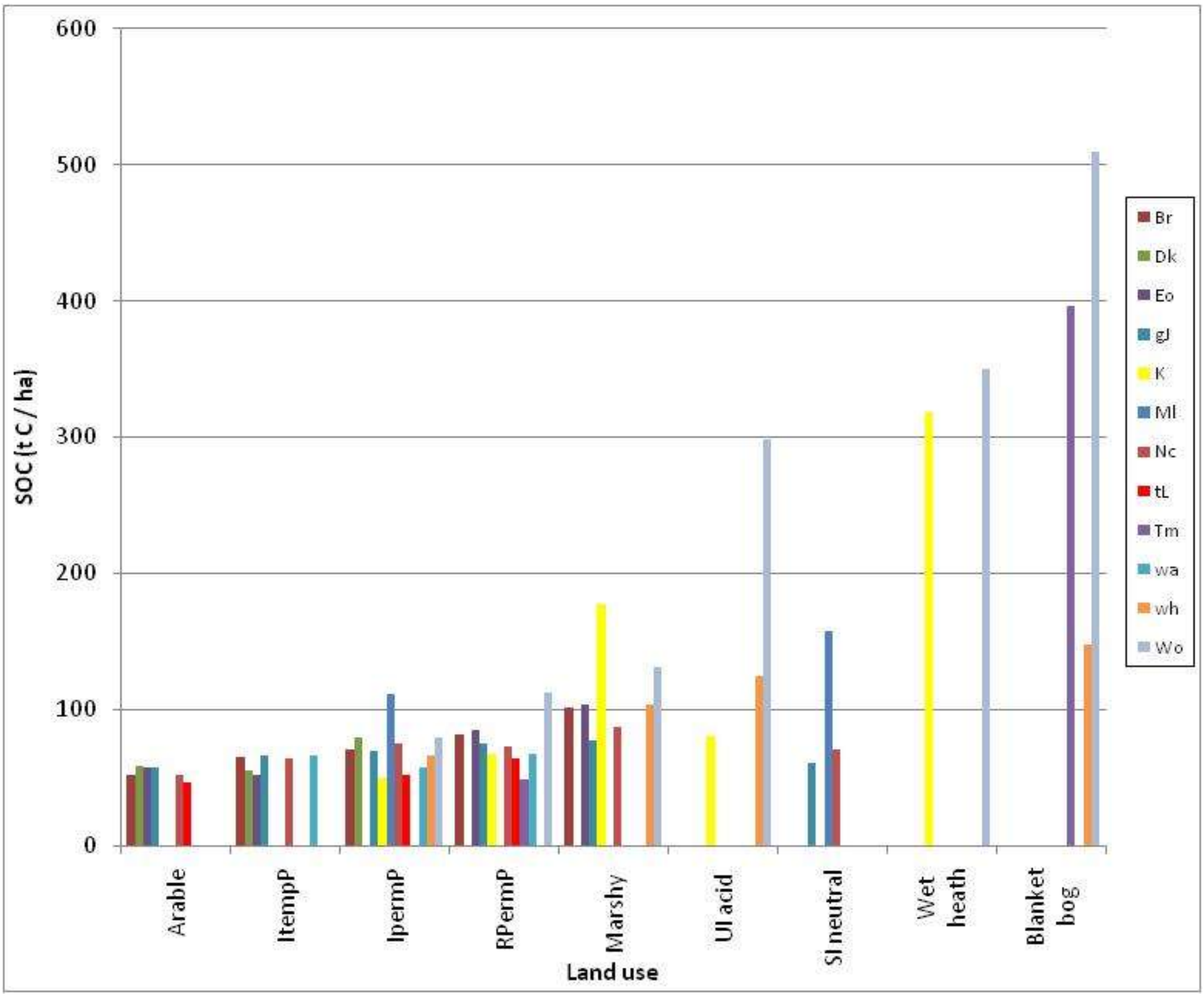


Figure 4.2. Mean SOC (t C ha^{-1}) by land use for each soil series including the revised habitat classifications on rough permanent pasture.

4.1.2. Land management practices

Within each land use category and soil series, the category 'management practice' aims to identify the impact of variables such as stock type (e.g. cattle or sheep), density (livestock units per ha), number of months grazed (equivalent livestock units per ha), grazing during the winter, and the potential impact on soils such as compaction, loss of biomass (grass) cover and increased risk of erosion, and loss of SOC. Other management variables may include use of chain harrow, application of inorganic N, organic N and type (e.g. as slurry) and method of application (e.g. surface or deep injection), presence of clover (and N fixation), phosphate, liming and artificial land drainage. A number of management practices have been documented by Bell (2010) and these will be used in combination with data gained from additional farm visits.

The analyses of management practice focused on soil series where comparisons were possible (multiple management practices existed within a soil series). The low number of sample sites at the field scale prevents spatial statistical analysis where management practice is unique to particular fields. The aggregation of this data also risks the between field management practice within a management practice being as great as between management practices.

The creation of baseline scenarios with which to calculate current SOC for each tenancy and predict the impact on SOC after implementation of HLS options required the disaggregation of data. Data was disaggregated to tenancy, land use within that tenancy and soil series within land use. The management practice typical of that tenancy was assigned to each land use as appropriate. It was evident that certain fields were managed differently despite being within the same land use. Different fields may be dominated by different soil series or several soil series are present in a single field. As a consequence, comparison of management practice for a given land use and soil series often utilised a relatively small number of sample sites. Secondly, not all soil series were present at each tenancy and so not all practices could be compared for each series. The assessment of practice concentrates on those series more widespread across the Estate (Br, gJ and Nc) for which comparisons can be made.

4.1.2.1. Rough permanent pasture

RpermP is often present on the periphery of tenancies and risks being sited on areas of former priority habitat and consisting of degraded / degrading soil conditions. The high priority soil series (Section 5.1) have been excluded from the assessment of management practice as it is considered that they are indicative of degraded priority habitat (the SOC present is not indicative of effective management practice). The stocking rates on RpermP are below 1 LU ha^{-1} where sheep only are grazed and up to 2.8 LU ha^{-1} (allowing for removal during winter) where cattle are grazed in combination. Cattle are removed during the winter, the sheep on some tenancies also removed. Where sheep are removed they are grazed on IpermP instead (following section). Management practices are summarised in Table 4.2.

Table 4.2. Land management practices on rough permanent pasture.

Species diversity	Inorganic fertiliser	Stock	Equivalent livestock units	Winter grazing	Species	Ground cover
RpermP G3	N	Sheep	0.05 – 2.8	Yes	Wild clover	Percent
RpermP G3-G4	P	Cattle		Part		
RpermP G4	N + P	Sheep + cattle		No		
	Basic slag					

All fertiliser was applied during the spring (March – May) with the exception of phosphate applied during October on one tenancy, no FYM was applied.

Previous authors have stated that on extensively managed grasslands the intensity (how closely grazed the sward is) and frequency (continuous or rotational) of grazing impact SOC. The Biological Survey (1999) classification of improved grassland (G3 to G4) was used as an indicator of grazing intensity (G4 highest grazing intensity) in an attempt to account for between field variation in management and potential within field preference by livestock to graze particular areas of a field and not others. Its use has been hindered to a certain extent by the presence of localised marshy ground not indicated by the Biological Survey (1999), particularly for the classification G3-G4 where SOC was highest. No apparent relationship existed between increased species diversity (decreased grazing intensity) (G3) and SOC. During field visits a number of samples within the G3-G4 classification where SOC on average was greatest, were noted to exist in areas with *Juncus* species present (although not noted on the Biological Survey, 1999) and the likelihood of wetter soil conditions. The soil water content has not been quantified. Species diversity on wetter soil conditions may be lower since it will favour more water tolerant species (i.e. *Juncus* species) which have taller vertical structure and dominate ground cover at the expense of other species. Sheep also do not tend to feed on such species therefore despite the lower species diversity rating compared to G3, it is probable that grazing intensity is now lower than G3 in such areas. As mentioned previously in Section 4.1.1.3., the presence of rushes may indicate previously cultivated soils several decades earlier with poor soil structure (National Trust, 2010). The land use history is defined to the early 1980's and not able to identify where such practices may have occurred. Although current grazing levels have been quantified, previous grazing levels are unknown. It is interesting to note that the Biological Survey (1999) describes the G3-G4 classification as permanent grassland most probably improved by drainage.

Bell (2010) found that the application of basic slag increased SOC on RpermP. Re-categorisation of the land uses within RpermP continues to support conclusions drawn by Bell (2010) but would benefit from additional sample sites for monitoring purposes. It is also of interest to note that for the soil series Br the application of zero fertiliser did not result in lower SOC on RpermP to which inorganic N was applied. The presence of wild clover would appear to contribute sufficient quantities of N for adequate grass growth on this land use.

The impact of soil compaction on soil structure and the implications for SOC accumulation is discussed in section 2. A Soil Compaction Indicator (SCI) was proposed by Cowell and Clift (2000) to assess soil compaction based on the Field Load Index (FLI) (Kuipers and van de Zande, 1994). The vehicle weight is multiplied by the time (hours ha^{-1}) present in the field, which is then multiplied by the area (ha) that the operation(s) is carried out on. Using a similar theory, the analysis of management practices on tenancies collated by Bell (2010) identified the number and type of stock, and the period for which they were grazed. This data has been used to compile an equivalent livestock unit (LU) for each tenancy and land use. Livestock units provide an arbitrary value corresponding to the relative weight of the animal (for example, one cow is 0.8 LU, one ewe is 0.08 LU, one ewe weighs approximately one tenth of a cow). Grazing for a period of 12 months with one cow is the equivalent to 0.8 LUs. Where tenants specified grazing for e.g. six months, the LU has been reduced by 50%. A scale of 1 to 5 has been derived to provide ranges of equivalent LUs from low (few livestock grazed for short periods) to high (high stock rates grazed all year). No relationship with stocking rate and SOC was evident. A possible reason, and one that is discussed in more detail in the next section, is behaviour of livestock, and their preference to graze or move more frequently in different parts of the field (and consequently increase the risk of compaction). As such, there is considerable potential for within field variability in compaction despite the same management practice. Finally, it was also possible that the stock on individual fields (for example, those furthest from the farmhouse) are removed for periods during the winter although not necessarily all stock from all RpermP on a tenancy.

In general, the management practices that accumulate SOC on permanent grassland (Table 2.3) are relatively subtle in comparison to e.g. SOC accumulation practices on cultivated land or temporary grassland. The detection of their impact, particularly when disaggregation of the data results in small numbers of sample sites per practice, is difficult.

4.1.2.2. Improved permanent pasture

Improved permanent pasture differs to rough permanent pasture mainly by increased stocking rates at certain times of the year, typically sheep, a more uniform sward structure, and receives inorganic N and P, and the application of lime as needed. It may also receive FYM if sufficient remains after application to temporary pasture, that has priority (consequently different fields on the same tenancy may receive different quantities of FYM). The spot treatment of weeds may also occur. More efficient drainage or the siting of this land use where waterlogging is not an issue is another (soil water content is unquantified) potential variable. Stocking rates may be similar to that of RpermP on some tenancies for parts of the year however the maximum stocking rate during the year tends to be higher. IpermP typically receives stock from temporary pasture during silage cutting in the summer (although this is not when soils are most vulnerable to compaction), and if stock are removed from RpermP during the winter (although many tenancies do not). It generally has lower SOC than RpermP. The dominant management practices are summarised in Table 4.3.

Table 4.3. Land management practices on improved permanent pasture.

Inorganic fertiliser	Organic fertiliser	Timing	Additional stock in winter	Additional stock in summer	Cut
N	FYM	Spring	Yes	Yes	Yes
P	none	Summer	No	No	No
N + P		Autumn			
Slag		Winter			
N + P + K					
Lime					

Management data was not procured for all tenancies and the analysis excludes these sites. The highest SOC observed on soil series Nc received basic slag (although this was not as pronounced for series Br also present on the tenancy). The highest SOC on fields where series Br was present had received FYM previously however only three sample sites existed for this management practice and the data was skewed by a single high value. Also, it did not receive additional stock from RpermP during the winter. The lowest SOC was observed where additional stock were received during the winter from RpermP.

The main factor detrimental to SOC accumulation on IpermP is likely to be compaction caused by higher stocking rates. Any positive effect of fertiliser addition will be hindered if compaction retards the growth of biomass. Compaction was not measured by Bell (2010) so attempts were made to predict the risk of particular sample locations. The locations of gates and feeding areas, and trees where stock may congregate for shade during hot weather, or proximity to watercourses to drink were noted in an attempt to predict which parts of the field stock were most likely to walk over frequently. Stock may be more likely to walk over areas in closer proximity to gates and the parts of the field leading up to them. Several farm tenants noted a preference by animals to frequent (and therefore trample, graze and deposit urine and faeces) the parts of the field closest to the farmhouse. It was noted that vehicle movement was frequently along site boundaries, sample sites in such areas are at further risk to compaction. The size of the field also has a potential impact because the proportion of edge to central area is greater on smaller fields. Where stock frequent a particular part of the field or a boundary, a larger proportion of the field may be grazed less frequently. These variables were used in attempt to estimate the risk of specific areas of the field, and consequently the sample sites within them, to compaction risk. It is acknowledged that there is an element of subjectivity in this approach and that it was not possible to visit each site individually during the farm visit. A recommendation to quantify soil compaction at each site has been made in the monitoring section. This will address the unavoidable consequence of the large scale sampling regime of the entire Wallington Estate and difficulty detecting within field variation.

Dawson and Smith (2007) consider rotational grazing (the site is not grazed all year) as means to enhance SOC. For IpermP this may not be an option since it is this land use that offers the opportunity to RpermP to be grazed on a rotational basis (e.g. Harwood Head). A question to consider is should IpermP act as a 'sacrificial area' under a low displacement risk scenario (section 5) in order to help reduce the risk of compaction on RpermP that covers greater areas on individual tenancies (stocking rates do not necessarily have to be reduced on the tenancy if IpermP is maintained for receiving stock from RpermP where SOC enhancing management is focused). This is particularly important for priority habitats (e.g. the specialised grazing regime on Harwood Head). Such sacrificial areas could be located where a soil series of low potential SOC equilibrium or compaction risk (Section 5) is present, or avoiding gradients to reduce erosion risk. Further, this land use offers potential to trial silvipasture since it is not reseeded but topsoil compaction may have reduced the SOC equilibrium potential by hindering grass growth. The inclusion of tree species where rooting is deeper may not be effected as adversely and deposition of leaf litter may improve the SOC of the topsoil.

4.1.2.3. Improved temporary pasture

At Wallington ItempP produces winter feed to enable cattle to be housed indoors and reduce the risk of compaction on RpermP. Since it is produced on farm it reduces the need to import feed and reduces transportation requirements. Because it is ploughed and reseeded at intervals, the SOC is lower than for IpermP and RpermP. Management practices are summarised in Table 4.4.

Table 4.4. Land management practices on improved temporary pasture.

Years since reseeded	Inorganic fertiliser	Organic fertiliser	Timing	Species mix	Other
2 to 20	N	FYM	Spring	Clover	Chain harrow
	P	none	Summer	PRG	Number of cuts
	N + P		Autumn		Rotational

					cutting
	Lime		Winter		

With respect to differences between management for ItempP, the number of years since the previous plough and reseed operation was a key factor and varied by field within individual tenancies. Land classed as temporary pasture had been reseeded between two and 20 years previously. Figure 4.3 displays data for the soil series Br and Nc. Maximising the duration between reseed operations appears to be the main way to increase the SOC of this land use. Dawson and Smith (2007) cite the conversion of permanent grassland to temporary grassland as resulting in a loss of 0.2 t C ha^{-1} $year^{-1}$ while an increased time elapsed between reseeding increases SOC by 0.2 – 0.5 t C ha^{-1} $year^{-1}$.

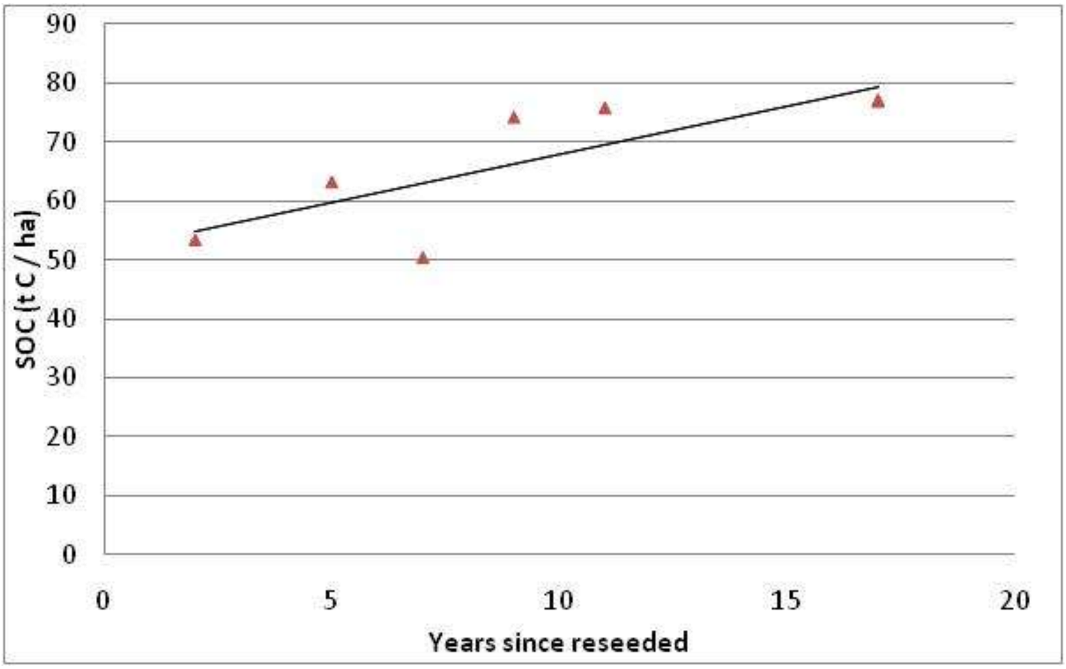


Figure 4.3. SOC (t C ha^{-1}) plotted against previous reseed date (R^2 = 0.645).

Temporary pasture has the opportunity to be alleviated of compaction by the reseed operation and probably is not such an issue as for IpermP however given that it may not be reseeded for long periods, high stocking rates should be avoided. Those tenancies that have cattle apply the FYM accumulated during the housing period to the ItempP. Where cattle are absent sheep manure is also applied but generally at lower quantities. The return of organic material to ItempP will have a positive impact on the SOC. Many tenants use contractors and were not aware of the exact rate applied, it depended on the number of cattle they had and the housing period (how much was stored).

An alternative to silage production is haymaking which may be implemented on suitable permanent grassland (species-rich upland hay meadows) with the extra costs covered by the HLS haymaking supplement. Opportunity exists to substitute ItempP with greater areas of permanent grassland if haymaking on such suitable areas were deemed by tenants to be a suitable alternative. Some tenants have expressed reservations on account of the additional drying period required for haymaking compared to silage and the need for suitable period of dry weather conditions (one tenant stated haymaking had not been possible for the past few years). Haylage (semi-wilted grass) is suitably dry after 24 hours (compared with 4 – 5 days for conventional haymaking) but is cut before seeding and would not have the conservation value for which haymaking is funded under HLS agreements.

The direct seeding of grassland used for silage production is another alternative to temporary grassland however this has already been attempted on the Wallington Estate with little success (the desired grass species could not compete effectively with the existing species). Site preparation was considered by the tenant to require either intensive grazing (this may risk compaction), burning (likely to cause loss of SOC from the surface layer) or treatment with herbicide.

4.1.2.4. Arable land

The management practices identified on arable land are summarised in Table 4.5.

Table 4.5. Land management practices on arable land.

Inorganic fertiliser	Organic fertiliser	Proportion as grass ley	Proportion as forage	Frequency of cultivation	Residue incorp
N	0	0.5	0.2	3 per 4 years	Yes
P		0	0	5 per 5 years	No
N + P		0 / 0.43 / 0.56		4 per 4 years	Preceding spring crops only
N + P + K				4 per 7 years	
				4 per 9 years	

In an assessment of arable land management on two farms the higher SOC was attributed by Bell (2010) to the incorporation of crop residues, a viable explanation. A second management practice also undertaken by the farm where the SOC was higher which is worthy of consideration, is the inclusion of a 2 year grass / clover ley in a four year rotation. This reduces the frequency of tillage to three operations per four years, compared to annual tillage in the other arable farm. Agricultural extensification (Table 2.3) is documented by several authors (Dawson and Smith, 2007; Falloon *et al*., 2004; Ostle *et al*., 2009) to increase SOC. The figures in Table 2.3 refer to a two year ley per six year rotation, the SOC accumulation rate where the ley exists within a four year rotation will probably be greater. The use of a winter cover crop (ungrazed) between harvest of the second winter oat crop and sowing of the red clover / grass ley the following spring would reduce the risk of soil erosion and nitrate leaching. Prior Hall has included a 3 – 5 year grass ley as an alternative break crop to winter oilseed rape but not on every arable field (individual fields have either had no grass ley, a 3 year grass ley or a 5 year grass ley but not at the same time). It is however evident for the soil series Nc where the fields in which this soil series is present have had a grass ley included within the rotation.

4.1.2.5. Forestry

Forestry is established on C rich soils. Provision of timber for biofuel offers potential to substitute 2.1 t C ha^{-1} $year^{-1}$ (Smith et al., 2000) but is likely to result in the degradation of soil of between 2.0 and 3.0 t C ha^{-1} $year^{-1}$ (Jackson et al., 2009). Trees for such a purpose would be better established on existing low SOC soils where there may be also potential to increase the SOC at equilibrium and on marginal land where agricultural production is poor.

4.1.2.6. Calculating changes to SOC

In order to calculate the quantity of C that may be accumulated the SOC at equilibrium of the new land use and management practice is required for a given soil series. Defra project BD2302 set the mean SOC values for one of four land uses (arable, pasture, semi-natural habitat and woodland) as the equilibrium for that land use and as the baseline to calculate the change in equilibrium between land uses (Equation 2).

Equation 2.

$$T = (SOCeqb_{(option)} - SOCeqb_{(baseline)}) / R_{(SOC)}$$

where: T = Time to establish new SOC equilibrium

$SOCeqb_{(option)}$ = potential SOC at equilibrium (t C/ha) of the option (new land use)

$SOCeqb_{(baseline)}$ = SOC at equilibrium (t C/ha) of the baseline scenario (current land use)

$R_{(SOC)}$ = SOC accumulation rate (t C/ha/year) for a given change in land management

This restricted the analysis to changes between land use categories. Warner *et al*. (2008a) estimated the potential increase in SOC at equilibrium within cultivated land to predict the impact of changes in management practices within that land use. It is proposed that this method be improved for the Wallington Estate using SOC figures derived by Bell (2010).

For each SOC baseline category the mean of the sampled values (Bell, 2010) defines which SOC values are categorised as high (above the mean), average (equal to the mean) or low (below the mean). The largest SOC value within the sample for a particular land use and management practice has been used to estimate the maximum SOC at equilibrium for that baseline. When land use categories are further disaggregated to soil series and land management practice, many contain small numbers of samples or, within a soil series, data exists for only one management practice and so a comparison cannot be made between multiple variables. Further, where one sample exists for a given soils series and land use, this method cannot be applied. Bell and Worrall (2009) explain variables over the tenancy. Disaggregation has been undertaken to explain variation at the field and tenancy level.

Caution must also be exercised where it is suspected that the SOC is a result of a previous land use e.g. priority habitat and not the current land use. Most high SOC values correspond to priority habitats (blanket bog, wet heath, unimproved acid grassland, marshy grassland) and are removed from the management practice analysis for RpermP (management practices tend to be limited on such areas according to tenants). For the remaining data it has been overcome in part by the removal of extreme values (values greater than 1.5 times the mean SOC for a given soil series and land use).

5.0. Wallington tenancies

In this section the farm maps for each tenancy display an Ordnance Survey (2010) map overlaid with the Biological Survey (1999) habitat classifications (using geo-correction in ArcView 10), then overlaid with the geo-referenced sample locations of Bell (2010). It describes the baseline SOC for each tenancy both as mean values for soil series and land use (in tables), and for individual sample points. The baseline SOC for land use and soil series on each tenancy has been set with the mean for the individual tenancy to account for potential within field spatial variability. The maximum SOC at equilibrium for a given soil series / soil series and land use has been set with the maximum value sampled for the Wallington Estate. For each tenancy the mean SOC for each soil series and land use is compared with the mean for the soil series and land use for the entire estate, and the maximum SOC for a given soil series and land use for the tenancy and Wallington Estate. The maximum SOC on the estate for a given land use and soil series has been estimated as the maximum SOC at equilibrium for that land use. There are four maps for each tenancy. The first provides an overview of the tenancy labelled with the original land use classification of Bell (2010) and equivalent t C ha^{-1} to 20 cm indicated by the extent of shading in each sample point. A further set of maps identify for individual sample sites on each tenancy where:

a) The SOC on the tenancy is above or below the mean for a given soil series and land use on the Wallington Estate (where a change in management practice has potential to increase SOC).

b) The SOC on the tenancy is above or below the mean for a given soil series on the Wallington Estate (where a change in land use has potential to increase SOC).

c) The SOC on the tenancy is above or below the mean for a given soil series compared to the UK mean NSRI data (identify areas that may be high with respect to the estate but are low compared to elsewhere in the UK).

The maximum SOC for the estate is indicative of the maximum SOC at equilibrium under a 'best case' scenario.

Most sample sites on the estate had been in their current land use for at least 28 years at the time of sampling with previous land use unknown. On low-medium priority soils (Table 5.1) the equilibrium has most likely been reached. On the higher SOC containing high priority soils it is possible that C loss may still be occurring although generally, losses upon a change in land use occur rapidly. The (b) maps for each tenancy described previously also display as a label the number of years within a particular land use. Those sites below 28 years and where previous land use is known have been highlighted. It is of importance where a generally lower SOC land use e.g. arable land has had a land use with a higher SOC previously that is responsible for the elevated SOC levels, as opposed to the current management being responsible for high SOC.

The implementation of HLS options calculated to accumulate C have been recommended based on the presence of priority habitats and their potential for restoration or creation, and then current dominant agricultural land use. Sites within agricultural land use have been prioritised by a combination of where SOC may be declining (previous and times since change in land use), where there is low SOC relative to the mean for the soil series (indicated in the maps), and by the dominant soil series present and whether this is high priority (Table 5.1). The prioritisation of soil series on the Estate has been undertaken using a combination of the maximum Wallington sample value (high potential equilibrium) and the value derived from the NSRI data.

Table 5.1. Priority of implementation of management conducive to SOC accumulation for soil series present on Wallington (highest to lowest) and deviation between Wallington and NSRI mean (red <-80; orange -80 < 0, green greater than the NSRI mean).

Soil series	Abbrev	Wallington mean	+ / - NSRI mean	Wallington max	Priority
Winter Hill	wh	peat	peat	peat	high
Cragside	cgs	388.8	[red]	808.7	high
Wilcocks	Wo	243.4	[green]	558.7	high
Thrunton	Tm	222.2	[green]	395.8	high
Kielder	K	133.0	[green]	408.1	high
Withnell	wm	265.8	[green]	387.6	high
Heapy	Hj	82.3	[orange]	314.7	high
Brickfield	Br	69.7	[orange]	214.2	moderate
Wigton Moor	ww	103.4	[red]	103.4	moderate / high
Disturbed / man-made	92	139.0	[green]	191.9	moderate
Waltham	Wa	65.6	[red]	83.8	moderate / high
	hH	70.6	[orange]	94.6	moderate
Dunwell	dz	116.4	[green]	116.4	moderate
Nercwys	Nc	69.3	[green]	157.8	moderate
Sulham	sj	14.9	[red]	14.9	moderate / high
Rivington	Rc	85.1	[orange]	85.1	low
	MI	123.4	[green]	124.8	low
Enborne	Eo	81.2	[green]	111.3	low
Freni	Fe	100.6	[green]	100.6	low
Greyland	gJ	66.8	[green]	110.7	low
Neath	nh	70.6	[orange]	72.4	low
Dunkeswick	Dk	69.8	[green]	98.8	low
Ticknall	tL	54.9	[green]	86.9	low
Quorndon	qn	46.2	[orange]	71.0	low

Soil series that are high both on Wallington and for the rest of the UK have been classed as high priority, series where SOC is low for both as low priority. No NSRI data was available for peat but because of the highly organic nature of these soils they have been classed as a high priority. The series Wa, ww and sj are also worthy of consideration because the NSRI mean SOC is high but relatively low at Wallington as indicated by the large negative difference between the two means (although only one sample of ww and sj were taken at Wallington). They have been classed as moderate/high as there is potential to increase the SOC of these soil series at Wallington. The prioritisation of soil series have been used to ascertain where the opportunity to substitute a land use e.g. relocate ItempP in order to minimise displacement, a field dominated by a series of lower priority may be considered. The implementation of options on land uses where compaction may be a risk e.g. IpermP have been further prioritised by the risk of the soil series to compaction (Section 2). The types of habitat and land use where particular soil series are present are displayed in Table 5.2.

Table 5.2. Priority soil series present on Wallington (highest to lowest) and land uses where present.

Soil series	Abbrev	Land uses
Winter Hill	wh	Blanket bog; marshy grassland; unimproved acid grassland; IpermP
Cragside	cgs	Marshy grassland (close to blanket bog)
Wilcocks	Wo	Marshy grassland; unimproved acid grassland; IpermP; RpermP
Thrunton	Tm	Blanket bog; unimproved acid grassland; RpermP
Kielder	K	Marshy grassland, unimproved acid grassland; RpermP
Withnell	wm	IpermP
Heapy	Hj	RpermP
Brickfield	Br	Marshy grassland; arable; ItempP; IpermP; RpermP
Wigton Moor	ww	RpermP
Disturbed / man-made	92	ItempP; IpermP; RpermP
Waltham	Wa	ItempP; IpermP; RpermP
	hH	Neutral grassland
Dunwell	dz	IpermP
Nercwys	Nc	Neutral grassland; arable; ItempP; IpermP
Sulham	sj	ItempP
Rivington	Rc	ItempP
	MI	Neutral grassland; IpermP
Enborne	Eo	Marshy grassland; neutral grassland; arable; ItempP; RpermP
Freni	Fe	Marshy grassland
Greyland	gJ	Marshy grassland; neutral grassland; ItempP; IpermP; RpermP
Neath	Nh	Neutral grassland; RpermP
Dunkeswick	Dk	Arable; ItempP; IpermP

Ticknall	tL	IpermP; RpermP
Quorndon	qn	RpermP

The highest priority soils are located on the priority habitats highlighted in Section 2. Series Br is one of the most widespread and highest priority for land use such as arable and ItempP.

The potential HLS options for each baseline land use on each tenancy have been subdivided by risk of displacement (loss of production) as follows:

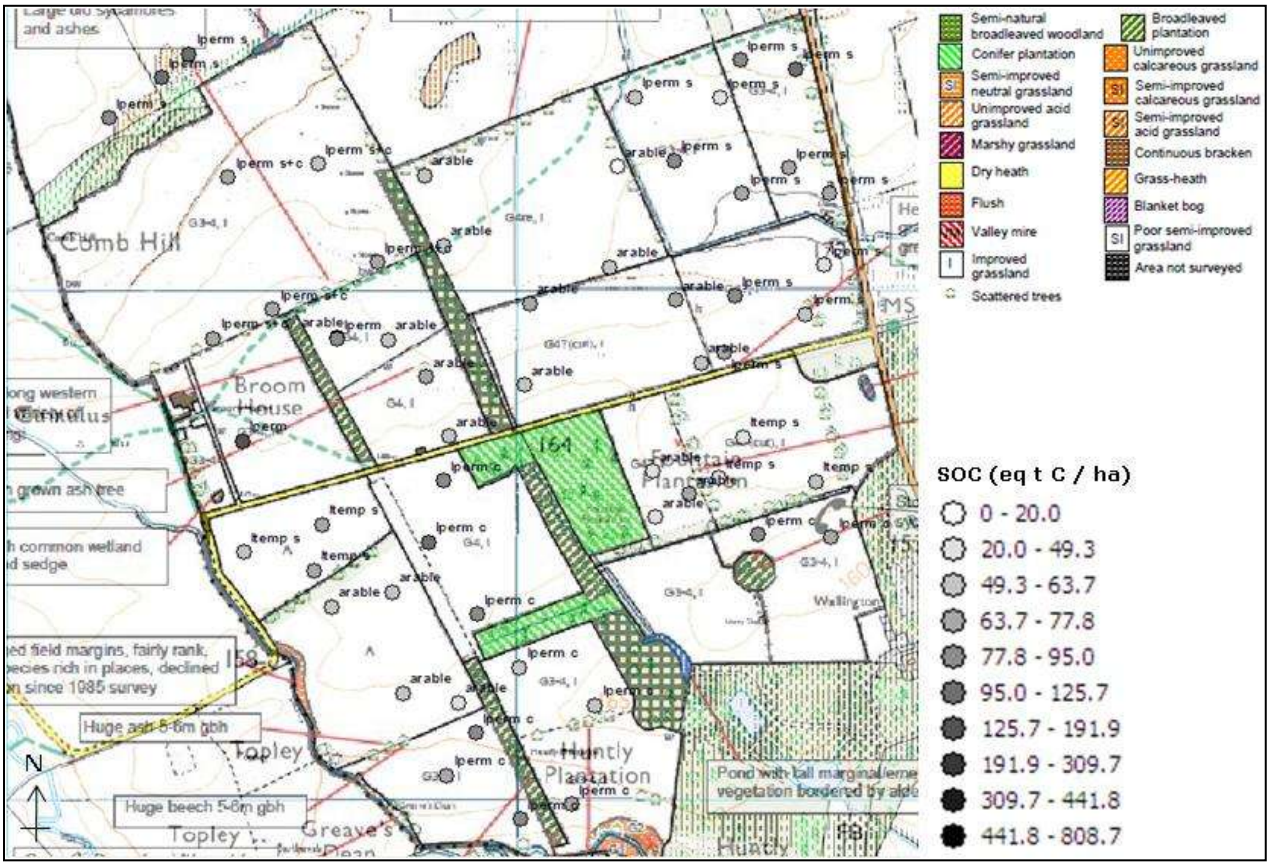
- Low displacement risk: no change in dominant land use of a field.
- Moderate displacement risk: no change in dominant land use of a field but a proportion of that land use is changed (removed from / lower production) e.g. buffer strips.
- High displacement risk: change in dominant land use of entire field to lower production or removed from production entirely.

The estimated SOC and biomass C accumulated after 10 and 20 years for each option averaged for all soil series is summarised for those options recommended for the tenancy.

The following section for each tenancy pinpoints where SOC is below the mean for three different baselines (land use, whole estate and UK) with attention given to priority habitats and soil series. Land uses and soil series where there is greatest potential to increase SOC and to which priority should be given are highlighted in red in the summary tables. This is where HLS options offer greatest potential to increase SOC. The position spatially where greatest potential exists to increase SOC are displayed on the tenancy maps. All suitable options for that tenancy with potential to increase SOC, and their estimated impact on SOC accumulation have then been listed. The aim is that the tenant is provided with a number of options from which they may choose in order to provide both gains in SOC but also provide some flexibility to suit as far as possible their own business needs.

5.1. Broom House

5.1.1. Site description



A mixed farm of arable, temporary and permanent grassland (MG6, *Lolium perenne-Cynosurus cristatus* grassland typical of free draining lowland soils) grazed by sheep and cattle. Areas of coniferous and broadleaved woodland are located in the centre of the tenancy. Features of interest (Biological Survey, 1999) include a river flanked by mature trees and species rich grassland to the south, a pond, small areas of marshy ground to the west, and hedgerows. The number of stock on the farm have been reduced in the past three years and land had been increased arable production for animal feed (sold off farm).

5.1.2. Baseline carbon

The mean SOC for each soil series and land use relative to the mean for the soil series and land use for the Wallington Estate is given in Tables BH1 and BH2. The SOC for individual sample sites relative to the mean for soil series and land use, and soil series overall for the Wallington Estate are displayed in Figures BH1a and BH1b respectively. The SOC for individual sample sites relative to the NSRI UK mean for soil series is given in Figure BH1c.

Table BH1. Mean SOC for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	**Soil series**	**Mean SOC tenancy**	**Mean SOC estate**	**+ / -**	**Max SOC tenancy**	**Max SOC estate**	**Max SOC estate <1.5**
Arable	Br	53.6	51.7	1.9	67.3	71.4	71.4
	Nc	54.3	51.6	2.7	68.6	68.6	68.6
ItempP	Br	50.4	64.8	-14.5	63.3	176.1	96.9
	Nc	63.2	64.7	-1.4	64.9	86.4	86.4
IpermP	Br	69.7	70.8	-1.1	97.3	138.7	97.3
	Nc	84.0	75.1	8.9	98.2	132.5	98.2

No colour if within + or −0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

Table BH2. Mean SOC with values in excess of 1.5 greater than the mean removed for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	**Soil series**	**Mean SOC tenancy**	**Mean SOC Wallington**	**+ / -**	**Max SOC tenancy**	**Max SOC Wallington**
Arable	Br	53.6	51.7	1.9	67.3	71.4
	Nc	54.3	51.6	2.7	68.6	68.6
ItempP	Br	50.4	58.8	-8.5	63.3	96.9
	Nc	63.2	64.7	-1.4	64.9	86.4
IpermP	Br	69.7	68.2	1.5	97.3	97.3
	Nc	79.6	73.7	5.9	98.2	98.2

No colour if within + or −0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

- On arable land the mean SOC is above average relative to the mean for arable land of the estate (highest arable SOC of the estate for soil series Nc most likely because of previous land use as ItempP (5 – 9 years previously depending on field).
- The field with soil series Nc classified as arable by the Biological Survey (1999) suggesting conversion to ItempP has increased SOC and although lower than the mean for the estate, is probably still increasing because of the recent change in management; field with soil series Br reseeded 9 years prior to 2010 (7 years before sampling in 2008).
- For soil series Br on IpermP two fields mainly above mean SOC for IpermP on Wallington (southern tip and north-eastern corner) and one field below (field adjacent to southern tip) suggesting differences in management of individual fields.

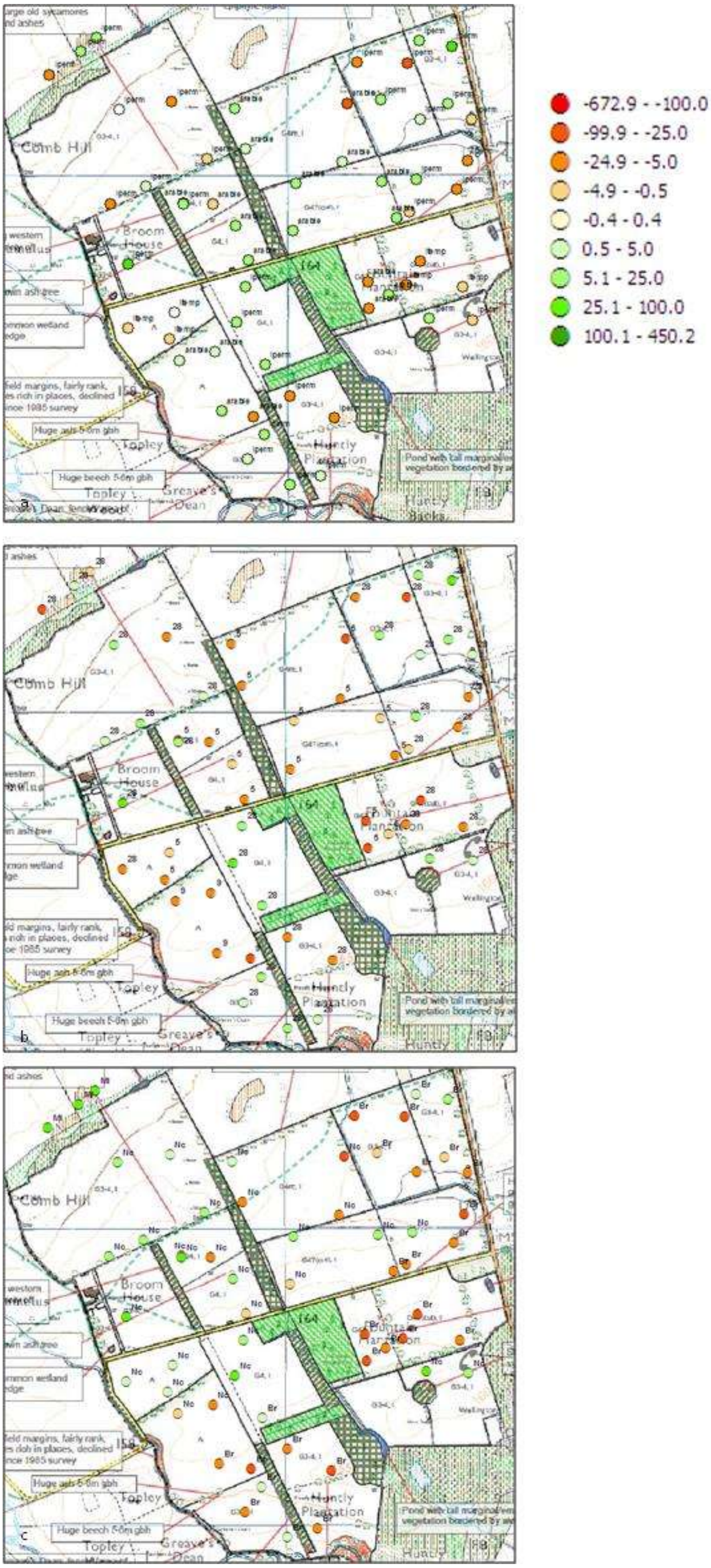


Figure BH1.

a) SOC (t C ha^{-1} eq to 20 cm) of individual sample sites within the tenancy relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the given land use of the Wallington Estate.

b) SOC (t C ha^{-1} eq to 20 cm) relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the whole Wallington Estate.

c) SOC (t C ha-1 eq to 20 cm) relative to the projected mean SOC (t C ha-1 eq to 20 cm) of the NSRI UK soil series**.**

5.1.3. Priority areas

The priority areas are summarised in Figure BH3. Areas of highest priority are labelled Priority 1 then follow in descending order of importance. Numbers in red indicate sections within Priority area 6.

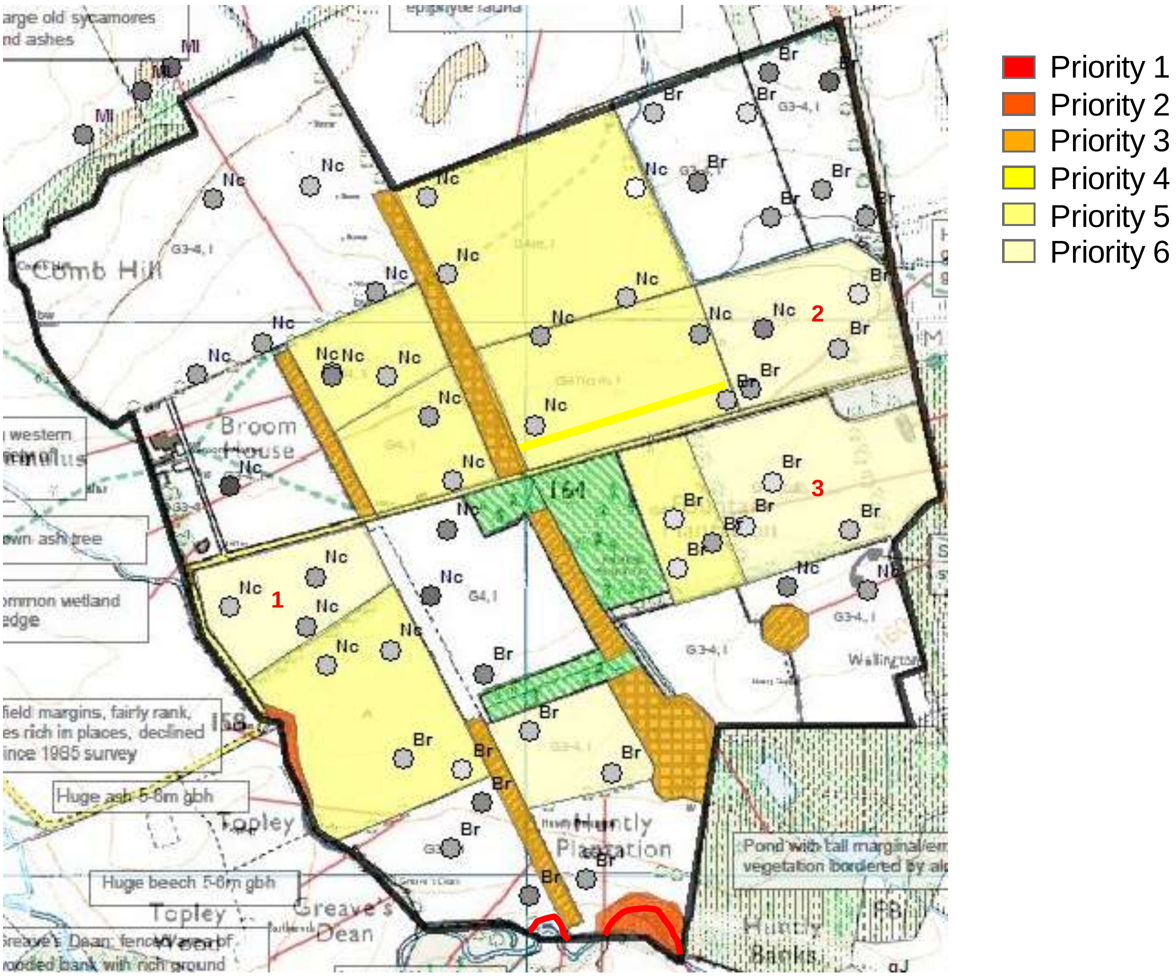


Figure BH3. Priority areas identified on Broomhouse Farm.

1. Priority habitat watercourse on medium priority soil series (Br). No samples taken close to the watercourse but risk of the congregation of livestock and resulting soil compaction. The prevention of access by livestock with fencing aims to reduce the risk of compaction and erosion. The area impacted by watercourse fencing assumes 4 m between the fence and watercourse.
2. Neutral grassland adjacent to priority habitat watercourse. Restoration offers potential to act as a buffer zone for watercourse protection, and increase grass species diversity.
3. Priority habitat woodland. Maintenance or restoration as appropriate. Protection of C in tree biomass with maintenance of woodland edge option on cultivated land.

4. Prevention of soil erosion risk where cultivated land with declining SOC is present on a gradient using grass strips.
5. Declining SOC where temporary grassland has been converted to cultivated land between 5 and 9 years previous to sampling. Winter stubbles currently precede spring sown crops within the rotation. The inclusion of a winter cover crop (ungrazed) preceding spring sown crops would be preferable as a means to reduce soil erosion. This option will also reduce the risk of N leaching by following the current winter oilseed rape in the rotation, where a potentially high soil nitrogen supply index (RB209, 2010) remains afterwards.
6. Priority area 6 includes areas where priority habitats or soil series are absent but the SOC of the soil series is below the mean for Wallington for both land use, the estate overall and the UK (Figure BH2a-c). Area 1 was previously cultivated land (Biological Survey, 1999) and SOC is likely to be increasing. Area 2 is permanent grassland and may benefit from winter stock removal. Area 3 to the east of the tenancy currently temporary grassland contains a number of mature tree lines both along the western and southern edges, and through the field centre. The SOC is low for both land use and nationally for the soil series Br. Its removal from cultivation and creation of wood pasture would prevent potential damage to tree roots. The area could remain grazed. The sowing of grassland as opposed to natural reversion may allow more rapid establishment and accumulation of SOC, at least initially, compared to natural reversion. Alternatively, this area offers potential for use as silvipasture. Both options have associated displacement risk from loss of temporary pasture but could be reduced by conversion of recently converted cultivated land elsewhere on the tenancy back to temporary pasture.

5.10.4. HLS Options

The options on marshy grassland, unimproved acid grassland, watercourses, improved temporary grassland, improved permanent grassland outside SDAs and boundary features are applicable. Table BH3 summarises by priority area (in descending order 1 to 6) preferred options.

Table BH3. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of priority HLS options for implementation in areas specified in Figure BH1.

	Code / Option		Dis^p Risk	ha	SOC	Bio^mas	Σ	SOC	Bio^mas	Σ
					10 years			20 years		
1	HJ11	Maintenance of watercourse fencing	low	312m	0.1	0.1	0.1	0.1	0.1	0.2
2	HK7	Restoration of species-rich, semi-natural grassland	mod	2	1.1	1.6	2.7	2.1	1.6	3.7
3	HC8	Restoration of woodland	low	9	0.5	24.8	25.3	0.9	49.6	50.6
3	HC4	Management of woodland edges	mod	0.8	5.4	2.0	7.3	10.7	2.0	12.7
4	EF7	Beetle banks	mod	0.08	0.5	0	0.6	1.1	0	1.1
5		Winter cover crops	low	48	43.7	0	43.7	87.4	0	87.4
6_2	HJ7	Seasonal livestock removal on grassland with no input restriction	low	8	2.7	0	2.7	5.4	0	5.4
6_3	HC14	Creation of wood pasture	high	10	12.7	33.6	46.3	25.3	61.6	86.9

Dis^p Risk: Displacement Risk
ha: estimated area (ha) where option may be implemented
Σ: Total increase in C

5.10.5. Non-HLS Options

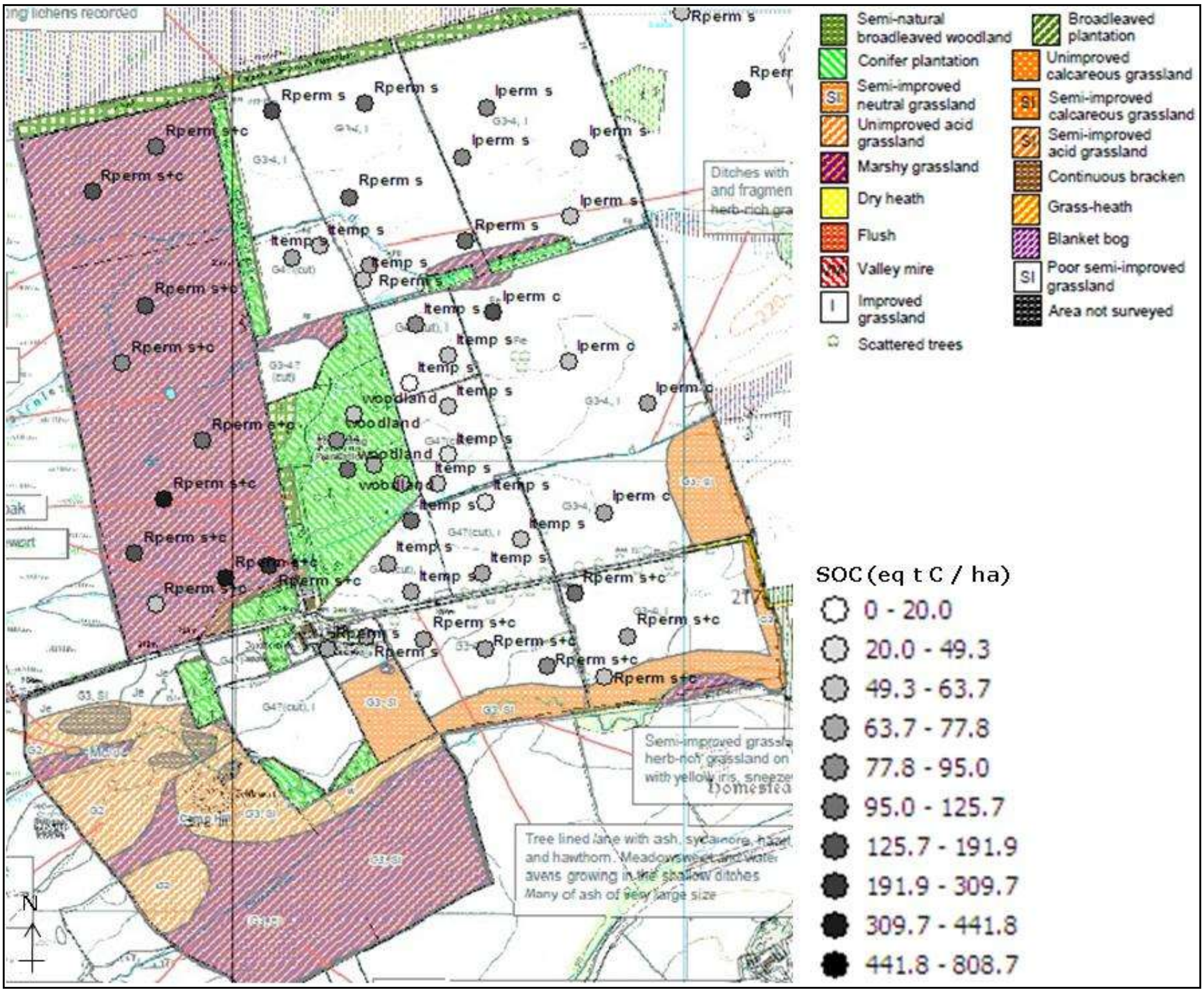
The potential impact of suggested non HLS options on recently converted cultivated land are summarised in Table BH4.

Table BH4. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of potential non HLS options for implementation in areas specified in Figure BH3.

	Option	Dis^p Risk	ha	SOC	Bio^mas	Σ	SOC	Bio^mas	Σ
				10 years			20 years		
5	Inclusion of 2 year grass/clover ley in rotation	low	Prevention of current decline in SOC						
6_3	Silvipasture	low	10	10.0	132.0	142.0	20.0	272.0	292.0

5.2. Catcherside

5.2.1. Site description



Rough permanent pasture (MG6, G3-G4) grazed by sheep and cattle, and sheep only are located to the south and north respectively. Improved temporary pasture grazed by sheep is present in the centre, with improved permanent pasture to the west. No arable land. The Biological Survey (1999) lists relict moorland habitats including unimproved acid grassland (U5, *Nardus stricta - Galium saxatile* grassland / U4, *Festuca ovina - Agrostis capillaries - Galium saxatile* grassland) and degraded wet heath (M25, *Molinia caerulea - Potentilla erecta* mire / M23, *Juncus effuses / acutiflorus - Galium palustre* rush- pasture), and pockets of species-rich calcareous grassland. Old ash trees are also present. Land drainage has been responsible for the degradation of wet heathland communities.

The Farm Environmental Plan (FEP) requests consideration of hay making on unimproved meadows (later cutting dates to allow wildflowers and grasses to shed and set seed), use of FYM but not during the winter as currently undertaken, reduced stocking rates during bird nesting periods, use of a mixture of sheep and cattle for grazing purposes and reduced over-wintering of stock on the land. Priority habitats include relict moorland habitats (acid grassland, fragments of species rich limestone grassland, degraded wet heath), wet and dry grasslands, herb rich grasslands on burnside banks, woodland and veteran trees and mature ash trees.

5.2.2. Baseline carbon

The mean SOC for each soil series and land use relative to the mean for the soil series and land use for the Wallington Estate is given in Tables CA1 and CA2. The SOC for individual sample sites relative to the mean for soil series and land use, and soil series overall for the Wallington Estate are displayed in Figures CA1a and CA1b respectively. The SOC for individual sample sites relative to the NSRI UK mean for soil series is given in Figure CA1c.

Table CA1. Mean SOC for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / -	Max SOC tenancy	Max SOC estate	Max SOC estate <1.5
ItempP	Br	59.1	64.8	-5.7	96.9	176.1	
	Nc	67.7	64.7	3.1	72.4	86.4	
	Rc	85.1	85.1	0.0	85.1	85.1	
IpermP	Br	78.0	70.8	7.1	138.7	138.7	
	Nc	71.8	75.1	-3.4	71.8	132.5	
RpermP	Br	83.8	78.3	5.5	126.9	214.2	
	Nc	65.3	75.6	-10.3	99.4	134.6	
	Nh	70.6	70.6	0.0	72.4	72.4	
	ww	103.4	103.4	0.0	103.4	103.4	

No colour if within + or –0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

Table CA2. Mean SOC with values in excess of 1.5 greater than the mean removed for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / - (<1.5)	Max SOC tenancy	Max SOC estate
ItempP	Br	59.1	58.8	0.3	96.9	96.9
IpermP	Br	67.9	68.2	-0.4	79.4	97.3
	Nc	71.8	73.7	-1.9	71.8	98.2
RpermP	Br	73.0	69.5	3.5	85.2	109.8

	Nc	65.3	73.3	-8.0	99.4	106.7

No colour if within + or −0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

- On ItempP the mean SOC is lower for series Br compared to SOC of ItempP for the estate, higher for series Nc (different soil series dominant on individual fields with Nc predominantly to the south, both series mean SOC similar and may be indicative of different management practice e.g. reseed date within the same land use).
- The mean SOC of IpermP is above the mean for soil series Br but significant within field variation exists in both fields to the north and east, below the mean for Nc (but only 1 sample site).
- For RpermP the series Br to the north is above the mean for Wallington RpermP, Wallington Br soils and UK Br mean; mainly below mean for series Nc to the south (although subject to within field variation), grazing with cattle may have contributed to soil compaction although the Nc series is classed as low compaction risk.

Removal of extreme values does not change trends except ItempP on Br and IpermP on Br (removal of values on tenancy lowers tenancy average more than estate average).

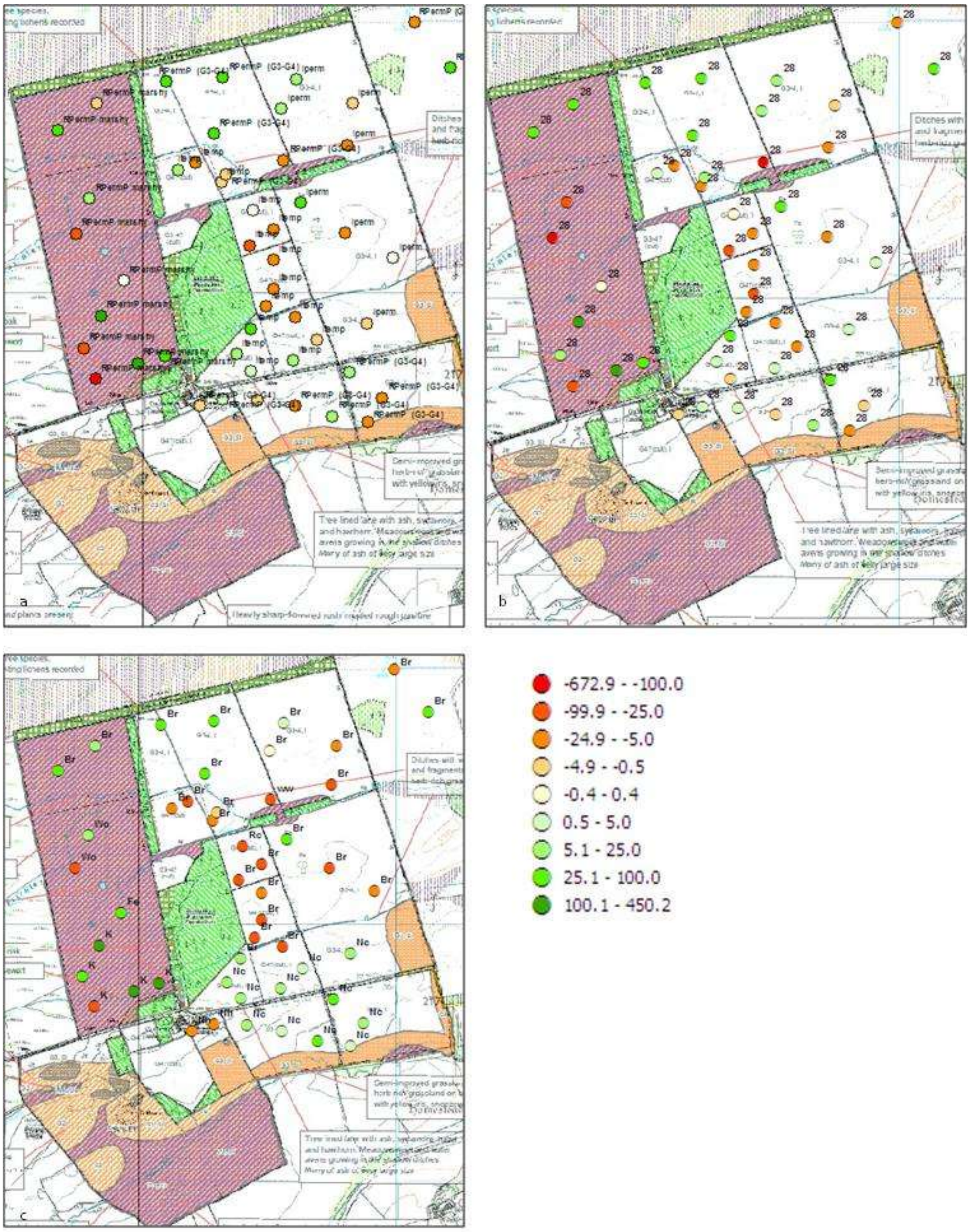


Figure CA1.

a) SOC (t C ha^{-1} eq to 20 cm) of individual sample sites within the tenancy relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the given land use of the Wallington Estate.

b) SOC (t C ha^{-1} eq to 20 cm) relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the whole Wallington Estate.

c) SOC (t C ha^{-1} eq to 20 cm) relative to the projected mean SOC (t C ha^{-1} eq to 20 cm) of the NSRI UK soil series.

5.2.3. Priority areas

The priority areas are summarised in Figure CA3. Areas of highest priority are labelled Priority 1 then follow in descending order of importance.

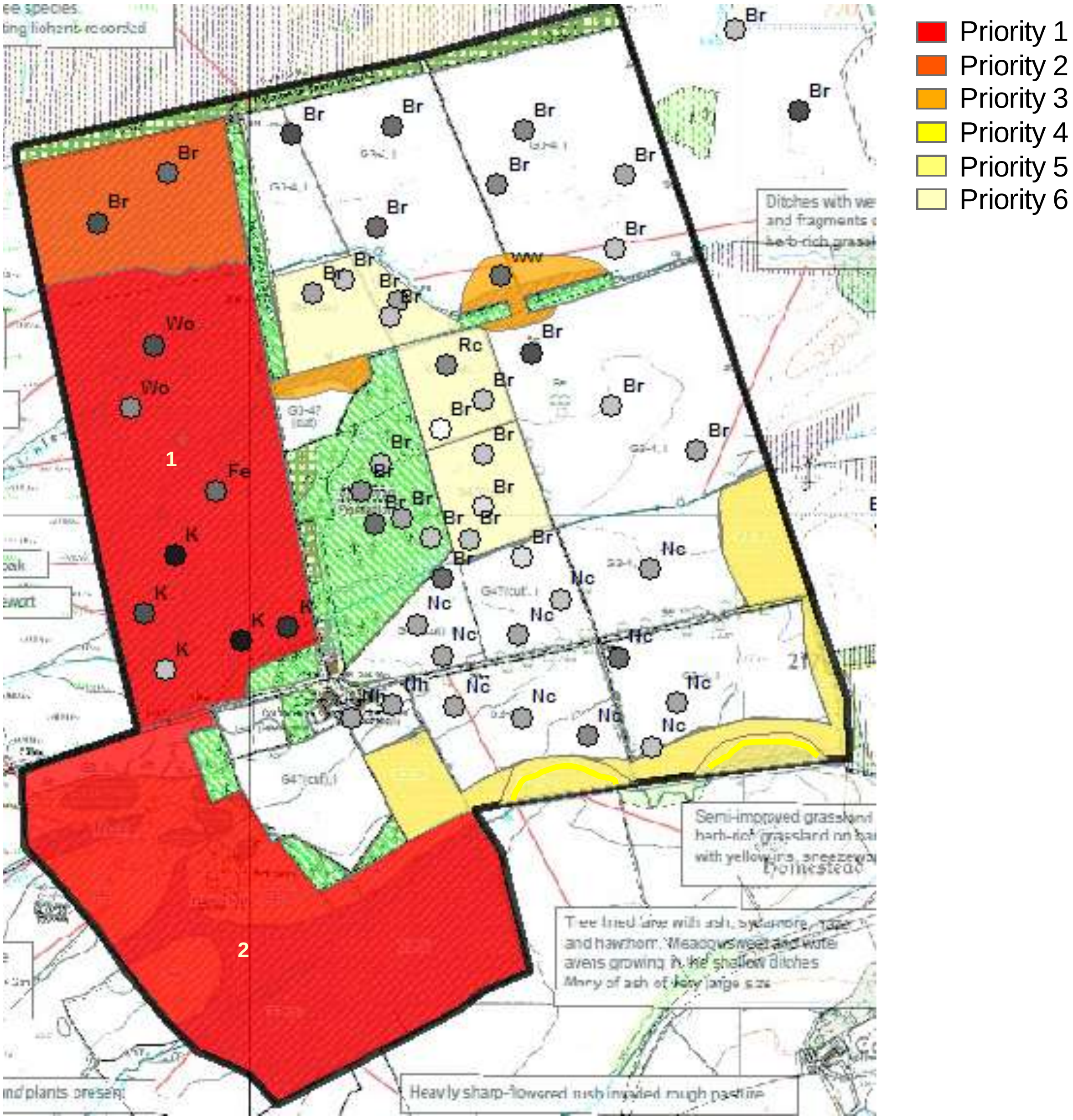


Figure CA3. Priority areas identified on Catcherside Farm.

1. High priority soil series K and Wo on marshy grassland and degraded acid grassland (Area 1) indicative of degraded priority habitat moorland. Soil series K is largely above the mean for Wallington and the UK, series Wo below the mean for the UK (Figure CA2b, c). Area 2 has not been sampled but the presence of patches of semi-improved acid grassland indicate degraded priority habitat

moorland. The restoration of moorland offers potential to increase SOC. There may be potential for a seasonal livestock exclusion supplement to reduce numbers at this time and reduce compaction risk (Harwood Head grazes between May and July).

2. Priority habitat marshy grassland on non high priority soil series. The presence of marshy grassland in low lying parts of the fields and adjacent to watercourses generally indicates naturally wetter grassland rather than degraded moorland habitat. The soil series Br is present in the north-west of the tenancy between priority soil series Wo to the south and the priority habitats bog and wet heath on Harwood Head to the north. Only 2 samples are present within this area but the area to the east is also dominated by series Br. Maintenance of / raising of water levels would be conducive with preservation of these habitats if moorland restoration options are not implemented.
3. Priority habitat marshy grassland on non high priority soil series. The areas of marshy grassland elsewhere on the tenancy may have potential to be extended. The growing of water tolerant tree species ('palludiculture') would not risk degradation of a priority soil series although it is not recommended they are grown in the area immediately south of Harwood Head (Priority 2).
4. Priority habitat watercourse on medium priority soil series (Nc). No samples taken close to the watercourse but risk of the congregation of livestock and resulting soil compaction. The prevention of access by livestock with fencing aims to reduce the risk of compaction and erosion. The area impacted by watercourse fencing assumes 4 m between the fence and watercourse.
5. Neutral grassland (herb rich in places) adjacent to priority habitat watercourse in parts. Restoration offers potential to act as a buffer zone for watercourse protection, and increase grass species diversity.
6. Priority area 6 includes areas where priority habitats or soil series are absent but the SOC of the soil series is below the mean for Wallington for both land use, the estate overall and the UK (Figure CA2a-c). The SOC is low for both land use (temporary grassland) and nationally for the soil series Br. The previous reseed date is unknown however all temporary grassland on this tenancy is included within this category. Winter feed production is necessary, particularly as cattle are present and the FEP requests reduced over-wintering of stock on the land. Conversion to permanent grassland would necessitate importing winter feed. The application of FYM during the spring or summer as recommended in the FEP will improve nutrient use efficiency and be conducive with enhanced biomass accumulation.

Although broadleaved woodland (stands of old oak) and the plantation to the north are identified as important components of the farm in the Biological Survey (1999) they have not been included as priority due to their close proximity to high priority soil series and / or habitats indicative of high priority soil series. New planting as requested in the Biological Survey (1999) should be preferably undertaken to the east of the tenancy.

5.2.4. HLS Options

The options on marshy grassland, unimproved acid grassland, watercourses, improved temporary grassland, improved permanent grassland outside SDAs and boundary features are applicable. Table CA3 summarises by priority area (in descending order) preferred options.

Table CA3. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of priority HLS options for implementation in areas specified in Figure BH1.

	Code / Option		Dis^p Risk	ha	SOC	Bio^mas	Σ	SOC	Bio^mas	Σ
					10 years			20 years		
1	HL10	Restoration of moorland	low	79.4	74.1	0	74.1	179.9	0	179.9
1	HL15	Seasonal livestock exclusion supplement	low		Facilitates option HL10					
2	HK19	Raised water levels (upland grassland)	low	11.7	62.3	0	62.3	124.6	0	124.6
3	HK19	Raised water levels (upland grassland)	low	3.6	19.2	0	19.2	38.4	0	38.4
4	HJ11	Maintenance of watercourse fencing	low	655m	0.1	0.2	0.3	0.1	0.2	0.3
5	HK7	Restoration of species-rich, semi-natural grassland	mod	13.3	7.1	10.6	17.7	14.2	10.6	24.8
6	HJ7	Seasonal livestock removal on grassland with no input restriction	low	14.6	4.9	0	4.9	9.8	0	9.8

Dis^p Risk: Displacement Risk
ha: estimated area (ha) where option may be implemented
Σ: Total increase in C

5.10.5. Non-HLS Options

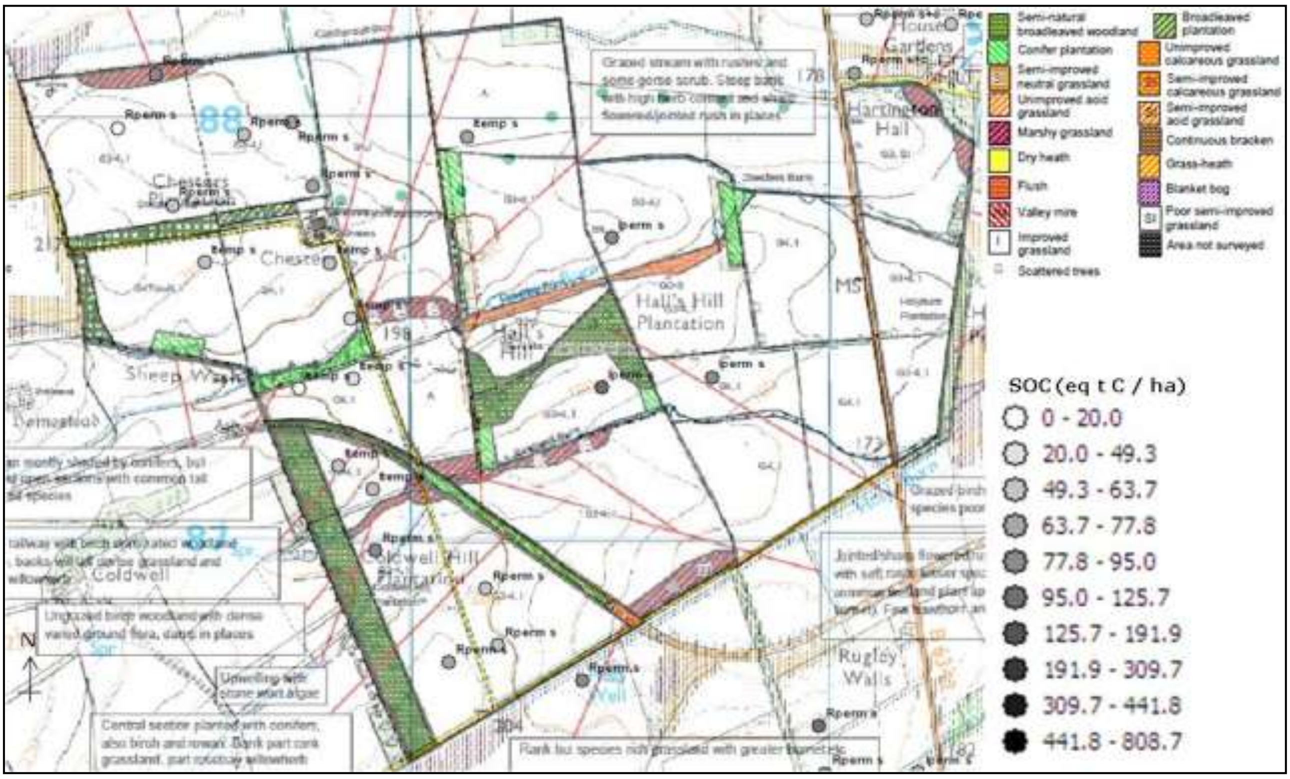
The potential impact of suggested non HLS options on recently converted cultivated land are summarised in Table CA4.

Table CA4. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of potential non HLS options for implementation in areas specified in Figure CA3.

	Option	Dis^p Risk	ha	SOC	Bio^mas	Σ	SOC	Bio^mas	Σ
				10 years			20 years		
3	Palludiculture	low	14.6	19.2	75.6	94.8	38.4	151.2	189.6

5.3. Chesters

5.3.1. Site description



Mainly rough permanent pasture grazed by sheep with improved temporary pasture in central areas of the tenancy and improved permanent pasture to the west, each grazed by sheep (classed as MG6, graded G3-G4 (*L. perene* with clover) and G4 (mainly *L. perene*). The Biological Survey (1999) lists marshy grassland, fen communities (S7 *Carex acutiformis* swamp) in the north-east corner, wood pasture, trees within field boundaries, and vegetation either side of Chesters and Coldwell burn as habitats of interest.

5.3.2. Baseline carbon

The mean SOC for each soil series and land use relative to the mean for the soil series and land use for the Wallington Estate is given in Tables CH1 and CH2. The SOC for individual sample sites relative to the mean for soil series and land use, and soil series overall for the Wallington Estate are displayed in Figures CH1a and CH1b respectively. The SOC for individual sample sites relative to the NSRI UK mean for soil series is given in Figure CH1c.

Table CH1. Mean SOC for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / -	Max SOC tenancy	Max SOC estate	Max SOC estate <1.5
ItempP	Br	50.8	64.8	-14.0	68.2	176.1	
	Nc	54.2	64.7	-10.5	61.4	86.4	
	sj	14.9	14.9	0.0	14.9	14.9	
IpermP	Br	83.8	70.8	12.9	83.8	138.7	
	gJ	96.1	70.0	26.1	102.5	102.5	
RpermP	Br	44.8	78.3	-33.5	75.4	214.2	
	gJ	67.0	74.4	-7.4	85.5	110.7	
	Nc	62.1	75.6	-13.5	67.4	134.6	

No colour if within + or –0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

Table CH2. Mean SOC with values in excess of 1.5 greater than the mean removed for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / - (<1.5)	Max SOC tenancy	Max SOC estate
ItempP	Br	50.8	58.8	-8.1	68.2	96.9
IpermP	Br	83.8	68.2	15.6	83.8	97.3
RpermP	Br	44.8	69.5	-24.7	75.4	109.8
	Nc	62.1	73.3	-11.2	67.4	106.7

No colour if within + or –0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

- ItempP: mean SOC lower for series Br and Nc compared to SOC of ItempP for the estate consistently on the same fields (1 – 2 sample sites per field); no cattle on farm so limited scope to apply FYM; SOC above mean for temporary pasture to the north (1 sample site); SOC for soil series Br and Nc below mean for the estate and UK therefore potential to increase SOC on this land use relative to other tenancies.
- IpermP: mean SOC for Br and gJ above mean on three fields (suggests consistent management practice but only 1 sample site per field), SOC above estate and UK mean.
- RpermP: series Br to the north, gJ to the south and Nc each below mean for Wallington RpermP land use; low SOC for Br and gJ relative to IpermP.

Figure CH1.

a) SOC (t C ha^{-1} eq to 20 cm) of individual sample sites within the tenancy relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the given land use of the Wallington Estate.

b) SOC (t C ha^{-1} eq to 20 cm) relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the whole Wallington Estate.

c) SOC (t C ha^{-1} eq to 20 cm) relative to the projected mean SOC (t C ha^{-1} eq to 20 cm) of the NSRI UK soil series.

5.3.3. Priority areas

The priority areas are summarised in Figure CH3. Areas of highest priority are labelled Priority 1 then follow in descending order of importance.

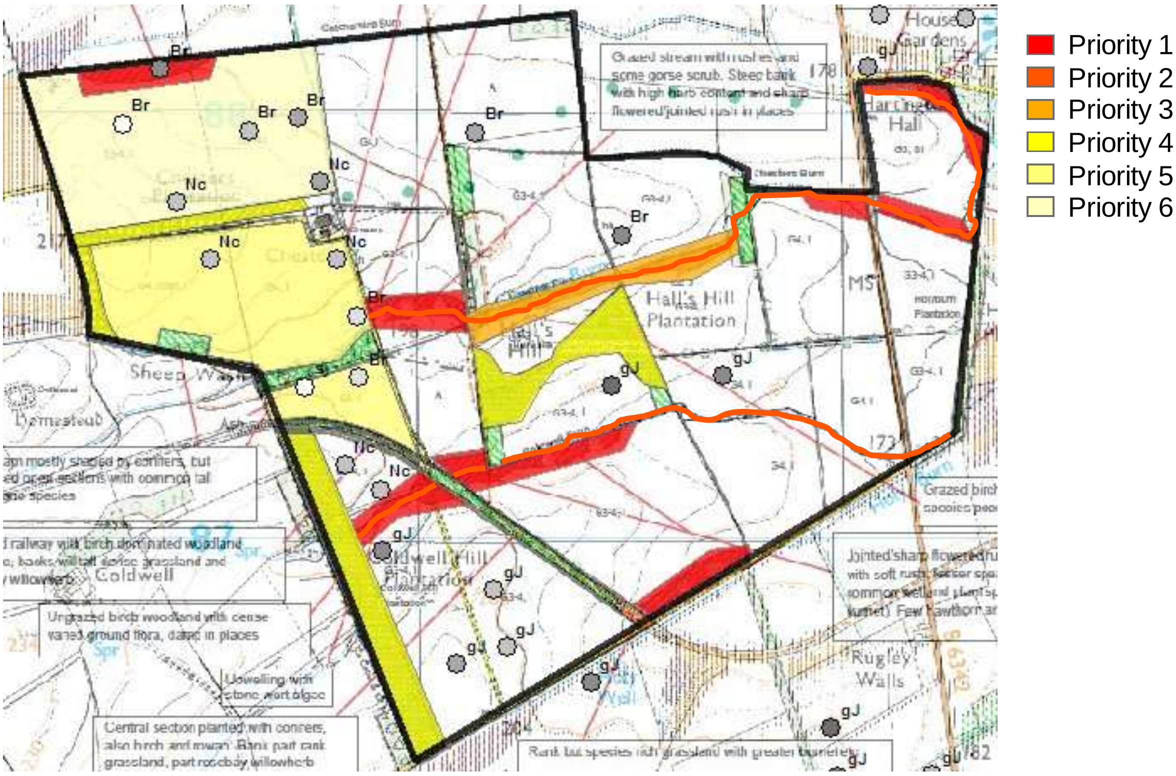


Figure CH3. Priority areas identified on Chesters Farm.

1. Priority habitat lowland marshy grassland on non high priority soil series (Br, Nc) indicates areas of naturally wet grassland and may have potential to be extended. The growing of water tolerant tree species ('palludiculture') would not risk degradation of a priority soil series.
2. Priority habitat watercourse on non high priority soil series (Nc). No samples taken close to the watercourse but risk of the congregation of livestock and resulting soil compaction. The prevention of access by livestock with fencing aims to reduce the risk of compaction and erosion. The area impacted by watercourse fencing assumes 4 m between the fence and watercourse.
3. Neutral grassland adjacent to priority habitat watercourse. Restoration offers potential to act as a buffer zone for watercourse protection, and increase grass species diversity.
4. Broadleaved woodland (grazed and ungrazed birch) on non high priority soil series. Listed by the Biological Survey (1999) as being species poor offering potential for maintenance or restoration as appropriate.

5. Permanent grassland converted to temporary grassland (8 years before sampling). Reseed operation will have reduced the SOC although stocks will increase until the next reseed occurs, the magnitude of which and new equilibrium is dependent on the frequency of reseeding. The absence of housed cattle on the tenancy during the winter limits the opportunity to apply FYM. SOC may be maximised by the time between reseed operations and limiting stock access during the winter.
6. Priority area 6 includes areas where priority habitats or soil series are absent but the SOC of the soil series is below the mean for Wallington for both land use, the estate overall and the UK (Figure CA2a-c). The SOC is low for both land use (rough permanent grassland) and nationally for the soil series Br and Nc. Winter livestock exclusion is recommended.

5.10.4. HLS Options

The options on marshy grassland, unimproved acid grassland, watercourses, improved temporary grassland, improved permanent grassland outside SDAs and boundary features are applicable. Table CH3 summarises by priority area (in descending order 1 to 6) options with the potential to have the greatest impact.

Table CH3. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of priority HLS options for implementation in areas specified in Figure GH1.

	Code / Option		Dis^{p} Risk	ha	SOC	Bio^{mas}	Σ	SOC	Bio^{mas}	Σ
					10 years			20 years		
1	HK19	Raised water levels (lowland grassland)	low	13.4	71.7	2.7	74.4	143.4	2.7	146.0
2	HJ11	Maintenance of watercourse fencing	low	3085m	0.3	1.0	1.3	0.6	1.0	1.6
3	HK7	Restoration of species-rich, semi-natural grassland	mod	4.3	2.3	3.4	5.7	4.6	3.4	8.0
4	HC7	Restoration of woodland	low	11.8	0	0	0	0	0	0
4	HC8	Maintenance of woodland	low	11.8	0.6	33.2	33.8	1.3	66.3	67.6
5	HJ7	Seasonal livestock removal on grassland with no input restriction	low	20.6	6.9	0.0	6.9	13.9	0	13.9
6	HJ7	Seasonal livestock removal on grassland with no input restriction	low	22.8	7.7	0.0	7.7	15.3	0	15.3

Dis^{p} Risk: Displacement Risk
ha: estimated area (ha) where option may be implemented
Σ: Total increase in C

5.10.5. Non-HLS Options

The potential impact of suggested non HLS options on marshy grassland and the soil series Wa are summarised in Table CH4. Short rotation coppice assumes harvest every 10 years, the equilibrium for biomass is reached after an average of 5 years.

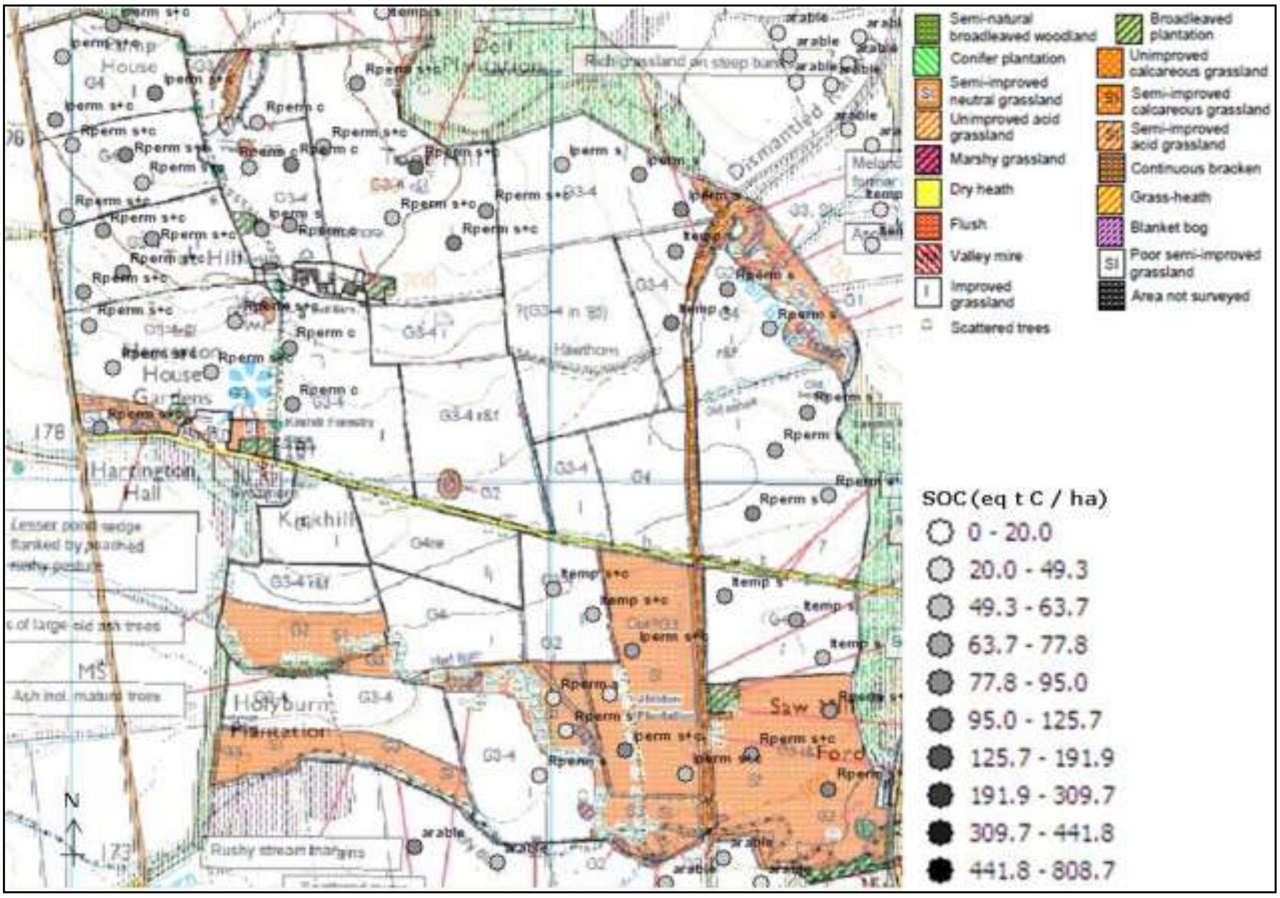
Table CH4. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of potential non HLS options for implementation in areas specified in Figure CH3.

	Option	**Dis^{p} Risk**	**ha**	**SOC**	**Bio^{mas}**	**Σ**	**SOC**	**Bio^{mas}**	**Σ**
				10 years			**20 years**		
1	Palludiculture	low	13.4	71.7	282.2	353.9	143.4	564.4	707.9

The use of short rotation coppice willow as a biofuel is cited by Smith *et al*. (2000) to have an additional energy substitution value of 2.1 t C ha^{-1} $year^{-1}$ equivalent to 282 and 564 t C ha^{-1} $year^{-1}$ after 10 and 20 years respectively.

5.4. Delf Burn (Tuthill)

5.4.1. Site description



The tenancy consists of rough permanent pasture grazed by cattle and sheep to the north-west, and a combination of improved temporary, improved permanent and rough permanent pasture grazed by sheep elsewhere. There is no arable land. Habitats of note (Biological Survey, 1999) include the Delf, Hart & Holy Burns and the vegetation either side, semi-improved calcareous grasslands to the south, small areas of marshy grassland, and trees in the field margins. Intense grazing near burns resulted in heavily poached and eroding sections of burn margin and grasslands with poor structure at the time of the 1999 Biological Survey which risks erosion and topsoil compaction.

Both cattle and sheep are present on the tenancy (cattle are housed during the winter) and so FYM is applied to ItempP. The ItempP was reseeded up to 17 years previously to sampling. Attempts to direct drill were made but failed owing to inability of the desired species to compete with existing grasses. IpermP is improved with lime as needed and inorganic N and P.

5.4.2. Baseline carbon

The tenancy includes the moderate priority series Nc and Wa, and the low priority gJ. The SOC of RpermP is lower than ItempP and IpermP for all soil series present. For the series Nc on IpermP and ItempP a greater number of samples have been taken on fields grazed by sheep only. Most of the Nc series on RpermP is grazed by cattle and sheep. The presence of cattle increases the number of LU above the maximum stated for IpermP and ItempP grazed by sheep only. The RpermP for series gJ has a low number (two) of sample sites.

Table DB1. Mean SOC for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / -	Max SOC tenancy	Max SOC estate	Max SOC estate <1.5
ItempP	gJ	63.5	66.6	-3.1	76.9	82.3	
	Nc	77.3	64.7	12.6	82.8	86.4	
IpermP	gJ	59.2	70.0	-10.8	83.8	102.5	
	Nc	69.2	75.1	-6.0	83.2	132.5	
	Wa	76.4	57.6	18.7	83.4	83.4	
RpermP	gJ	57.2	74.4	-17.2	69.7	110.7	
	Nc	68.9	75.6	-6.7	107.1	134.6	
	Wa	66.2	67.1	-0.9	83.8	83.8	

No colour if within + or −0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

Table DB2. Mean SOC with values in excess of 1.5 greater than the mean removed for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / - (<1.5)	Max SOC tenancy	Max SOC estate
IpermP	Nc	69.2	73.7	-4.5	83.2	98.2
RpermP	Nc	66.7	73.3	-6.6	82.4	106.7

No colour if within + or −0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

- ItempP: series Nc (grazed by sheep) SOC above mean for land use at Wallington, series gJ below mean on average but above or below mean depending on the individual field, (above mean where grazed by sheep only and below the mean where grazed by sheep and cattle), and years lapsed since reseed (estimated reseed dates varied but up to 17 years before sampling undertaken); both series above UK mean at present but certain field(s) require reseeding which is likely to reduce SOC immediately afterwards, long duration between reseed dates however has favourable impact on SOC.

- IpermP: SOC above mean for land use on the estate for soil series Wa in fields grazed by sheep to the north, below mean for series Nc grazed by sheep and cattle in fields to the north-east and for series gJ to the south; series Wa SOC significantly below UK mean suggesting degraded soil conditions, both Nc and Wa classed as moderate priority soil series.
- RpermP: series gJ (single sites to the south and east) and Nc (small fields to the north-east) below mean for Wallington RpermP (higher average stocking rates than most tenancies); SOC of series Nc is above the UK mean.

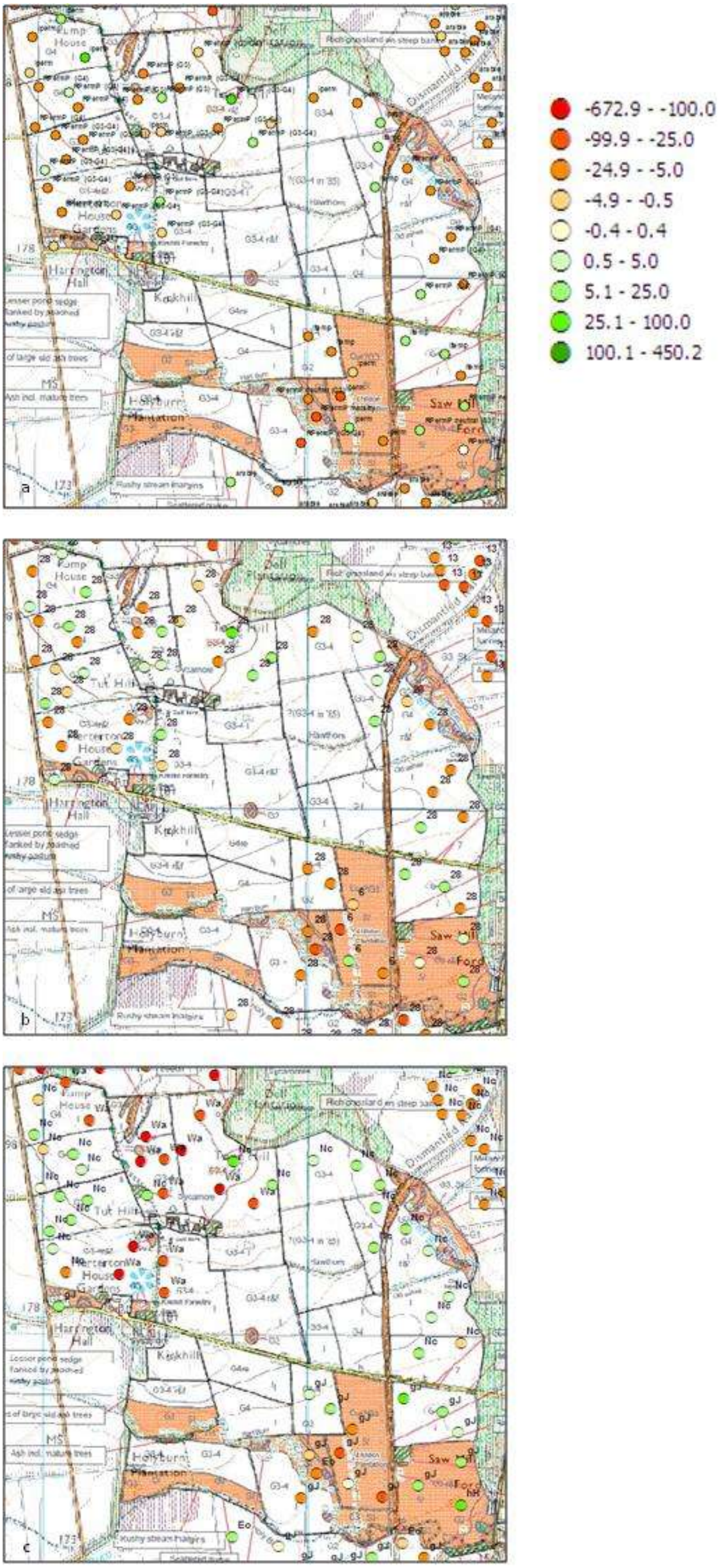


Figure DB1.

a) SOC (t C ha^{-1} eq to 20 cm) of individual sample sites within the tenancy relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the given land use of the Wallington Estate.

b) SOC (t C ha^{-1} eq to 20 cm) relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the whole Wallington Estate.

c) SOC (t C ha^{-1} eq to 20 cm) relative to the projected mean SOC (t C ha^{-1} eq to 20 cm) of the NSRI UK soil series.

5.4.3. Priority areas

The priority areas are summarised in Figure DB3. Areas of highest priority are labelled Priority 1 then follow in descending order of importance.

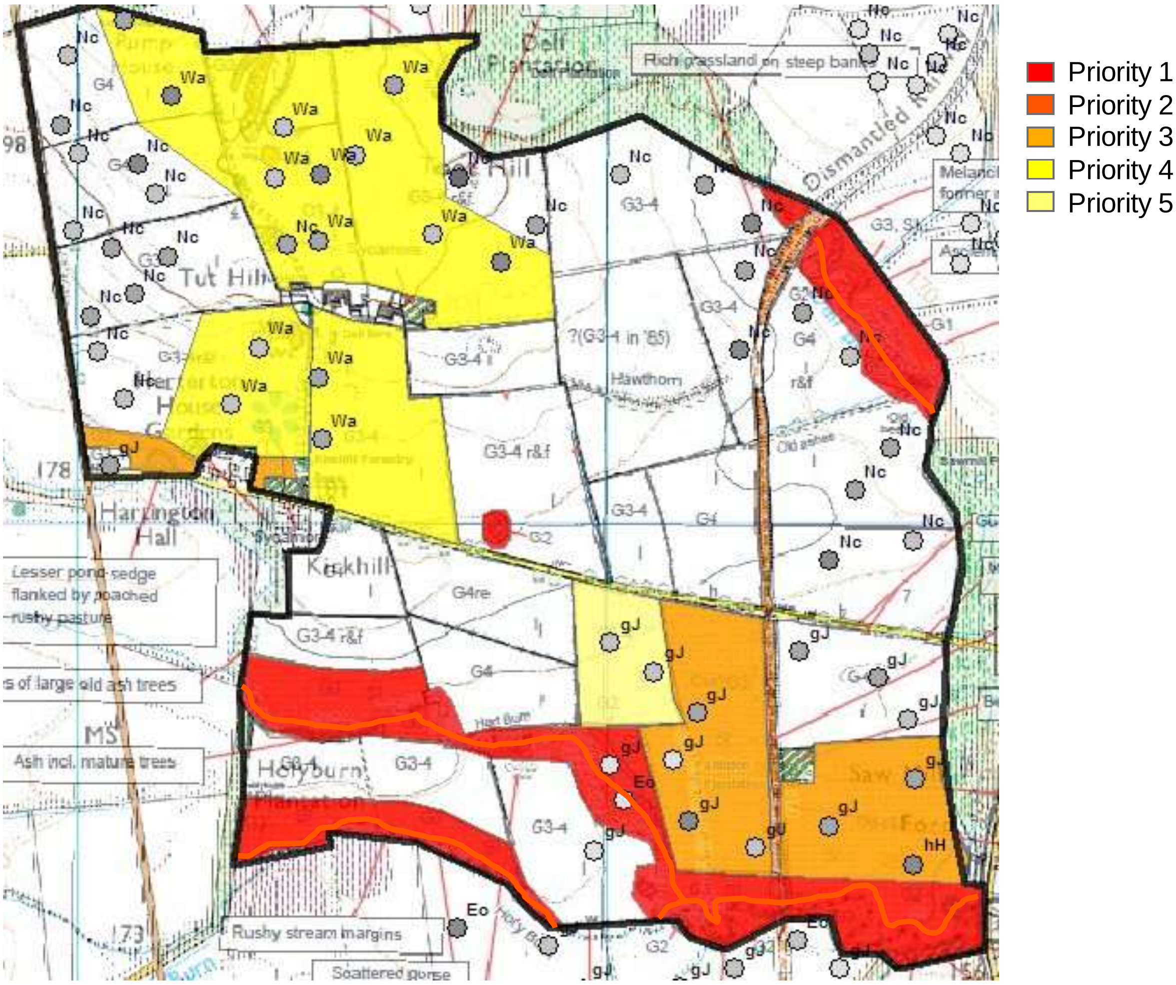


Figure DB3. Priority areas identified on Delf Burn.

1. Priority habitat marshy grassland on non priority soil series. The presence of marshy grassland occurs mainly adjacent to watercourses, offering potential to be extended. The growing of water tolerant tree species (‘palludiculture’) would not risk degradation of a priority soil series. Alder are already present on marshy ground in the south-eastern corner of the tenancy.
2. Priority habitat watercourse. Samples close to the watercourse in the south-east of the tenancy have low SOC, possibly due to the congregation of livestock and resulting soil compaction. Fencing to prevent access by livestock will reduce the risk of compaction and erosion. The area impacted by watercourse fencing assumes 4 m between the fence and watercourse.

3. Neutral grassland, some noted as herb and species rich (Biological Survey, 1999), is present mainly toward the south of the tenancy in close proximity to watercourses. Restoration offers potential to increase species diversity and provide buffer zones for watercourse protection. The area dominated by series gJ to the south and directly east of the old railway line is described by the Biological Survey (1999) as heavily poached with areas of bare ground. Restoration to increase ground cover and enhance species diversity will potentially benefit this area most. Compaction may have occurred which will slow recovery.
4. The moderate/high priority soil series Wa is located on higher ground to the north of the farmhouse extending south down the hill. It generally has SOC below the mean for Wallington and the UK (Figure DB2a-c). Options to prevent compaction and permit optimal recovery and SOC equilibrium, namely seasonal livestock exclusion to remove stock during the winter when soils are most vulnerable, offer benefit. This series is within the 'brown earth' major soil series (i.e. not organic) but appears to be present at higher altitudes and, in reference to UK mean data, has a high potential SOC at equilibrium. The trialling of silvipasture may be an option on this series since the presence of trees would not damage organic soil layers by drying them out but SOC accumulation could increase. The presence of boundary hedgerows and trees imply viable growing conditions for broadleaved species.
5. Area 5 has SOC below the mean for Wallington for both land use (temporary grassland) and the estate overall (Figure GH2a, b). Removal of stock during the winter or conversion to low input permanent grassland are options. The latter has an associated high production displacement risk which for a low priority soil series such as gJ will not reap such high benefits in the long term as higher priority soil series (lower SOC equilibrium).

5.4.4. HLS Options

The options on marshy grassland, unimproved acid grassland, watercourses, improved temporary grassland, improved permanent grassland outside SDAs and boundary features are applicable. Table DB3 summarises by priority area (in descending order 1 to 5) options with the potential to have the greatest impact.

Table DB3. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of priority HLS options for implementation in areas specified in Figure DB1.

	Code / Option		Dis^{p} Risk	ha	SOC	Bio^{mas}	Σ	SOC	Bio^{mas}	Σ
					10 years			20 years		
1	HK19	Raised water levels (lowland grassland)	low	21.9	116.5	4.4	120.9	233.1	4.4	237.4
2	HJ11	Maintenance of watercourse fencing	low	3054m	0.3	1.0	1.3	0.6	1.0	1.6
3	HK7	Restoration of species-rich, semi-natural grassland	mod	19.3	10.3	15.4	25.7	20.5	15.4	36.0
4	HJ7	Seasonal livestock removal on grassland with no input restriction	low	42.2	14.2	0.0	14.2	28.4	0.0	28.4
5	HJ7	Seasonal livestock removal on grassland with no input restriction	low	4.4	1.5	0.0	1.5	3.0	0.0	3.0
5	HK2	Permanent grassland with low inputs (outside SDAs)	high	4.4	10.3	3.5	13.9	20.7	3.5	24.2

Dis^{p} Risk: Displacement Risk
ha: estimated area (ha) where option may be implemented
Σ: Total increase in C

5.4.5. Non-HLS Options

The potential impact of suggested non HLS options on marshy grassland and the soil series Wa are summarised in Table DB4. Short rotation coppice assumes harvest every 10 years, the equilibrium for biomass is reached after an average of 5 years.

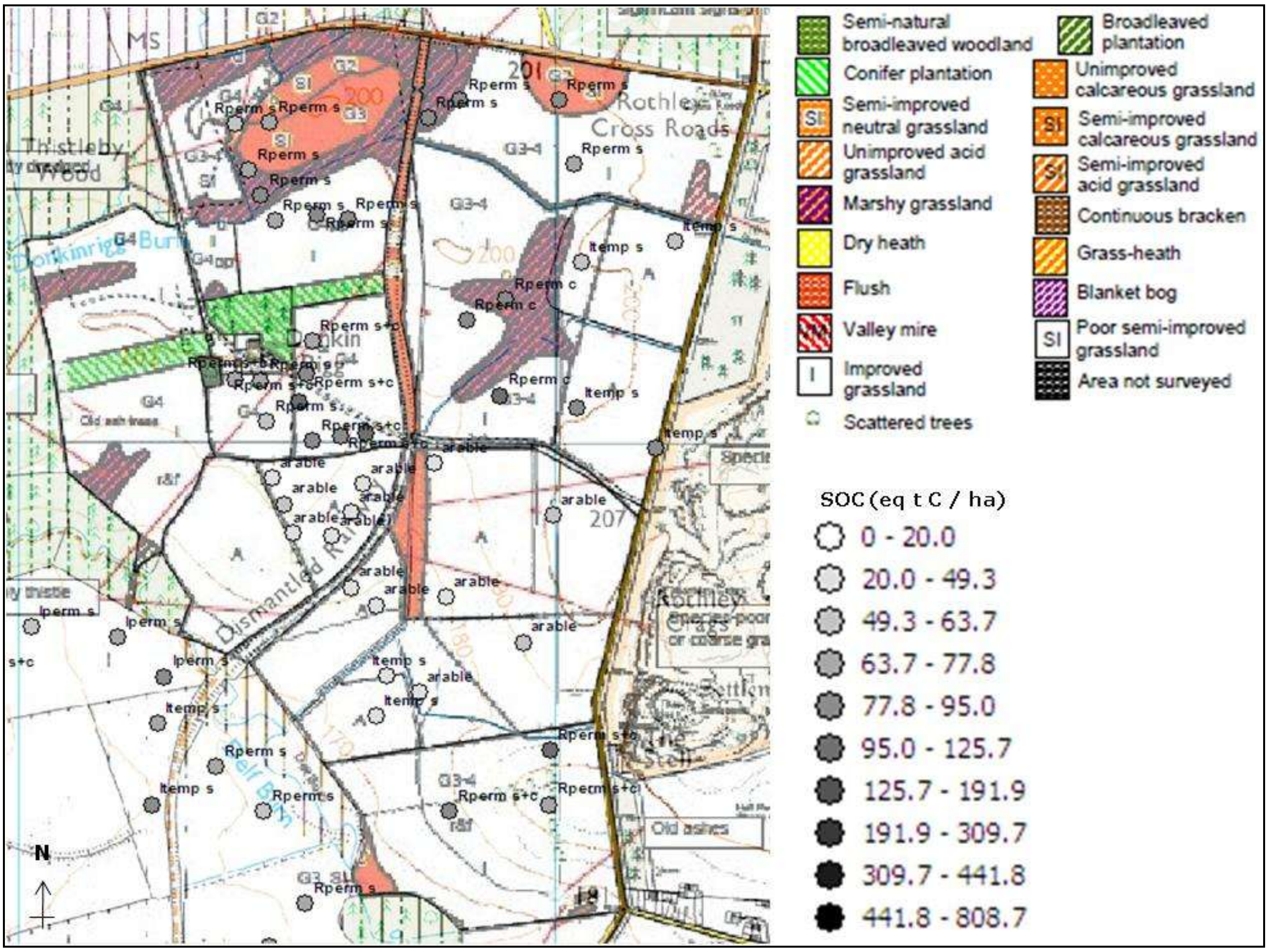
Table DB4. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of potential non HLS options for implementation in areas specified in Figure DB3.

	Option	Dis^{p} Risk	ha	SOC	Bio^{mas}	Σ	SOC	Bio^{mas}	Σ
				10 years			20 years		
1	Willow (short rotation coppice)	low	21.9	116.5	458.9	574.4	233.1	917.7	1150.8
4	Silvipasture	low	42.2	11.2	556.4	567.6	22.5	1146.5	1169.0

The use of short rotation coppice willow as a biofuel is cited by Smith *et al*. (2000) to have an additional energy substitution value of 2.1 t C ha^{-1} year^{-1}, equivalent to 459 and 918 t C after 10 and 20 years respectively if the marshy grassland areas are fully exploited.

5.5. Donkin Rigg

5.5.1. Site description



A mixed farm of arable in the southerly part of the tenancy with predominantly rough permanent pasture grazed by sheep, or sheep and cattle on the remainder of the land. An area of improved temporary pasture is located to the east. Marshy grassland and semi-improved calcareous grassland is situated o the north. The deep dredging of long sections of drain was highlighted by the Biological Survey (1999) which will reduce the prevalence of anaerobic soil conditions and potentially cause a loss of SOC. A number of old ash trees were subject to damage by livestock (bark-stripping by sheep) and as a significant C store should be protected. The tenancy is currently undergoing conversion to organic production.

5.5.2. Baseline carbon

The mean SOC for each soil series and land use relative to the mean for the soil series and land use for the Wallington Estate is given in Tables DR1 and DR2. The SOC for individual sample sites relative to the mean for soil series and land use, and soil series overall for the Wallington Estate are displayed in Figures DR1a and DR1b respectively. The SOC for individual sample sites relative to the NSRI UK mean for soil series is given in Figure DR1c.

Table DR1. Mean SOC for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / -	Max SOC tenancy	Max SOC estate	Max SOC estate <1.5
Arable	Eo	40.7	57.3	-16.6	40.7	79.2	79.2
	Nc	45.3	51.6	-6.4	52.0	68.6	68.6
ItempP	Eo	58.8	52.0	6.8	61.9	61.9	61.9
	Nc	64.0	64.7	-0.7	86.4	86.4	86.4
RpermP	Eo	85.4	84.9	0.5	111.3	111.3	111.3
	Nc	83.8	75.6	8.2	106.7	134.6	106.7

No colour if within + or –0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

Table DR2. Mean SOC with values in excess of 1.5 greater than the mean removed for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / - (<1.5)	Max SOC tenancy	Max SOC estate
RpermP	Nc	83.8	73.3	10.5	106.7	106.7

No colour if within + or –0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

- Arable: SOC below mean for this land use for both Eo (one sample) and Nc series; below equilibrium and significant potential to increase SOC for this land use. Does not include (at the time of sampling) a grass/clover ley or incorporate residues. Stock are grazed on a forage crop one year in five adding organic material via deposition. The rotation will change since the tenancy is currently undergoing organic conversion.
- ItempP: the Eo series to the north-east of the tenancy (above the mean for Wallington for this land use) was previously arable land and has experienced issues with drainage (the reason arable production was abandoned). The SOC on these

fields may be higher as a result of greater soil water content. The presence of winter housed cattle provides FYM to apply post cutting.

- RpermP: SOC on series Nc above the mean for land use although below the mean on one field directly south of the farmhouse (possible compaction caused by greater movement of stock through this field because it is directly adjacent to housing areas); applies basic slag; close to maximum equilibrium for this land use.

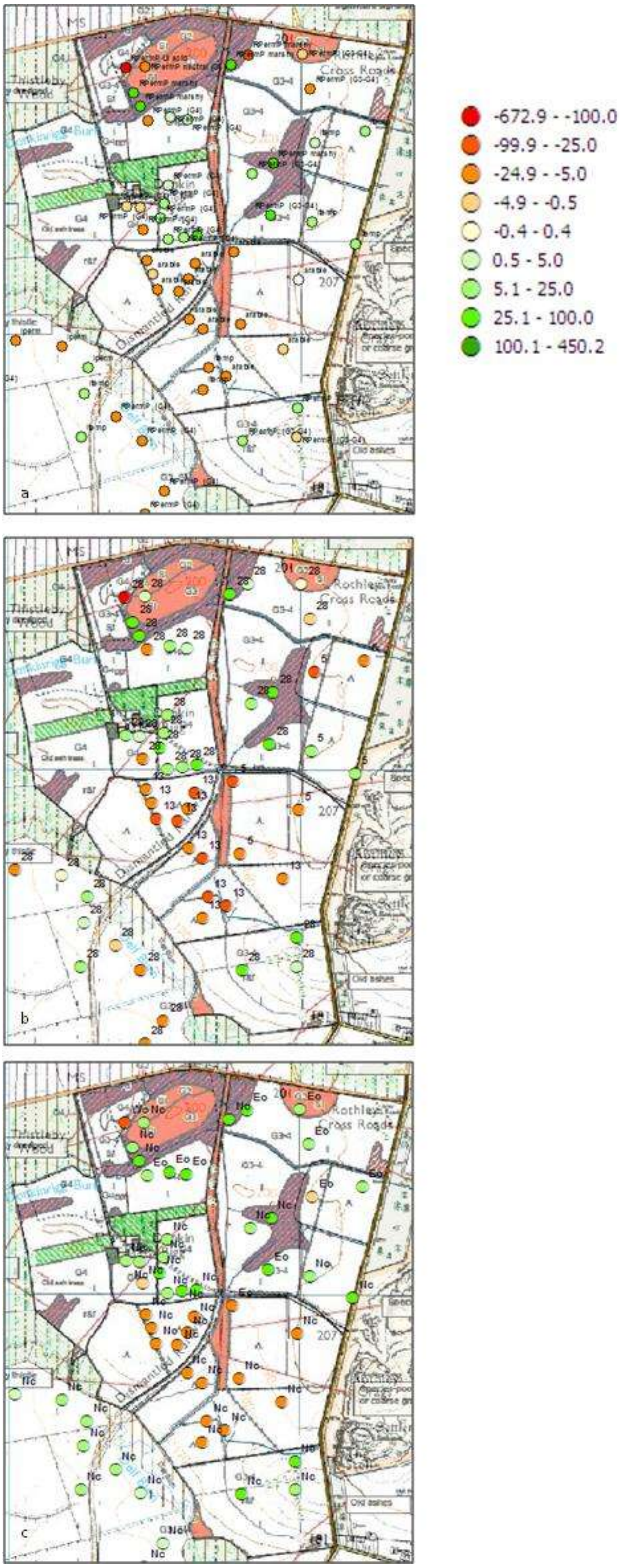


Figure DR1.

a) SOC (t C ha^{-1} eq to 20 cm) of individual sample sites within the tenancy relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the given land use of the Wallington Estate.

b) SOC (t C ha^{-1} eq to 20 cm) relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the whole Wallington Estate.

c) SOC (t C ha^{-1} eq to 20 cm) relative to the projected mean SOC (t C ha^{-1} eq to 20 cm) of the NSRI UK soil series.

5.5.3. Priority areas

The priority areas are summarised in Figure DR3. Areas of highest priority are labelled Priority 1 then follow in descending order of importance.

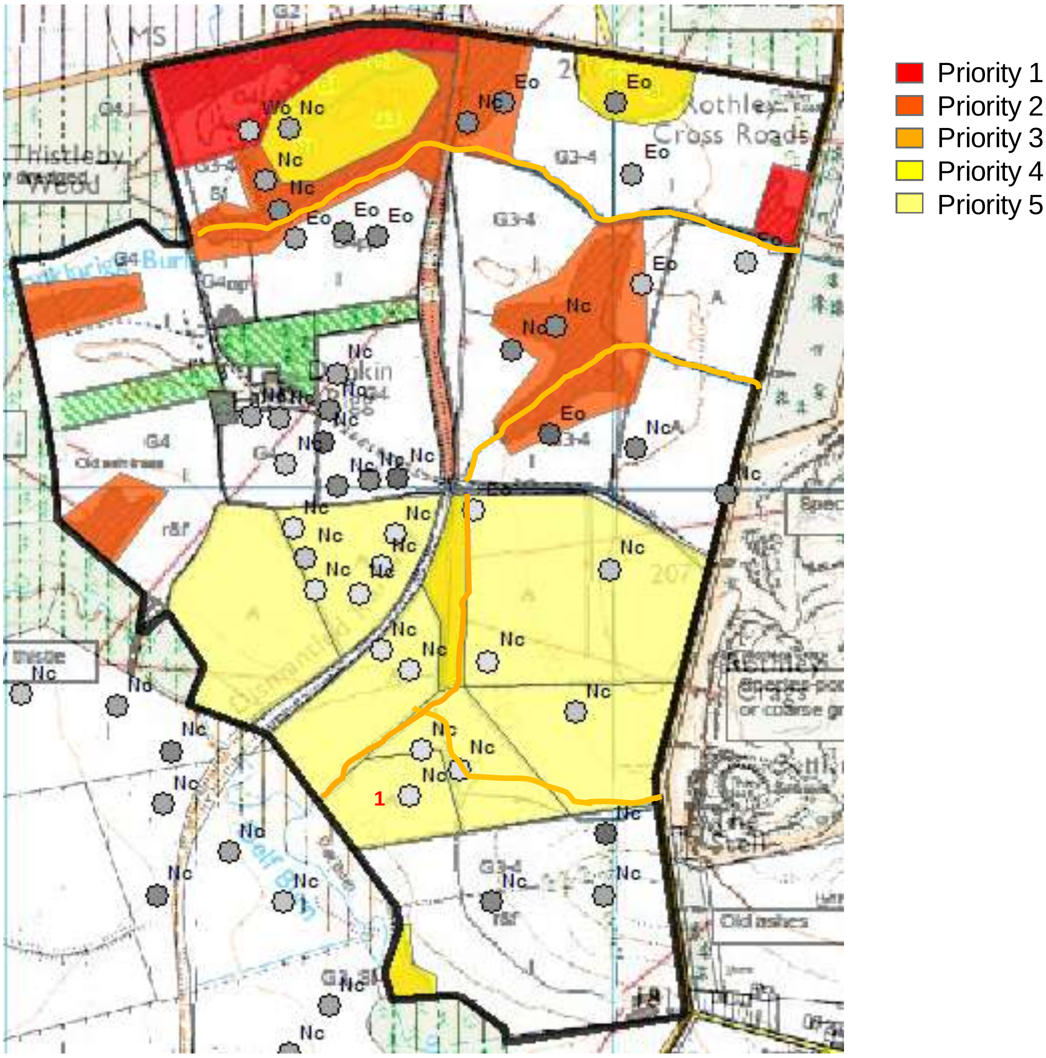


Figure DR3. Priority areas identified on Donkin Rigg.

1. Priority soil series Wo indicative of potential degraded priority habitat moorland. Area may be too small or fragmented for effective moorland restoration. Raised water levels are advised if not. Priority habitat mire to the northeast, water levels should be maintained and area extended if possible.
2. Priority habitat marshy grassland on non priority soil series Nc and Eo. The main areas of marshy grassland occur adjacent to watercourses, and have potential to be extended. The remaining areas should be at least preserved. The growing of water tolerant tree species ('palludiculture') would not risk degradation of a high priority soil series.

3. Priority habitat watercourse. Samples close to the watercourse in the south-east of the tenancy have low SOC, possibly due to the congregation of livestock and resulting soil compaction. Fencing to prevent access by livestock will reduce the risk of compaction and erosion. The area impacted by watercourse fencing assumes 4 m between the fence and watercourse.
4. Neutral grassland described as species rich in central belt (Biological Survey, 1999). Remaining areas generally species poor, potential to increase species diversity with restoration.
5. Areas of low SOC for land use at Wallington and relative to the UK. Mostly cultivated land, currently undergoing conversion to organic production which is predicted to alter the current rotations to include grass/clover leys in the future. It is envisaged that SOC will increase in response. Area 1 is ItempP, maximising the period between reseed operations is one option to enhance SOC. Conversion to permanent grassland will incur a high risk of displaced production.

5.5.4. HLS Options

The options on marshy grassland, unimproved acid grassland, watercourses, improved temporary grassland, improved permanent grassland outside SDAs and boundary features are applicable. Table DR3 summarises by priority area (in descending order 1 to 6) options with the potential to have the greatest impact.

Table DR3. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of priority HLS options for implementation in areas specified in Figure GH1.

	Code / Option		**Dis^p Risk**	**ha**	**SOC**	**Bio^{mas}**	**Σ**	**SOC**	**Bio^{mas}**	**Σ**
					10 years			**20 years**		
1	HL10	Restoration of moorland	low	5.1	4.7	0	4.7	11.4	0	11.4
1	HL15	Seasonal livestock exclusion supplement	low		Facilitates option HL10					
1	HK19	Raised water levels (upland grassland)	low	0.8	4.5	0	4.5	9.0	0	9.0
2	HK19	Raised water levels (upland grassland)	low	15.6	83.3	0	83.3	166.5	0	166.5
3	HJ11	Maintenance of watercourse fencing	mod	2281m	0.2	0.7	1.0	0.4	0.7	1.2
4	HK7	Restoration of species-rich, semi-natural grassland	low	6.6	3.5	5.2	8.7	7.0	5.2	12.2
5_1	HJ7	Seasonal livestock removal on grassland with no input restriction	low	2.8	0.9	0	0.9	1.9	0	1.9
5_1	HK2	Permanent grassland with low inputs (outside SDAs)	high	2.8	6.4	2.2	8.6	12.8	2.2	15.0

Dis^p Risk: Displacement Risk

ha: estimated area (ha) where option may be implemented
Σ: Total increase in C

5.5.5. Non-HLS Options

The potential impact of suggested non HLS options on marshy grassland and cultivated land are summarised in Table DR4. Short rotation coppice assumes harvest every 10 years, the equilibrium for biomass is reached after an average of 5 years.

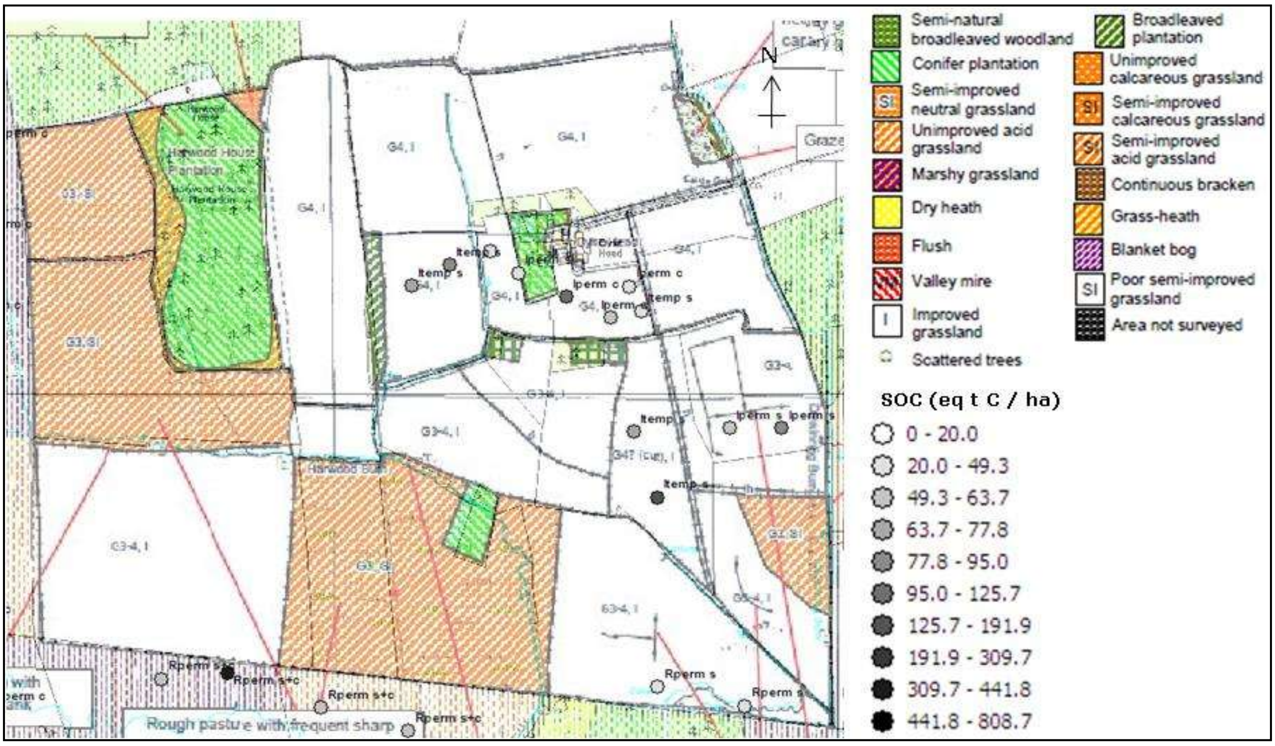
Table DR4. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of potential non HLS options for implementation in areas specified in Figure DB3.

	Option	Dis^p Risk	ha	SOC	Bio^mas	Σ	SOC	Bio^mas	Σ
				10 years			20 years		
1	Palludiculture	low	9.3	49.6	195.3	244.9	99.2	390.6	489.8

The use of short rotation coppice willow as a biofuel is cited by Smith et al. (2000) to have an additional energy substitution value of 2.1 t C ha^{-1} $year^{-1}$, equivalent to 195 and 391 t C after 10 and 20 years respectively if the marshy grassland areas are fully exploited.

5.6. Dyke Head

5.6.1. Site description



A combination of mainly improved temporary pasture grazed by sheep and improved permanent pasture (with high broadleaved herb content such as white clover) grazed by sheep or cattle. An area of rough permanent pasture (with rush species) grazed by sheep exists to the south of the tenancy, and semi-improved acidic rough pasture to the south and the east. To the side of the conifer plantation is relict moorland community with encroaching birch (due to absence of grazing) although damp areas exist where rush species are present. There are a number of shelter belts containing broadleaved tree species and hawthorn hedges. The southern fields were previously moorland (Biological Survey, 1999) and remnants of habitat remain.

The WFP identifies management of hay meadows, appropriate management of ditches and watercourses, the creation of additional areas of standing water and damp grassland, rush management and the fencing off of selected areas of watercourses from stock.

5.6.2. Baseline carbon

The mean SOC for each soil series and land use relative to the mean for the soil series and land use for the Wallington Estate is given in Tables DH1 and DH2. The SOC for individual sample sites relative to the mean for soil series and land use, and soil series overall for the Wallington Estate are displayed in Figures DH1a and DH1b respectively. The SOC for individual sample sites relative to the NSRI UK mean for soil series is given in Figure DH1c.

Table DH1. Mean SOC for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / -	Max SOC tenancy	Max SOC estate	Max SOC estate <1.5
ItempP	Br	74.3	64.8	9.5	176.1	176.1	96.9
	Nc	75.9	64.7	11.3	83.4	86.4	86.4
IpermP	Br	61.1	70.8	-9.8	85.7	138.7	97.3
	dZ	116.4	116.4	0.0	116.4	116.4	116.4
	Nc	46.8	75.1	-28.3	48.9	132.5	98.2
RpermP	qn	46.2	46.2	0.0	71.0	71.0	71.0
	wo	70.0	110.2	-40.1	77.8	117.5	92.2

No colour if within + or –0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

The maximum SOC on ItempP was noted on marshy ground with some rush (*Juncus* spp) present. It would not be realistic to expect this SOC to be achieved for this land use and therefore it has not been used as the assumed maximum at equilibrium for ItempP. Revised figures are given in Table DH2.

Table DH2. Mean SOC with values in excess of 1.5 greater than the mean removed for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / - (<1.5)	Max SOC tenancy	Max SOC estate
ItempP	Br	51.0	58.8	-7.8	75.8	96.9
IpermP	Br	61.1	68.2	-7.1	85.7	97.3
	Nc	46.8	73.7	-26.9	48.9	98.2
RpermP	wo	70.0	69.7	0.3	77.8	92.2

No colour if within + or –0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

- ItempP: highest SOC for ItempP for soil series Br although this was located at the base of a large slope where there is potential for drainage water to accumulate;

SOC above mean on field to the south, below mean on field located to the east (acquired in 2001) and single site adjacent to farmhouse suggesting different management histories at the field scale (latter two fields have greatest potential to accumulate SOC); no reseeding in 'over 10 years' on any field; FYM applied without chain harrow post cutting during the summer (potentially large volumes available until the 1990s when stocking rates were reduced, this management excludes the field to the east acquired after this time).

- IpermP: SOC below mean for series Br and Nc in two fields adjacent to the east and west of the farmhouse although the SOC is greater in the third IpermP field moving further east; NPK is applied as 20:10:10 during the spring however the land has been subject to previously high stocking rates from both sheep and cattle, potential soil compaction and lower potential SOC at equilibrium.
- RpermP: SOC of priority soil series Wo is below the mean for the land use of the estate and UK overall, potential to increase SOC in the eastern side of this field where series Wo appears dominant. The two sample sites are located to the east in the recently acquired land and are grazed by cattle. Two of the sample sites for series qn to the south of the tenancy (both below the mean SOC for land use and UK) are located close to a watercourse under trees where stock may have congregated for shade and caused compaction.

Figure DH1.

a) SOC (t C ha^{-1} eq to 20 cm) of individual sample sites within the tenancy relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the given land use of the Wallington Estate.

b) SOC (t C ha^{-1} eq to 20 cm) relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the whole Wallington Estate.

c) SOC (t C ha^{-1} eq to 20 cm) relative to the projected mean SOC (t C ha^{-1} eq to 20 cm) of the NSRI UK soil series.

5.6.3. Priority areas

The priority areas are summarised in Figure DH3. Areas of highest priority are labelled Priority 1 then follow in descending order of importance.

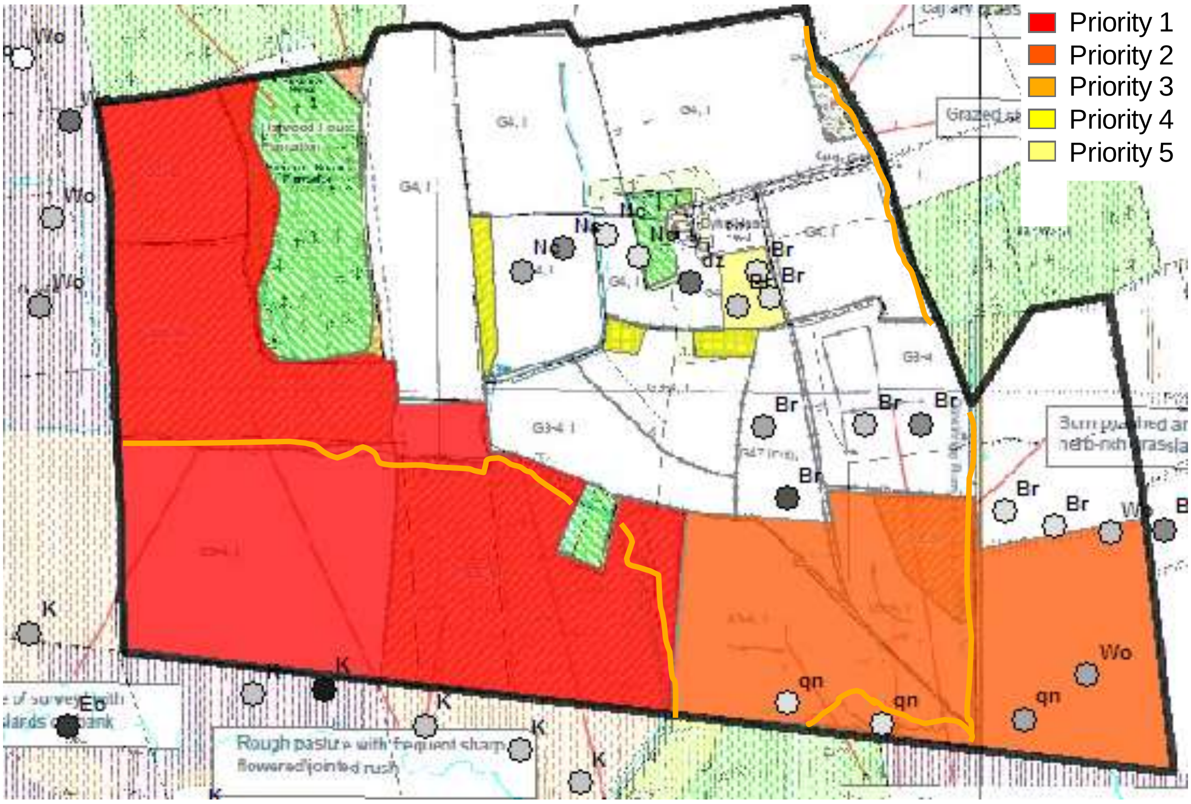


Figure DH3. Priority areas identified on Dyke Head.

1. Presence of semi-improved acid grassland indicative of degraded moorland habitat, and in close proximity to high priority soil series K on Gallows Hill to the south, K and Wo on Ralph Shield to the east, and Wo to the west of the tenancy. The Biological Survey (1999) states these areas are reclaimed moorland. The appropriate management of ditches and watercourses conducive to SOC accumulation is to block them however the tenant believes they have silted naturally and that there is no need to do so. The natural silting of existing drainage channels should allow this to occur without further intervention. Restoration of moorland in these areas would link with the moorland restoration recommended for the two tenancies mentioned previously.
2. Priority soil series Wo to the west, potential (but not sampled) priority soil series K and Wo in this area. Also stated as being reclaimed moorland by the Biological Survey (1999). Potential for moorland restoration or the creation of additional areas of standing water and damp grassland, also conducive to SOC accumulation.

3. Priority habitat watercourse. The fencing off of selected areas of watercourses from stock will prevent erosion and compaction where stock congregate. The area impacted by watercourse fencing assumes 4 m between the fence and watercourse.
4. Priority habitat broadleaved woodland on non high priority soil series. Not situated immediately adjoining high priority soil series. Maintenance or restoration as necessary.
5. Areas of low SOC for land use at Wallington and relative to the UK. Improved permanent pasture receives sheep from rough permanent pasture during the winter. It represents a small area on the tenancy but permits non overwintering of stock on large areas elsewhere on the tenancy. May be suitable for trialling silvipasture where the presence of trees allows build up of SOC in the upper soil layers and roots are able to penetrate compacted topsoil.

5.6.4. HLS Options

The options on marshy grassland, unimproved acid grassland, watercourses, improved temporary grassland, improved permanent grassland outside SDAs and boundary features are applicable. Table DH3 summarises by priority area (in descending order 1 to 4) options with the potential to have the greatest impact.

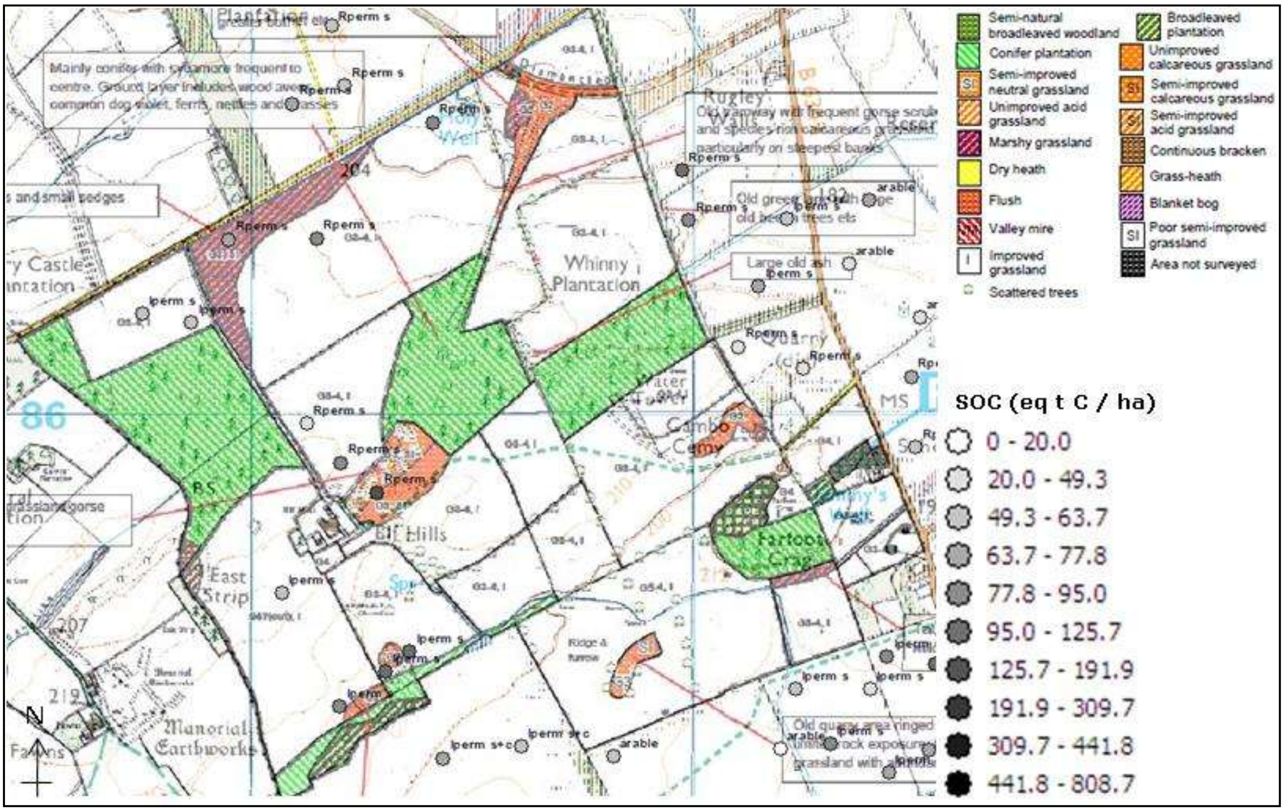
Table DH3. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of priority HLS options for implementation in areas specified in Figure DH1.

	Code / Option		**Dis^p Risk**	**ha**	**SOC**	**Biomas**	**Σ**	**SOC**	**Biomas**	**Σ**
					10 years			**20 years**		
1	HL10	Restoration of moorland	low	65.6	61.2	0	61.2	148.7	0	148.7
1	HL15	Seasonal livestock exclusion supplement	low		Facilitates option HL10					
2	HL10	Restoration of moorland	low	36.7	34.2	0	34.2	83.1	0	83.1
2	HL15	Seasonal livestock exclusion supplement	low		Facilitates option HL10					
3	HJ11	Maintenance of watercourse fencing	mod	4060m	0.4	1.3	1.7	0.8	1.3	2.1
4	HC8	Restoration of woodland	low	1.9	0.1	5.4	5.5	0.2	10.8	11.0

Dis^p Risk: Displacement Risk
ha: estimated area (ha) where option may be implemented
Σ: Total increase in C

5.7. Elf Hills

5.7.1. Site description



Predominantly rough permanent pasture (with white clover) grazed by sheep. Areas of marshy grassland are present to the north, with patches of unimproved calcareous grassland and trees along field boundaries.

5.7.2. Baseline carbon

The mean SOC for each soil series and land use relative to the mean for the soil series and land use for the Wallington Estate is given in Tables EH1. The SOC for individual sample sites relative to the mean for soil series and land use, and soil series overall for the Wallington Estate are displayed in Figures EH1a and EH1b respectively. The SOC for individual sample sites relative to the NSRI UK mean for soil series is given in Figure EH1c.

Table EH1. Mean SOC for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / -	Max SOC tenancy	Max SOC estate	Max SOC estate <1.5
IpermP	gJ	54.2	70.0	-15.8	57.2	102.5	102.5
	MI	111.9	111.9	0.0	124.8	124.8	124.8
	tL	52.1	52.1	0.0	52.1	52.1	52.1
RpermP	gJ	82.0	74.4	7.6	85.2	110.7	110.7
	tL	63.8	64.1	-0.3	86.9	86.9	86.9

No colour if within + or −0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

- IpermP: SOC for series gJ below mean for land use at Wallington (two samples to the west).
- RpermP: SOC for series gJ above mean for RpermP at Wallington (two samples in two separate fields to the north); in close proximity to marshy grassland / watercourse where soil water content may be higher (remainder of field unknown).

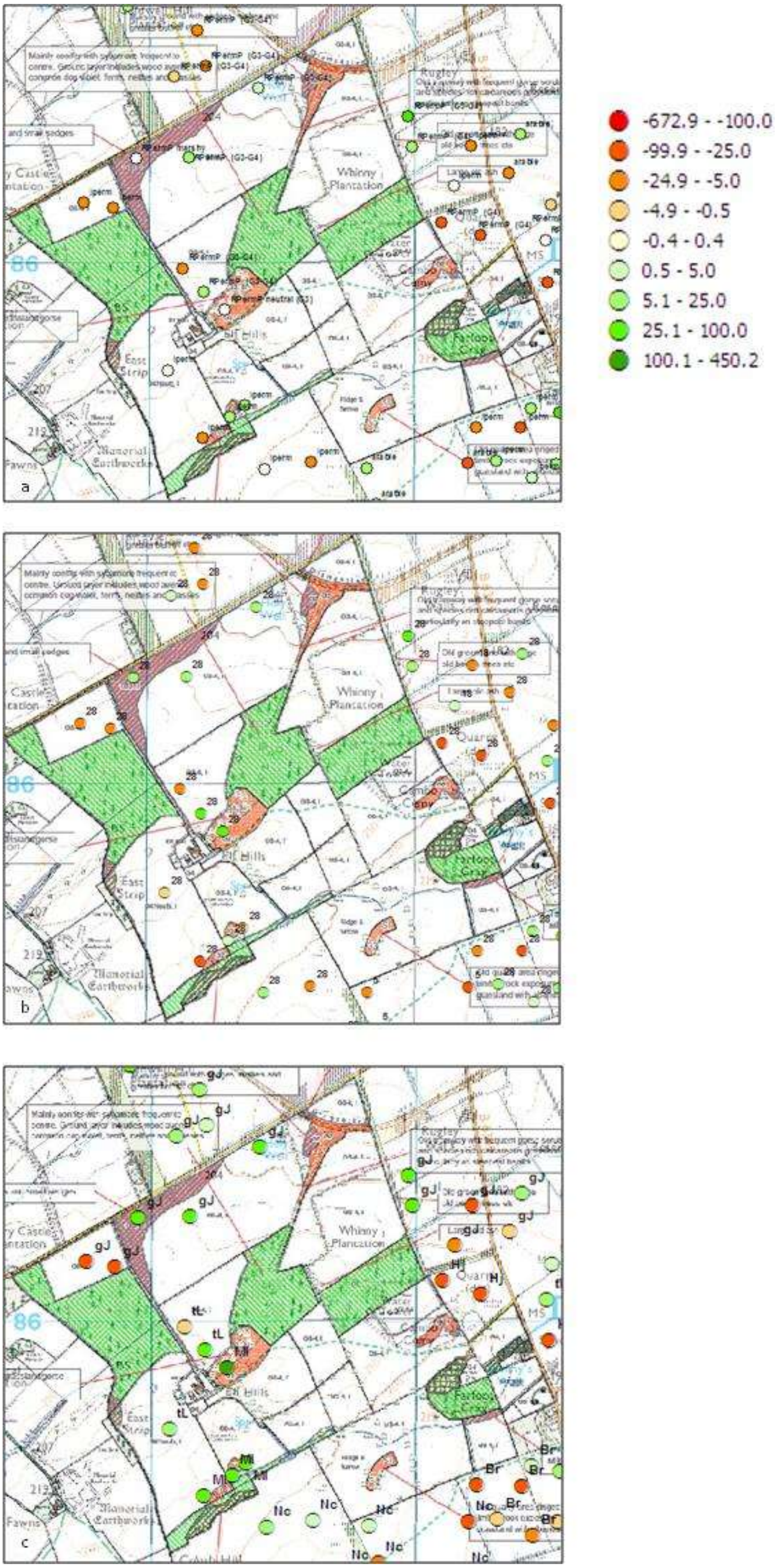


Figure EH1.

a) SOC (t C ha^{-1} eq to 20 cm) of individual sample sites within the tenancy relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the given land use of the Wallington Estate.

b) SOC (t C ha^{-1} eq to 20 cm) relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the whole Wallington Estate.

c) SOC (t C ha^{-1} eq to 20 cm) relative to the projected mean SOC (t C ha^{-1} eq to 20 cm) of the NSRI UK soil series.

5.7.3. Priority areas

The priority areas are summarised in Figure EH3. Areas of highest priority are labelled Priority 1 then follow in descending order of importance.

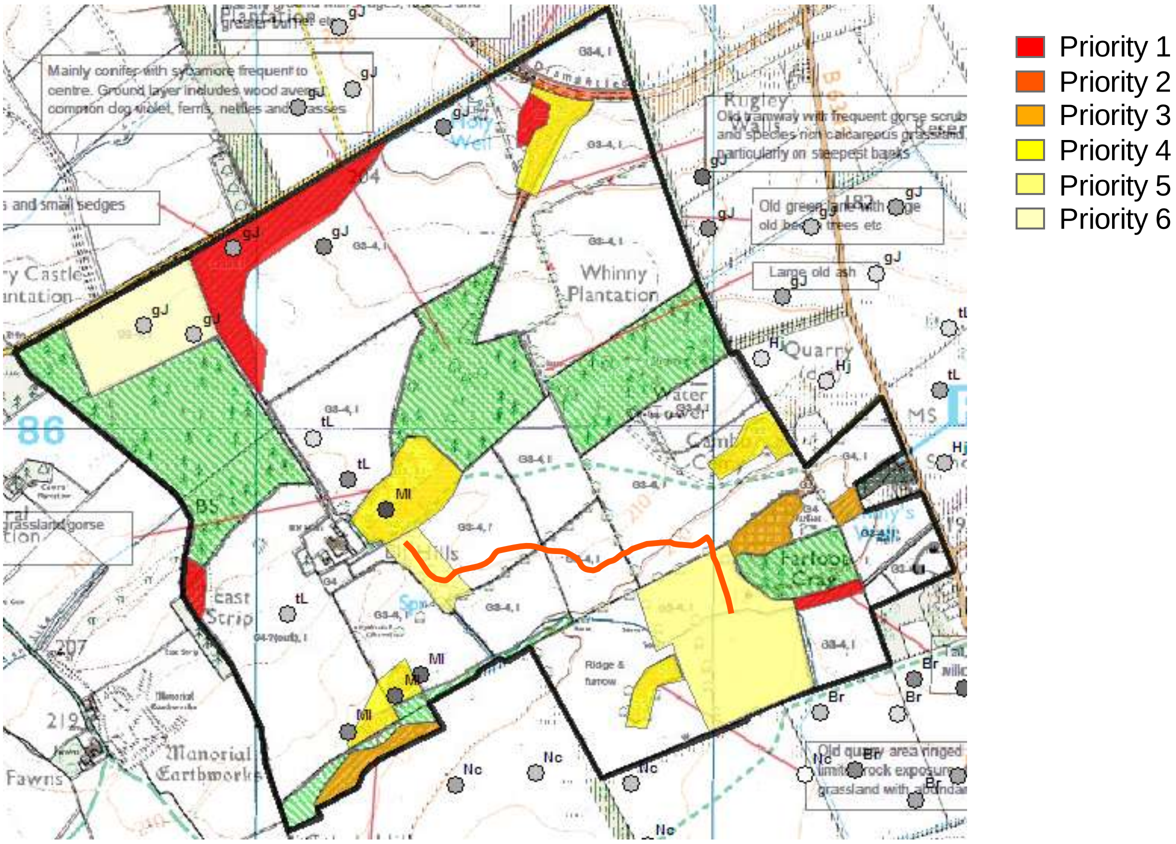


Figure EH3. Priority areas identified on Elf Hills.

1. Priority habitat marshy grassland on non high priority soil series.
2. Priority habitat watercourse. Fencing to prevent access by livestock in order to reduce the risk of compaction and erosion. The area impacted by watercourse fencing assumes 4 m between the fence and watercourse.
3. Priority habitat broadleaved woodland on non high priority soil series. Restoration (replacement of dead trees) and additional tree planting (ash, beech, hawthorn) recommended by the Biological Survey (1999).
4. Priority habitat unimproved calcareous grassland, maintenance / restoration as necessary. Areas of semi-improved neutral grassland are present to the south-west with potential for restoration to increase species diversity.
5. Areas of existing mature trees in boundaries and within field, with potential for restoration of wood pasture (conducive with the Biological Survey 1999 management recommendations to increase broadleaved tree numbers).

6. Low SOC for land use (IPermP) at Wallington and relative to the UK. Non overwintering of stock or trialling of silvipasture are potential options.

5.7.4. HLS Options

Table EH3 summarises by priority area (in descending order 1 to 6) options with the potential to have the greatest impact.

Table EH3. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of priority HLS options for implementation in areas specified in Figure EH1.

	Code / Option		**Dis^{p} Risk**	**ha**	**SOC**	**Bio^{mas}**	**Σ**	**SOC**	**Bio^{mas}**	**Σ**
					10 years			**20 years**		
1	HK7	Restoration of species-rich, semi-natural grassland	mod	7.0	37.2	1.4	38.6	74.3	1.4	75.7
2	HJ11	Maintenance of watercourse fencing	mod	580m	0.1	0.2	0.2	0.1	0.2	0.3
3	HC8	Restoration of woodland	low	2.7	0.1	7.6	7.7	0.3	15.2	15.5
4	HK7	Restoration of species-rich, semi-natural grassland	mod	8.0	4.3	6.4	10.7	8.5	6.4	14.9
5	HC13	Restoration of wood pasture and parkland	mod	9.3	4.9	31.1	36.1	4.9	57.1	62.0
6	HJ7	Seasonal livestock removal on grassland with no input restriction	low	5.5	1.8	0	1.8	3.7	0	3.7

Dis^{p} Risk: Displacement Risk
ha: estimated area (ha) where option may be implemented
Σ: Total increase in C

5.5.5. Non-HLS Options

The potential impact of suggested non HLS options on marshy grassland and cultivated land are summarised in Table EH4. Short rotation coppice assumes harvest every 10 years, the equilibrium for biomass is reached after an average of 5 years.

Table EH4. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of potential non HLS options for implementation in areas specified in Figure EH3.

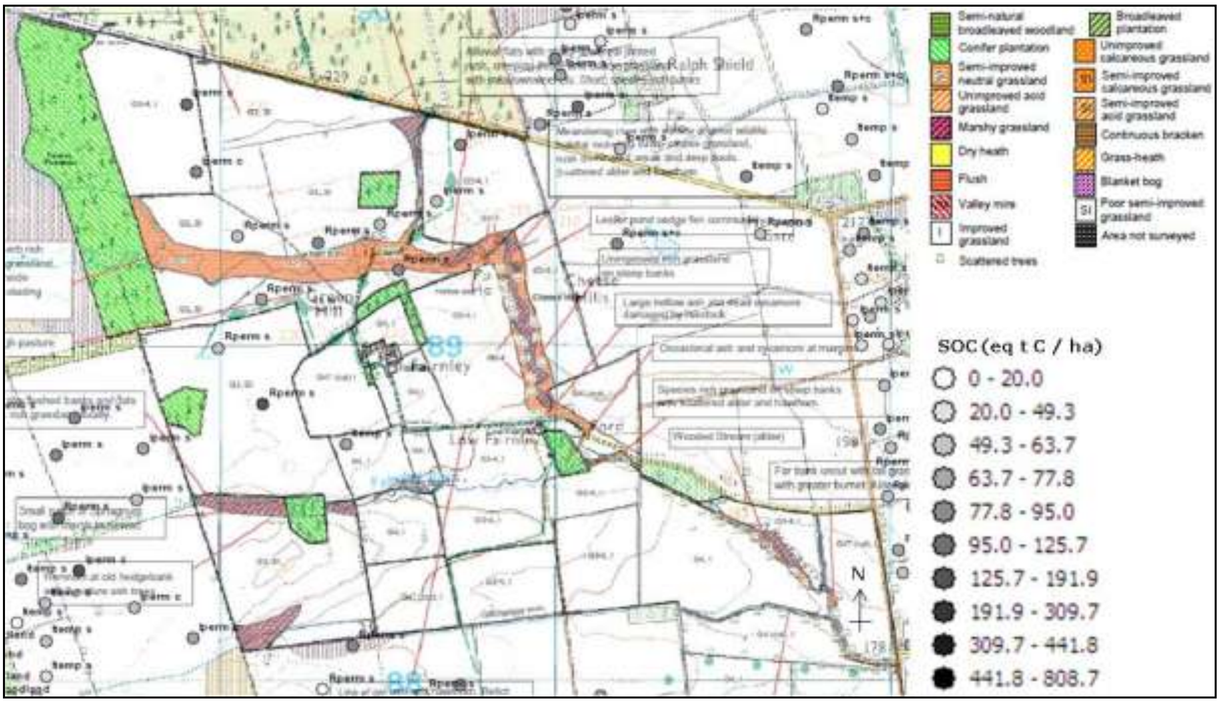
	Option	**Dis^p Risk**	**ha**	**SOC**	**Bio^{mas}**	**Σ**	**SOC**	**Bio^{mas}**	**Σ**
				10 years			**20 years**		
1	Palludiculture	low	7.0	37.2	146.4	183.5	74.3	292.7	367.1
6	Silvipasture	low	5.5	1.5	71.9	73.4	2.9	148.2	151.1

The use of short rotation coppice willow as a biofuel is cited by Smith et al. (2000) to have an additional energy substitution value of 2.1 t C ha^{-1} $year^{-1}$, equivalent to 146 and 293 t C after 10 and 20 years respectively if the marshy grassland areas are fully exploited.

5.8. Fairnley

See also Harwood Head.

5.8.1. Site description



The tenancy consists of a combination of rough permanent pasture grazed by sheep or by sheep and cattle, and improved permanent pasture grazed by sheep (M6, white clover present). A number of the G3 classified fields are 'damper fields' with species such as common sedge and rush (Biological Survey, 1999). The G4 fields are dominated by *L. Perenne*. Along the Hart Burn is an area of tall grassland, rushes and fen. The areas of marshy grassland are dominated by dominated by rushes (soft rush and sharp-flowered/jointed rush). A small patch of sphagnum bog is located in to the south west. Old ash trees and other broadleaved trees are present along the field boundaries.

FYM is applied during the winter, as priority to the temporary permanent pasture to the south of the tenancy, then the areas of improved permanent pasture. The rate of application varies (exact quantities unknown), with a tendency for lower rates applied to the permanent pasture because of insufficient quantities produced to apply to all improved areas equally. Previously the improved permanent pasture in closest proximity to the farmhouse received the greatest quantities of FYM. Improved permanent pasture is cut for silage (C removed entirely as not re-deposited) in addition to the temporary pasture. The WFP identifies damage to ground adjacent to the burns by stock, damage to old ash trees by stock and the lack of planting of new field boundary trees.

5.8.2. Baseline carbon

The mean SOC for each soil series and land use relative to the mean for the soil series and land use for the Wallington Estate is given in Tables FN1 and FN2. The SOC for individual sample sites relative to the mean for soil series and land use, and soil series overall for the Wallington Estate are displayed in Figures FN1a and FN1b respectively. The SOC for individual sample sites relative to the NSRI UK mean for soil series is given in Figure FN1c.

Table FN1. Mean SOC for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / -	Max SOC tenancy	Max SOC estate	Max SOC estate <1.5
ItempP	Br	71.8	64.8	7.0	71.8	176.1	96.9
IpermP	Br	72.4	70.8	1.5	82.3	138.7	97.3
	Wo	100.4	79.9	20.5	117.7	165.7	165.7
RpermP	Br	86.2	78.3	8.0	155.8	214.2	109.8
	Eo	82.1	75.6	6.5	82.1	134.6	134.6
	Wo	58.6	70.6	-11.9	58.6	72.4	72.4

No colour if within + or −0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

Table FN2. Mean SOC with values in excess of 1.5 greater than the mean removed for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / - (<1.5)	Max SOC tenancy	Max SOC estate
ItempP	Br	71.8	58.8	13.0	71.8	96.9
IpermP	Br	72.4	68.2	4.2	82.3	97.3
RpermP	Br	68.8	69.5	-0.7	92.5	109.8

No colour if within + or −0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

- ItempP: one sample site above mean for land use on Wallington; receives FYM as priority although is applied during the winter.
- IpermP: SOC above mean for soil series Br and Wo on IpermP on Wallington; series Wo is a high priority soil series and may potentially be decreasing in SOC if drainage has been undertaken; may have received FYM in the past subject to quantities available after spreading on ItempP (however would be variable between individual fields and years).
- RpermP: SOC above mean for Br and Eo although Br is skewed by a single high value in the field to the west of the tenancy (is below average if this site is

removed); sample sites for series Br in close proximity to the burn and SOC is mainly below average for series and land use, possibly due to the increased movement of livestock along the feature (as observed during field visit) and compaction or erosion (it would benefit from being fenced off). High priority series Wo is low for this land use.

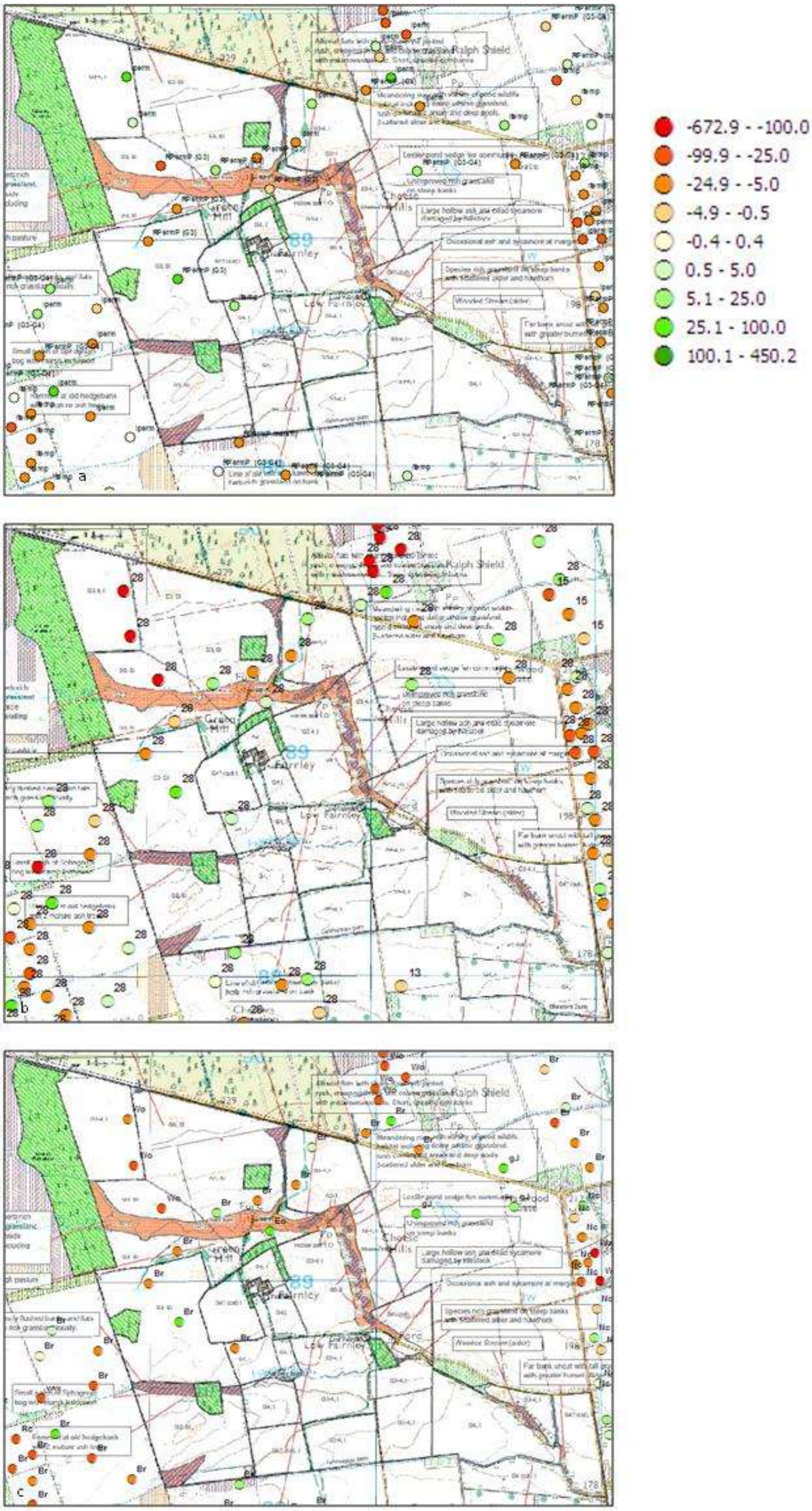


Figure FN1.

a) SOC (t C ha^{-1} eq to 20 cm) of individual sample sites within the tenancy relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the given land use of the Wallington Estate.

b) SOC (t C ha^{-1} eq to 20 cm) relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the whole Wallington Estate.

c) SOC (t C ha-1 eq to 20 cm) relative to the projected mean SOC (t C ha-1 eq to 20 cm) of the NSRI UK soil series.

5.8.3. Priority areas

The priority areas are summarised in Figure FL3. Areas of highest priority are labelled Priority 1 then follow in descending order of importance.

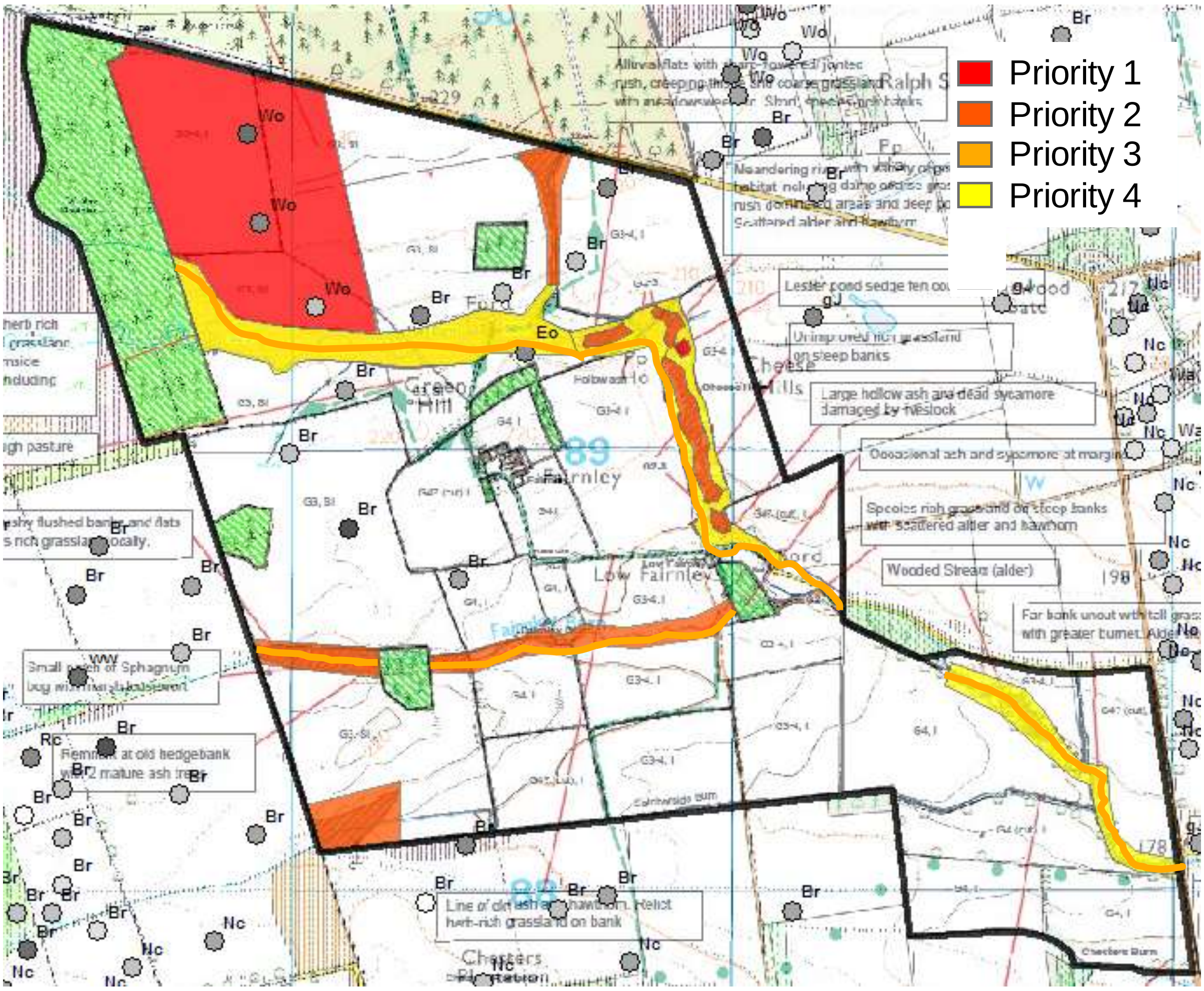


Figure FL3. Priority areas identified on Fairnley.

1. Priority soil series Wo. Potential for restoration of moorland. The coniferous shelter belt forms a barrier between this area and the larger moorland area of Harwood Head. Priority habitat fen. A relatively small area adjacent to priority habitat water course.
2. Priority habitat marshy grassland on non high priority soil series. Potential for extension in naturally low lying areas. Areas present within burn area limited scope for expansion due to steep banks.
3. Priority habitat watercourse with steep sided banks and risk of erosion. The ground adjacent to the burns is identified as vulnerable to damage by stock (has low SOC for the soil series in these areas). Maintenance of fencing to prevent livestock access and decrease risk of compaction and erosion.

4. Priority habitat species rich grassland adjacent to priority habitat watercourse. Restoration as necessary accumulates SOC coupled with provision of a buffer zone and protection of priority habitat watercourse.
5. Protection of veteran trees and the planting of new field boundary trees as appropriate will enhance C stocks.

5.8.4. HLS Options

The options on marshy grassland, unimproved acid grassland, watercourses, improved temporary grassland, improved permanent grassland outside SDAs and boundary features are applicable. Table FN3 summarises by priority area (in descending order 1 to 6) options with the potential to have the greatest impact.

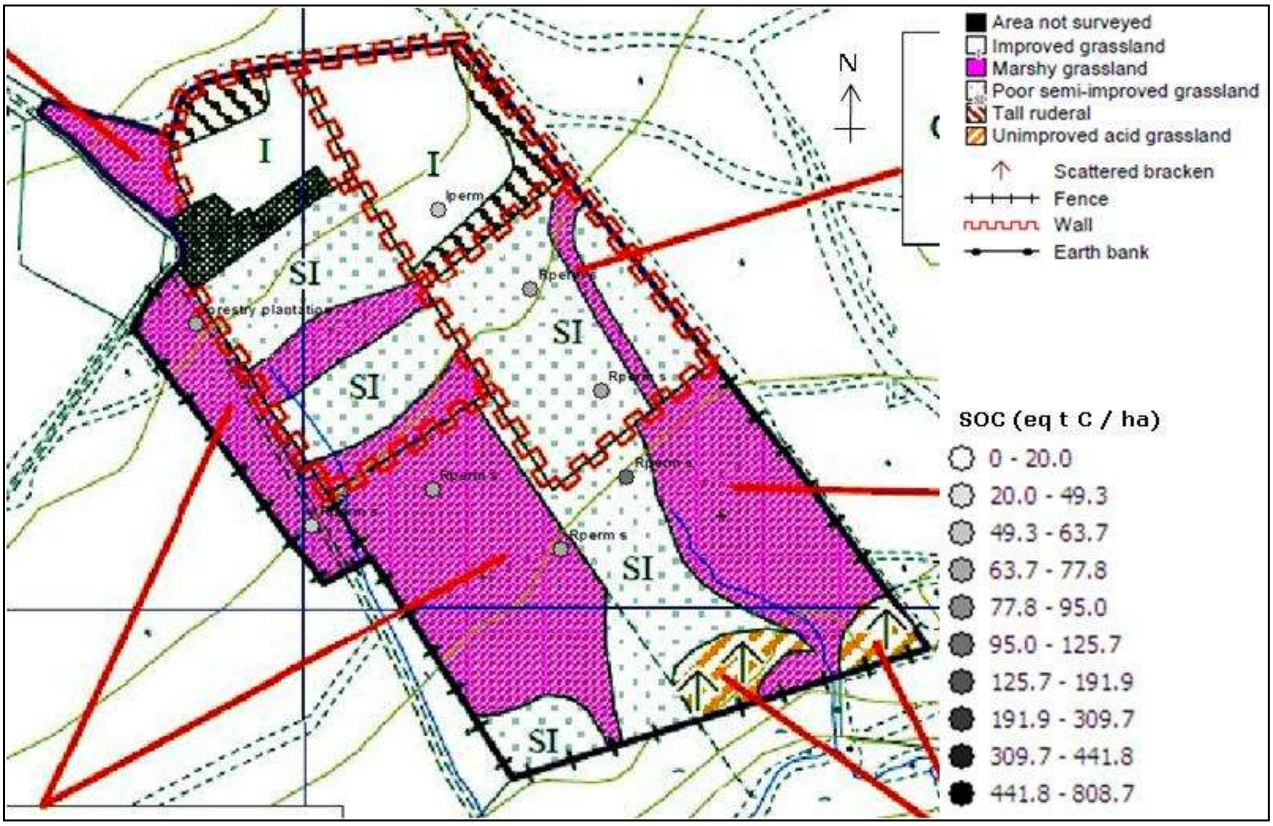
Table FN3. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of priority HLS options for implementation in areas specified in Figure GH1.

	Code / Option		**Dis^p Risk**	**ha**	**SOC**	**Bio^mas**	**Σ**	**SOC**	**Bio^mas**	**Σ**
					10 years			**20 years**		
1	HL10	Restoration of moorland	low	25.7	23.9	0	23.9	58.2	0	58.2
1	HL15	Seasonal livestock exclusion supplement	low		Facilitates option HL10					
1		Maintenance of fen	low	0.1	0.1	0	0.1	0.3	0	0.3
2	HK19	Raised water levels (lowland grassland)	low	11.2	59.8	2.2	62.0	119.6	2.2	121.8
3	HJ11	Maintenance of watercourse fencing	mod	4158.0	0.4	1.3	1.7	0.8	1.3	2.1
4	HK7	Restoration of species-rich, semi-natural grassland	low	16.1	8.6	12.9	21.5	17.2	12.9	30.1

Dis^p Risk: Displacement Risk
ha: estimated area (ha) where option may be implemented
Σ: Total increase in C

5.9. Fallowlees

5.9.1. Site description



Mainly rough permanent pasture grazed by sheep, much of which is categorised as marshy grassland.

5.9.2. Baseline carbon

The mean SOC for each soil series and land use relative to the mean for the soil series and land use for the Wallington Estate is given in Tables FL1 and FL2. The SOC for individual sample sites relative to the mean for soil series and land use, and soil series overall for the Wallington Estate are displayed in Figures FL1a and FL1b respectively. The SOC for individual sample sites relative to the NSRI UK mean for soil series is given in Figure FL1c.

Table FL1. Mean SOC for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / -	Max SOC tenancy	Max SOC estate	Max SOC estate <1.5
IpermP	Wo	61.5	79.9	-18.4	61.5	165.7	117.7
RpermP	Wo	82.9	110.2	-27.3	117.5	117.5	92.2

No colour if within + or −0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

Table FL2. Mean SOC with values in excess of 1.5 greater than the mean removed for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / - (<1.5)	Max SOC tenancy	Max SOC estate
IpermP	Wo	61.5	73.3	-11.8	61.5	117.7
RpermP	Wo	65.5	69.7	-4.2	66.6	92.2

No colour if within + or −0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

- IpermP: single sample site below mean for series Wo and land use, and UK average; high priority soil series with a relatively intensive land management use; small field sizes renders a greater proportion of the field at risk to compaction around e.g. gates.
- RpermP: individual sample sites mostly below Wallington mean for RpermP and Wo series; all sites below UK mean for Wo series; stock grazed for 2 months during the summer then likely to be moved onto IpermP (which therefore has higher stocking rates for a greater proportion of the year).

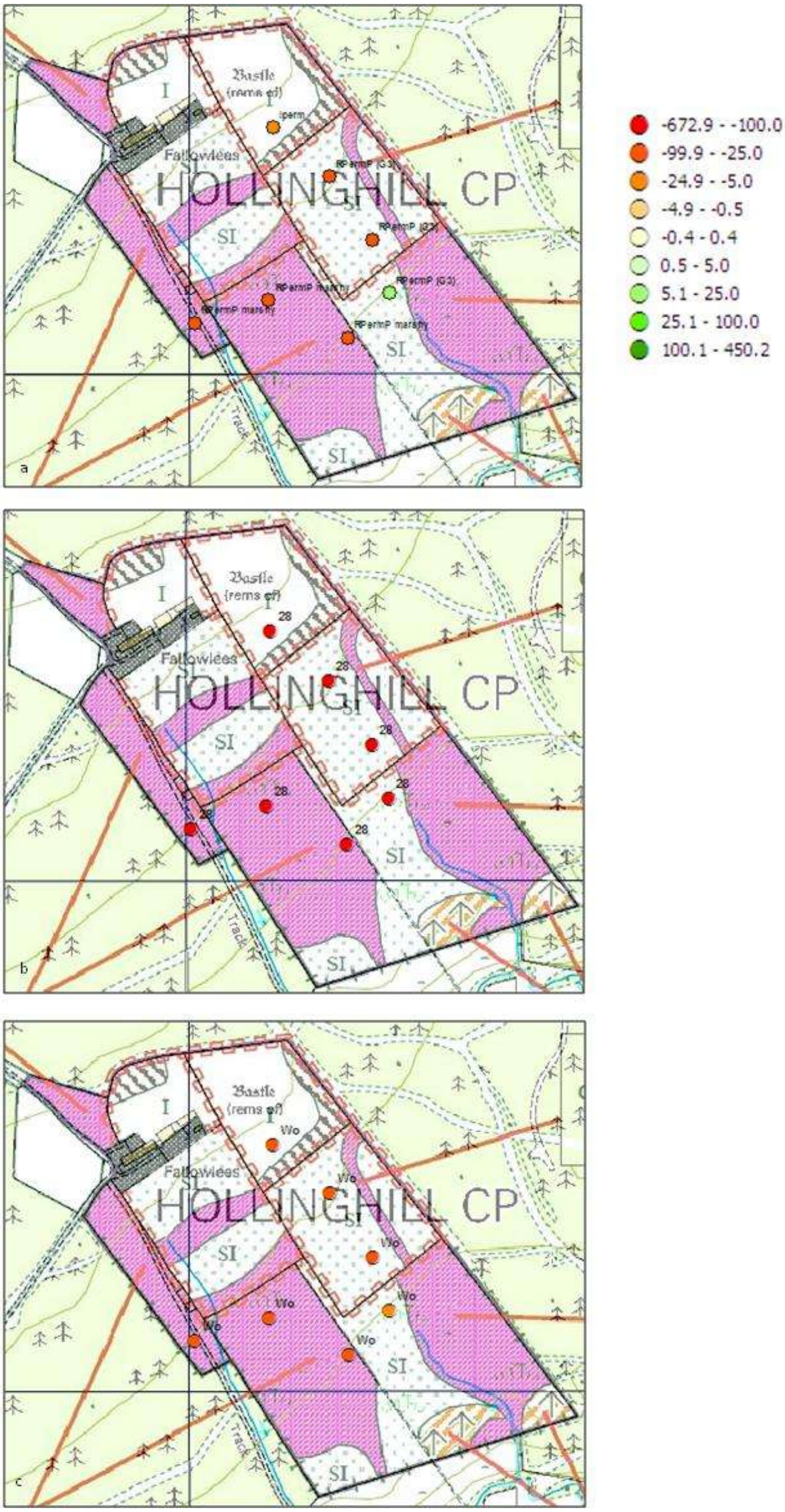


Figure FL1.

a) SOC (t C ha^{-1} eq to 20 cm) of individual sample sites within the tenancy relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the given land use of the Wallington Estate.

b) SOC (t C ha^{-1} eq to 20 cm) relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the whole Wallington Estate.

c) SOC (t C ha^{-1} eq to 20 cm) relative to the projected mean SOC (t C ha^{-1} eq to 20 cm) of the NSRI UK soil series

5.9.3. Priority areas

The priority areas are summarised in Figure FL3. Areas of highest priority are labelled Priority 1 then follow in descending order of importance.

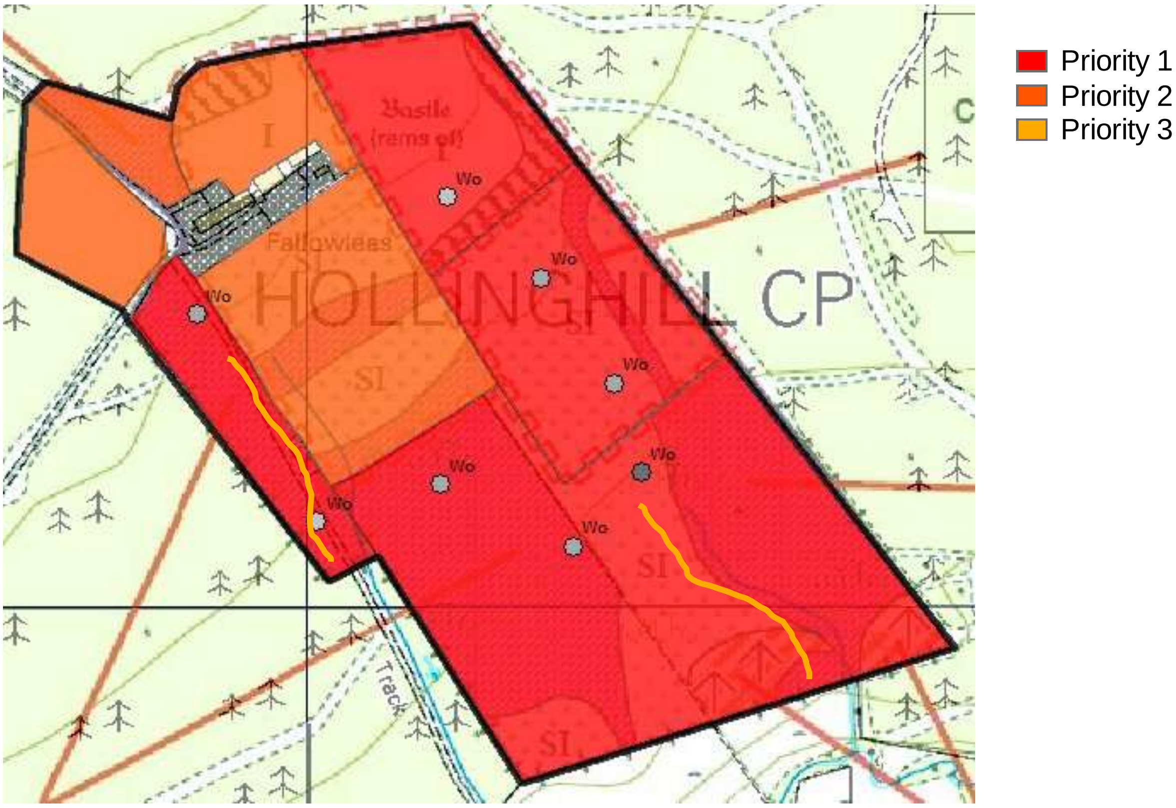


Figure FL3. Priority areas identified on Fallowlees.

1. Priority soil series Wo. Restoration of moorland is the preferred option however the presence of wall boundaries may inhibit this in the fields to the north of the tenancy.
2. Probable priority soil series Wo. Potential for restoration to moorland however close proximity to dwellings and presence of walled enclosures may render this impractical.
3. Priority habitat watercourse. Fencing as necessary to prevent compaction and erosion by livestock.

5.9.4. HLS Options

Table FL3 summarises by priority area (in descending order 1 to 3) options with the potential to have the greatest impact.

Table FL3. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of priority HLS options for implementation in areas specified in Figure FL1.

	Code / Option		Dis^p Risk	ha	SOC	Bio^{mas}	Σ	SOC	Bio^{mas}	Σ
					10 years			20 years		
1	HL10	Restoration of moorland	low - mod	15.5	14.5	0	14.5	35.2	0	35.2
1	HL15	Seasonal livestock exclusion supplement	low		Facilitates option HL10					
2	HL10	Restoration of moorland	low - mod	5.8	5.4	0	5.4	13.1	0	13.1
2	HL15	Seasonal livestock exclusion supplement	low		Facilitates option HL10					
3	HJ11	Maintenance of watercourse fencing	mod	397m	0.1	0.1	0.2	0.1	0.1	0.2

Dis^p Risk: Displacement Risk
ha: estimated area (ha) where option may be implemented
Σ: Total increase in C

5.10. Gallows Hill

Degraded acid grassland or the priority soil series K are indicative of areas where potential exists for the restoration of the priority habitat heather moorland. Elsewhere, the extension of marshy grassland located where moorland has not been degraded (priority habitat but not priority soil series), and species rich calcareous grassland (priority habitat) may be undertaken as appropriate to local site conditions. The prevention of access by stock to the Hardwood Burn area will reduce the risk of erosion and compaction adjacent to the watercourse. On the moderate/high priority soil series Wa options to reduce the risk of compaction by livestock (seasonal exclusion) are recommended. A recently reseeded area of temporary grassland on moderate priority series Br offers potential to be converted to permanent grassland. Such a land use change risks displacement of production through either the necessity to reduce stock or the need to import feed. The use of marshy areas for growing energy crops, or the trialling of silvipasture on series Wa are suggested in addition to the HLS options listed.

5.10.1. Site description

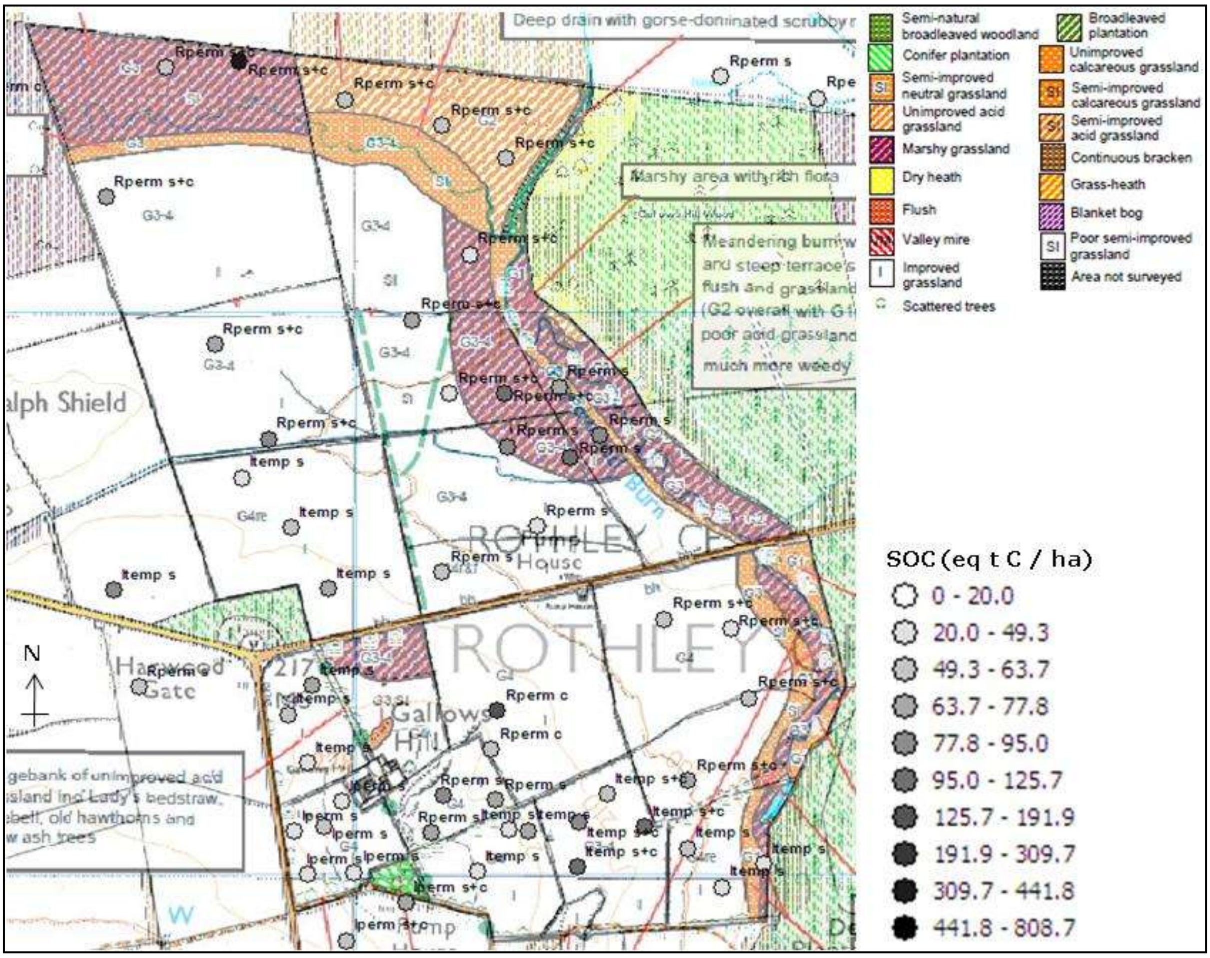


Figure GH1. Priority areas on Gallows Hill.

No arable land. The Biological Survey (1999) identifies areas of marshy grassland (predominantly rush and unimproved acid grassland containing cotton grass) to the north of the tenancy. This was corroborated by a farm visit in 2010. These habitats are on flatter areas. The unimproved grassland is grazed during spring when the cotton grass is acceptable to sheep. The Biological Survey (1999) distinguishes unimproved (low levels of FYM, no herbicides or mineral N) and semi-improved grasslands (mineral N, slurry, intensive grazing, herbicides or drainage), no distinction was made by the farmer for management practices for these land uses other than preference by livestock to graze different areas. Unimproved acid grassland is classed by Bell (2010) as grazed by sheep and cattle, however livestock tend to graze only during spring when cotton grass is acceptable to sheep. Cattle and sheep tend to be grazed on areas of rougher vegetation (cattle are able to graze species such as rush) therefore care must be taken correlating the SOC of such areas with the grazing regime, the grazing regime is a response to the vegetation present. Some sample points had isolated high SOC, these may possibly be localised depressions or hydrology (not displayed in the Biological Survey or by vegetation, or where run-off has drained into). Moving south, the gradient becomes steeper and is more heavily grazed, largely because of preference by the sheep for these areas in closer proximity to the location of the main supplementary feeding areas (there is no boundary between this area and the habitats described previously therefore technically, no difference in stocking rate exists, it is the preference of the animal i.e. they tend not to graze those areas). Species composition includes wild clover (a source of N), Yorkshire fog, bent and perennial ryegrass (PRG). These fields receive no supplementary N (either as FYM or inorganic N). Localised patches of marshy ground exist where there is no slope, and rainwater run-off has the potential to accumulate. Attempts at drainage have been made (pre 20 years ago, date unknown) although they have silted up and are not efficient. At the base of the slope is a stream with marshy ground either side. Beyond the stream, moving south the gradient becomes steep (northern aspect) and is managed as improved temporary pasture (ploughed and reseeded 8 year previously). Small areas are present on the slope where the ground is flat and becomes marshy. Nitrogen is applied as both inorganic N and FYM, followed by a chain harrow. The temporary grassland produces silage or, weather permitting, hay, for winter feed.

The fields immediately surrounding the farmhouse were previously cultivated and reseeded, between 15 and 20 years ago. Nitrogen and FYM are applied. Boundary features include a number of hawthorn trees, the apparent remnants of hedgerows, but currently with large gaps and a number of isolated standard trees. A small number of veteran trees are also present. Sheep are grazed for 12 months of the year, cattle (where present) between May and October. To the east of the tenancy is a burn with mature trees on the eastern side, marshy grassland to the west. Within field spatial variation i.e. same stocking rate and calendar, but a preference by livestock to graze different areas or different areas at different times of the year may cause difficulty in isolating any single management practice. The Biological Survey

(1999) in combination with on farm observations provide an indication of more heavily grazed areas by use of a grass index between G1 and G4, where G4 is the most improved and has the lowest diversity. These grass indices have been included in the baseline management conditions in an effort to distinguish where grazing is concentrated. They are also indicative of where agricultural improvement, if any (e.g. fertiliser application) will have most likely been focused. Lowland calcareous grassland is present on the southern boundary and along the crags/quarry near the farmhouse.

5.10.2. Baseline carbon

The SOC of the tenancy relative to the whole estate for a given land use is summarised in Tables GH1 and GH2. The SOC of individual sample points and soil series relative to the mean for the same land use, the mean of the estate overall and the mean for the UK are summarised in Figures GH2a-c.

Table GH1. Mean SOC for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / -	Max SOC tenancy	Max SOC estate	Max SOC estate <1.5
ItempP	Br	53.4	64.8	-11.4	65.7	176.1	96.9
	Nc	60.9	64.7	-3.7	74.0	86.4	86.4
	Wa	66.3	85.1	-18.8	102.2	85.1	85.1
IpermP	Nc	42.3	75.1	-32.9	53.9	132.5	98.2
	Wa	38.9	57.6	-18.7	47.5	83.4	83.4
RpermP	Br	58.1	78.3	-20.1	80.4	214.2	109.8
	K	45.0	67.6	-22.5	70.1	70.1	70.1
	Nc	99.3	75.6	23.7	134.6	134.6	100.5
	Wa	72.5	67.1	5.3	67.1	83.8	83.8

No colour if within + or –0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

Table GH2. Mean SOC with values in excess of 1.5 greater than the mean removed for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / - (<1.5)	Max SOC tenancy	Max SOC estate
ItempP	Br	53.4	58.8	-5.5	65.7	96.9
IpermP	Nc	42.3	73.7	-31.4	53.9	98.2
RpermP	Br	58.1	69.5	-11.4	80.4	109.8
	Nc	53.9	73.3	-19.4	53.9	100.5

No colour if within + or −0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

With the exception of RpermP the SOC for each soil series is mainly below the mean for the land use at Wallington. The series Wa on ItempP varies between fields, possibly because of differences between reseed dates. Although above the mean for the estate in some areas, it is below the mean for the UK. Its significance is discussed further in section 5.10.3.

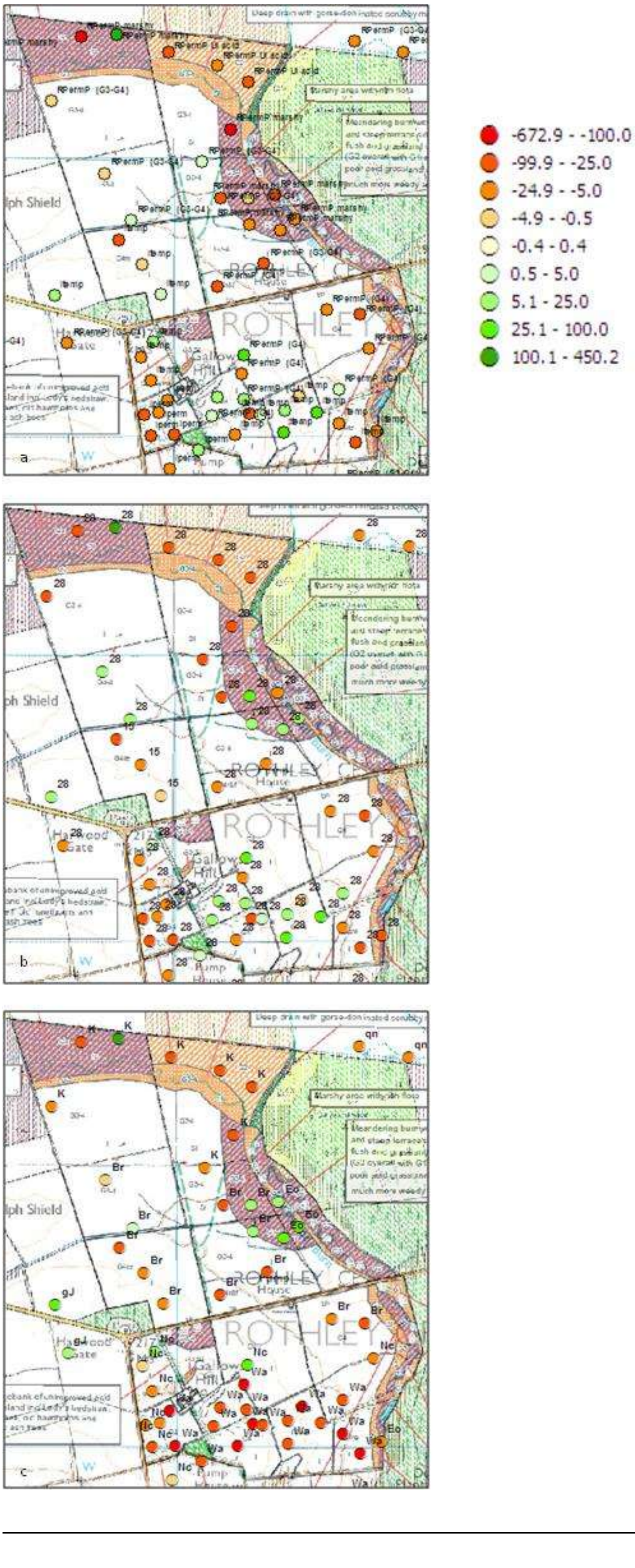


Figure GH2.

a) SOC (t C ha^{-1} eq to 20 cm) of individual sample sites within the tenancy relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the given land use of the Wallington Estate.

b) SOC (t C ha^{-1} eq to 20 cm) relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the whole Wallington Estate.

c) SOC (t C ha^{-1} eq to 20 cm) relative to the projected mean SOC (t C ha^{-1} eq to 20 cm) of the NSRI UK soil series

5.10.3. Priority areas

The priority areas are summarised in Figure GH3. Areas of highest priority are labelled Priority 1 then follow in descending order of importance. Numbers in red indicate sections within Priority area 6.

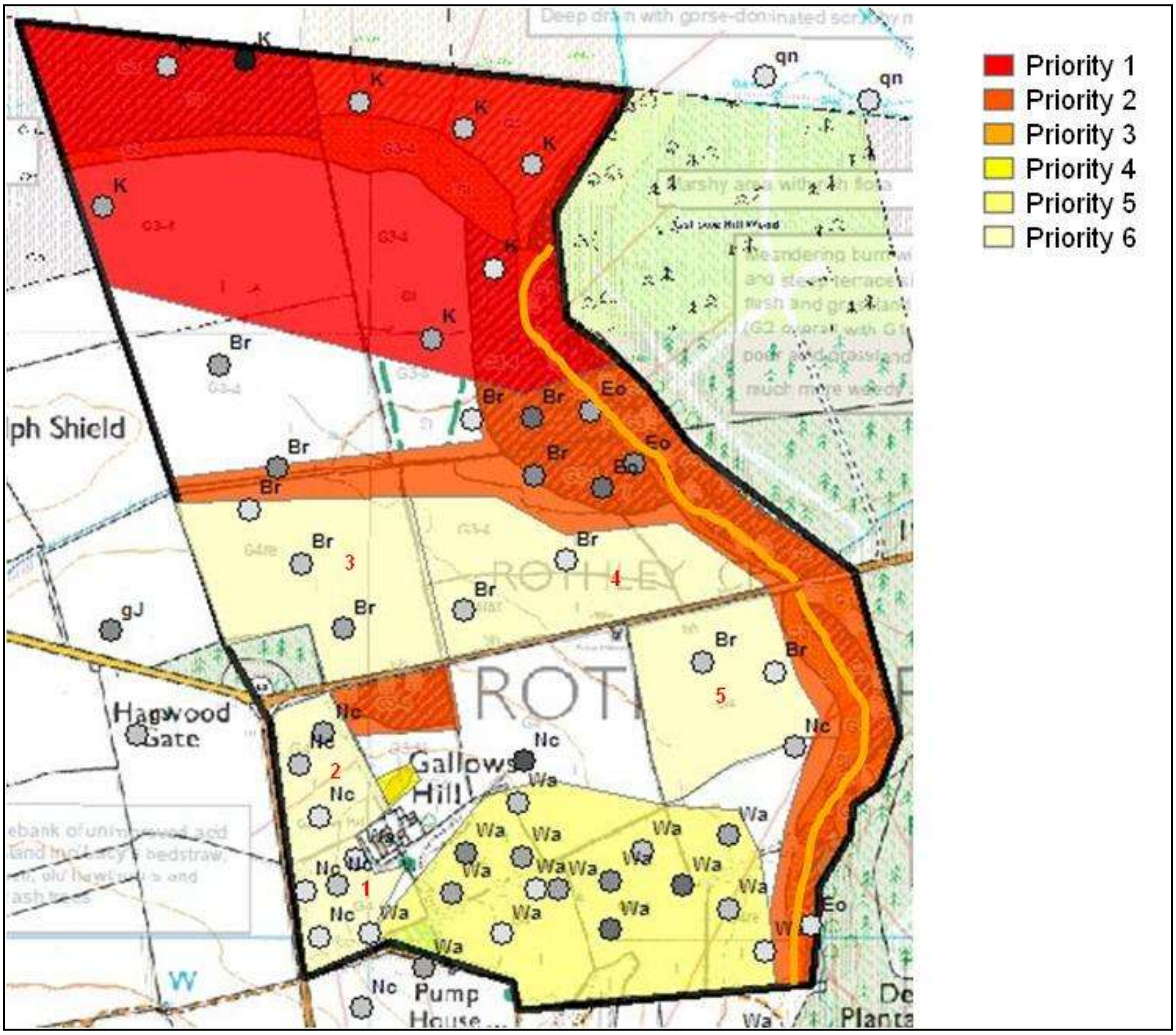


Figure GH3. Priority areas identified on Gallows Hill.

1. High priority soil series K / priority habitat unimproved acid grassland. SOC is below the mean for this land use and for soil series K on Wallington and the UK (Figure GH2a-c), the area has been subject to drainage and representative of degraded moorland habitat. The highest SOC on unimproved acid grassland for series K is located on Harwood Head therefore the SOC for this land use on this tenancy tends to be lower than average for the estate and land use. Series K on the unimproved acid grassland and marshy grassland to the north is below the UK mean and restoration of these habitats may offer potential to increase SOC to levels observed at Harwood Head. Series K extends beyond the current boundary

of these priority habitats southwards suggesting potential to create / restore moorland where this soil series is present. Sheep numbers increase on unimproved acid grassland during the spring when they prefer to graze cotton grass, the area is not grazed for the remainder of the year and as such there may be potential for a seasonal livestock exclusion supplement to reduce numbers at this time and reduce compaction risk (Harwood Head grazes between May and July).

2. Priority habitat marshy grassland on medium priority soil series. The presence of marshy grassland in low lying parts of the fields adjacent to watercourses and dominated by soil series Br suggest this is naturally wetter grassland rather than degraded moorland habitat. The area of marshy grassland has potential to be extended. The growing of water tolerant tree species ('palludiculture') would not risk degradation of a high priority soil series.
3. Priority habitat watercourse. Samples close to the watercourse in the south-east of the tenancy have low SOC, possibly due to the congregation of livestock and resulting soil compaction. The prevention of access by livestock with fencing aims to reduce the risk of compaction and erosion. The area impacted by watercourse fencing assumes 4 m between the fence and watercourse.
4. Priority habitat species rich calcareous grassland is present in small areas toward the south of the tenancy and requires maintenance/restoration as necessary.
5. The moderate/high priority soil series Wa is located on higher ground to the south-east of the farmhouse and generally has SOC above the mean for Wallington (although most samples of this series are present on this tenancy) but below the UK mean (Figure GH2c). This land is likely to have been subject to agricultural improvement for several decades. Most has been ploughed and reseeded although not recently, and no further plans exist to repeat this management. The close proximity to the farm buildings limits the land management options available. It is possible that SOC is recovering from the previous reseed operations. Options to prevent compaction and permit optimal recovery and SOC equilibrium, namely seasonal livestock exclusion to remove stock during the winter when soils are most vulnerable, would be of greatest benefit. This series is within the 'brown earth' major soil series (i.e. not organic) but appears to be present at higher altitudes and, in reference to UK mean data, has a high potential SOC at equilibrium. The trialling of silvipasture may be an option on this series since the presence of trees would not dry out and damage organic soil layers but could increase the rate of SOC accumulation. The presence of boundary hedgerows and trees imply viable growing conditions for broadleaved species.
6. Priority area 6 includes areas where priority habitats or soil series are absent but the SOC of the soil series is below the mean for Wallington for both land use, the estate overall and the UK (Figure GH2a-c). The maximum SOC at equilibrium will be potentially lower than higher priority soil series. If stock are to be grazed at higher rates or overwintered outdoors, these areas are preferred to (5) above.

Area 2 has been subject to previous reseeding although not recently, area 3 is reseeded every four years and supplies winter feed. The replacement of area 3 with permanent grassland carries a high risk of displaced production or the need to import feed from external sources. A reduction of stocking rates, particularly areas 1 and 2, also carry a high production displacement risk, while seasonal stock removal with low displacement risk is dependent on the capacity of the tenancy to locate stock elsewhere.

5.10.4. HLS Options

The options on marshy grassland, unimproved acid grassland, watercourses, improved temporary grassland, improved permanent grassland outside SDAs and boundary features are applicable. Table GH3 summarises by priority area (in descending order 1 to 6) options with the potential to have the greatest impact.

Table GH3. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of priority HLS options for implementation in areas specified in Figure GH1.

	Code / Option		**Dis^{p} Risk**	**ha**	**SOC**	**Bio^{mas}**	**Σ**	**SOC**	**Bio^{mas}**	**Σ**
					10 years			**20 years**		
1	HL10	Restoration of moorland	low	40	37.3	0	37.3	90.7	0	90.7
1	HL15	Seasonal livestock exclusion supplement	low	40	Facilitates option HL10					
2	HK19	Raised water levels (lowland grassland)	low	23	122.7	4.6	127.3	245.3	4.6	249.9
3	HJ11	Maintenance of watercourse fencing	low	1500m	0.2	0.5	0.6	0.3	0.5	0.8
4	HK7	Restoration of species-rich, semi-natural grassland	mod	1	0.5	0.8	1.3	1.1	0.8	1.9
5	HJ7	Seasonal livestock removal on grassland with no input restriction	low	18	6.1	0	6.1	12.1	0	12.1
$6_{1,2,4,5}$	HJ7	Seasonal livestock removal on grassland with no input restriction	low	22	7.4	0	7.4	14.8	0	14.8
6_{3}	HK2	Permanent grassland with low inputs (outside SDAs)	high	10	23.3	8.0	31.3	46.7	8.0	54.7

Dis^{p} Risk: Displacement Risk
ha: estimated area (ha) where option may be implemented
Σ: Total increase in C

5.10.5. Non-HLS Options

The potential impact of suggested non HLS options on marshy grassland and the soil series Wa are summarised in Table GH4. Short rotation coppice assumes harvest every 10 years, the equilibrium for biomass is reached after an average of 5 years.

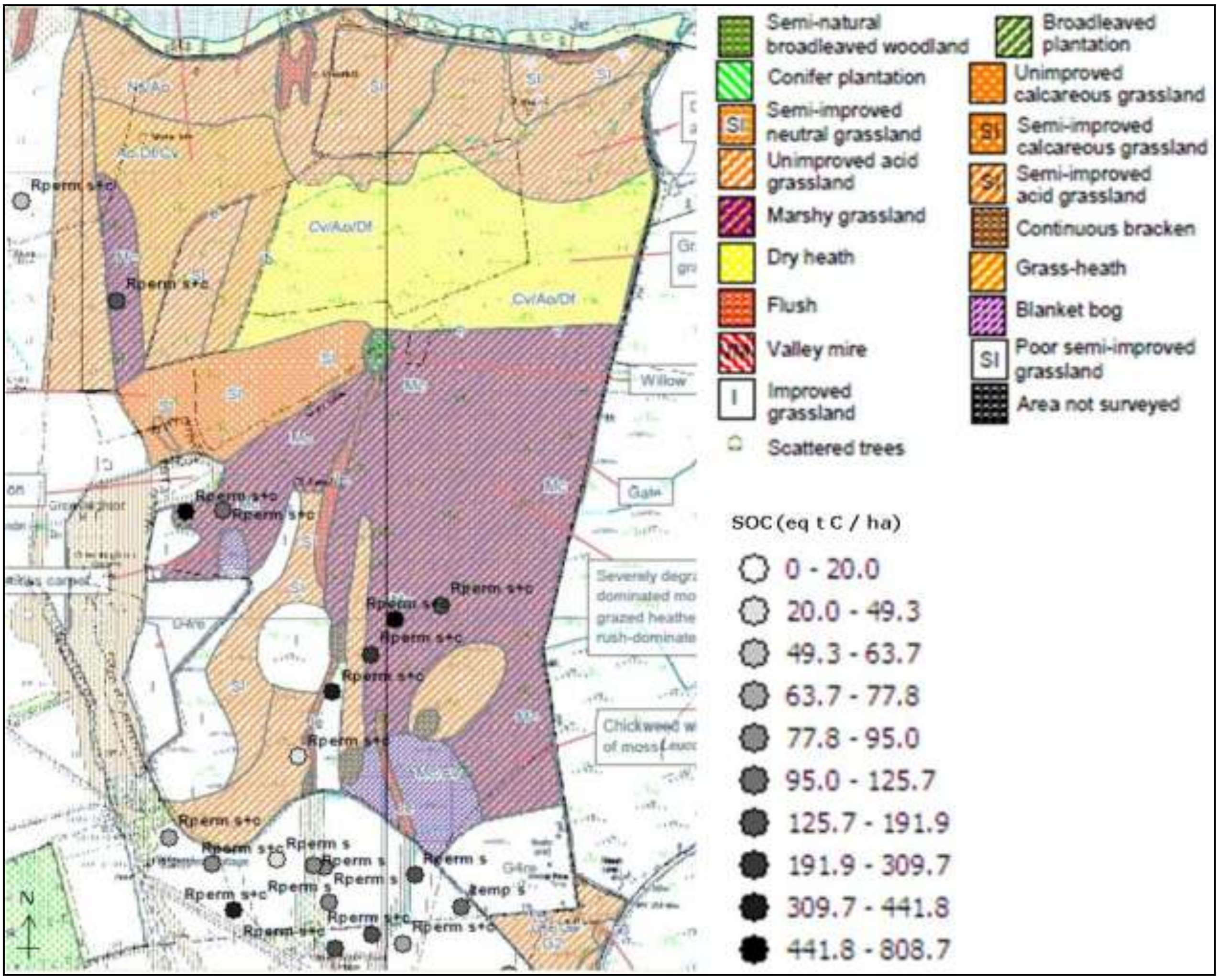
Table GH4. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of potential non HLS options for implementation in areas specified in Figure GH3.

	Option	**Dis^p Risk**	**ha**	**SOC**	**Bio^mas**	**Σ**	**SOC**	**Bio^mas**	**Σ**
				10 years			**20 years**		
2	Palludiculture	low	23	122.7	483.0	605.7	245.3	966.0	1211.3
5	Silvipasture	low	18	4.8	237.6	242.4	9.6	489.6	499.2

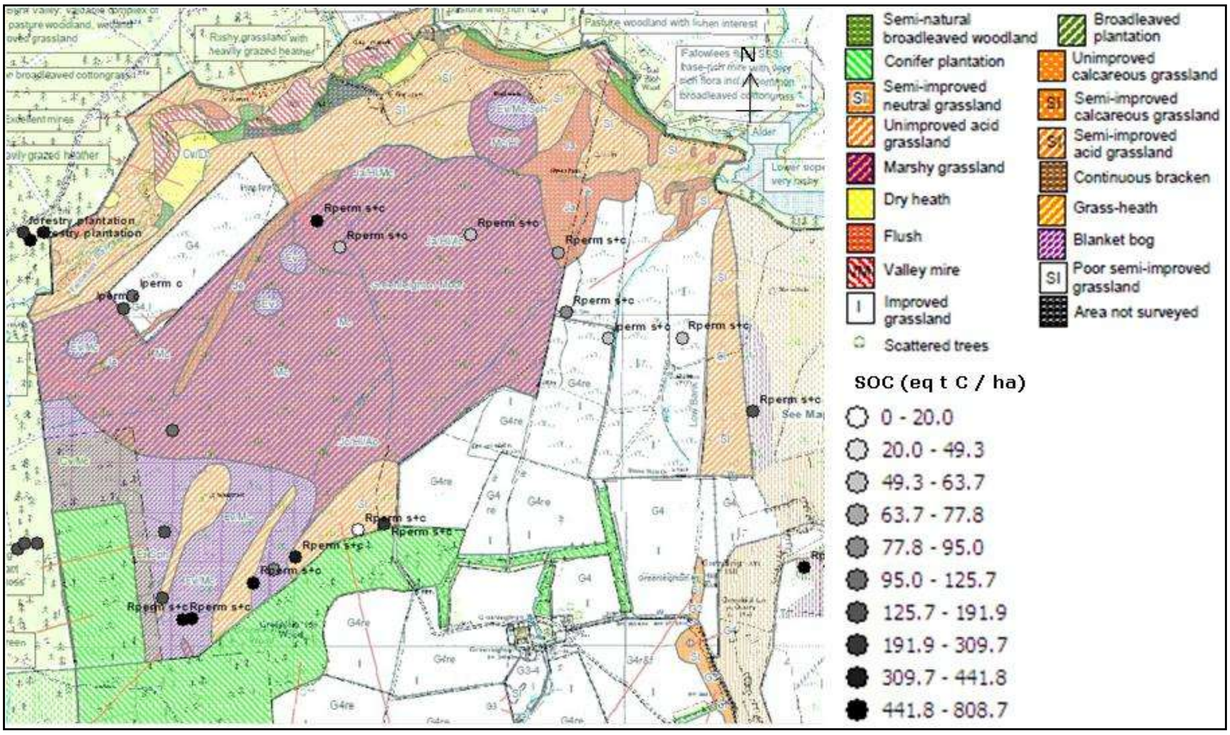
The use of short rotation coppice willow as a biofuel is cited by Smith et al. (2000) to have an additional energy substitution value of 2.1 t C ha^{-1} $year^{-1}$, equivalent to 483 and 966 t C after 10 and 20 years respectively if the marshy grassland areas are fully exploited.

5.11. Greenleighton

5.11.1. Site description



Greenleighton (part ii) consists of extensive areas of marshy grassland (some areas with occasional cushions of the moss species *Leucobryum glaucum;* other areas have vegetation indicative of less acidic and more mesotrophic soils), dry heath (H12, *Calluna vulgaris - Vaccinium myrtillus* heath), grass heath (H10c, *Calluna vulgaris - Erica cinerea* heath, *Festuca ovina - Anthoxanthum odoratum* sub-community), unimproved acid grassland (U4, *Festuca ovina - Agrostis capillaris - Galium saxatile* grassland; U5, *Nardus stricta - Galium saxatile*) and semi-improved neutral grassland. Grazing is by a combination of sheep and cattle. The Biological Survey (1999) describes the area as degraded moorland because of drainage and supplementary fertilisation.



Greenleighton (part i) has an area of blanket bog to the south-west adjacent to a conifer plantation, with extensive areas of marshy grassland in the centre and west, and areas of unimproved and semi-improved acid grassland to the north. Grazing is undertaken by both sheep and cattle. The SOC to 20 cm depth is consistently higher across much of the tenancy relative to many other tenancies, particularly the area of blanket bog to the south-west of Greenleighton part i and the marshy grassland areas of Greenleighton part ii. Historically the site was reclaimed moorland with peat soils therefore SOC levels were high previously to agricultural management. The management on the land itself is not responsible for the high levels of SOC, rather they would have been responsible for its degradation. A band of lower SOC transverses the north of the site in a south-easterly direction, on both marshy grassland and rough permanent pasture. The Biological Survey (1999) identifies the fields in the centre as reseeded (G4re) although this has not been undertaken since. Much of the area has been extensively drained. The drainage of organic soils has been reported as increasing emission of CO_2 from soils and this has been corroborated with measurements taken at Greenleighton Mire lowland raised bog, on the Wallington Estate. Emission of CO_2 was greatest where conifer plantations were present. The Biological Survey (1999) identifies that the presence of trees to the south-west intercept a significant proportion of rainwater decreasing water levels further. Greenleighton Mire is currently undergoing restoration to remove Sitka spruce and block drainage ditches which will serve to eventually slow CO_2 release. The previously reseeded areas will have lost SOC accelerated by a combination of drainage and cultivation. Fragments of wood pasture / semi-natural woodland are present.

5.11.2. Baseline carbon

The mean SOC for each soil series and land use relative to the mean for the soil series and land use for the Wallington Estate is given in Tables GR1 and GR2. The SOC for individual sample sites relative to the mean for soil series and land use, and soil series overall for the Wallington Estate are displayed in Figures GR1a and GR1b respectively. The SOC for individual sample sites relative to the NSRI UK mean for soil series is given in Figure GR1c.

Table GR1. Mean SOC for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / -	Max SOC tenancy	Max SOC estate	Max SOC estate <1.5
IpermP	Wo	104.4	79.9	24.5	165.7	165.7	117.7
RpermP	Tm	48.7	48.7	0.0	48.7	48.7	48.7
	Wo	71.0	110.2	-39.2	86.9	117.5	92.2

No colour if within + or −0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

Table GR2. Mean SOC with values in excess of 1.5 greater than the mean removed for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / - (<1.5)	Max SOC tenancy	Max SOC estate
IpermP	Wo	84.0	73.3	10.7	102.1	117.7
RpermP	Wo	71.0	69.7	1.3	86.9	92.2

No colour if within + or −0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

- Priority habitats: blanket bog dominated by soil series Wo (the only tenancy where this habitat was sampled), SOC mostly above the UK mean for this series. Series cgs on marshy grassland SOC below the UK mean. Three samples of the soil series cgs in close proximity to each other to the south of the tenancy are highly variable (147.7 – 808.7 t C ha^{-1} eq) and all below the UK mean suggesting degraded habitat.
- IpermP: SOC of series Wo (two sample sites) above the Wallington mean for this land use but below the mean for the estate overall; the site close to the periphery of the field with adjacent marshy grassland is above the UK mean for this soil series; series Tm is only found on this tenancy. The site has been drained and reseeded previously (but not recently). These soil series are classed as high

priority and conversion to less intensive management (restoration to priority habitat NVC M18 / M19 / M25) is considered a priority.

- RpermP: series Wo significantly below the land use mean and UK mean. Grazed by sheep (Jan – Oct) and cattle (May – Nov) at low stocking rates. Although now permanent grassland the site has been drained and reseeded previously. Restoration to priority habitat is classed as priority.

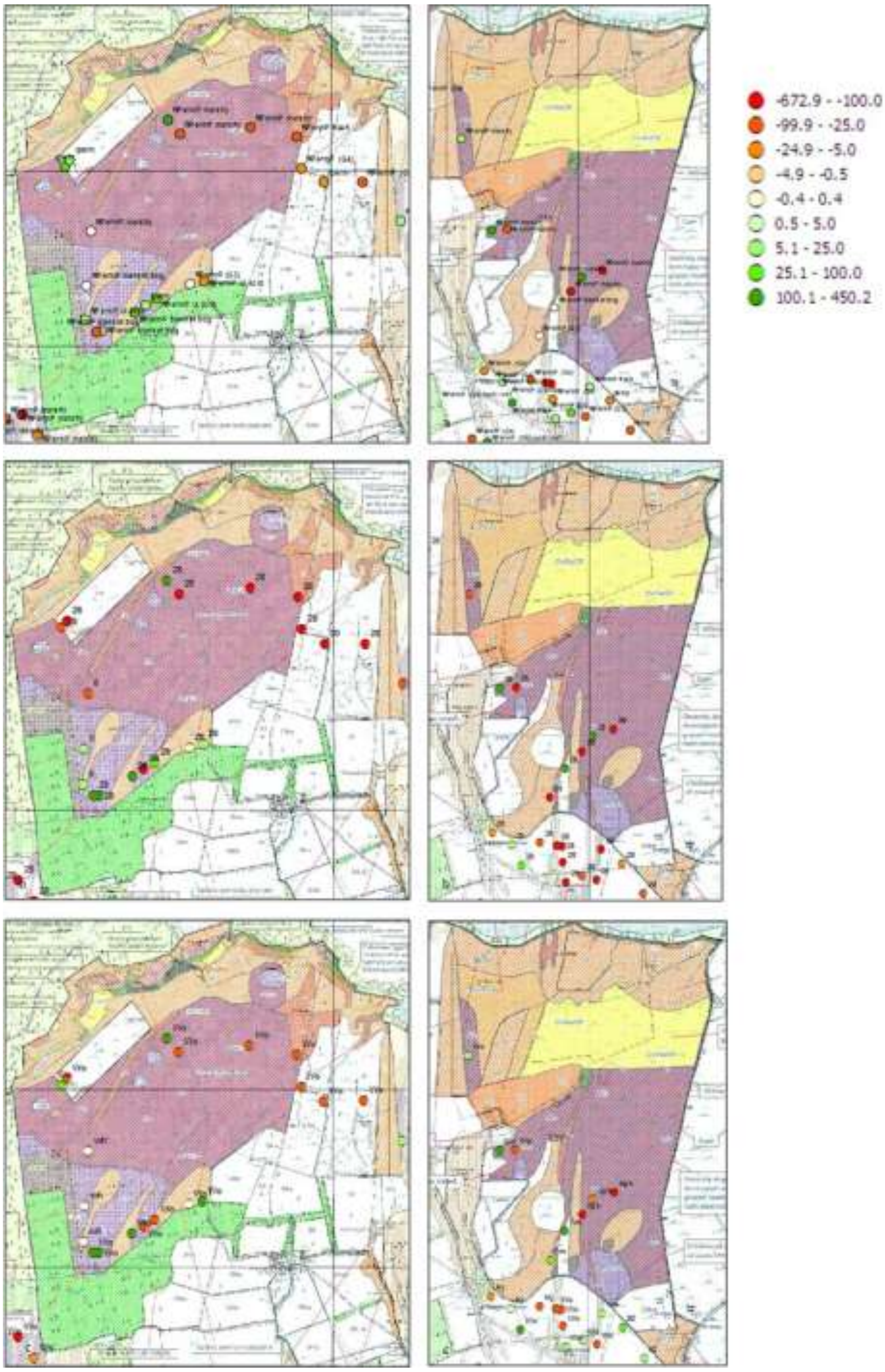


Figure GR1.

a) SOC (t C ha^{-1} eq to 20 cm) of individual sample sites within the tenancy relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the given land use of the Wallington Estate.

b) SOC (t C ha^{-1} eq to 20 cm) relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the whole Wallington Estate.

c) SOC (t C ha^{-1} eq to 20 cm) relative to the projected mean SOC (t C ha^{-1} eq to 20 cm) of the NSRI UK soil series

5.11.3. Priority areas

The priority areas are summarised in Figure 3. Areas of highest priority are labelled Priority 1 then follow in descending order of importance.

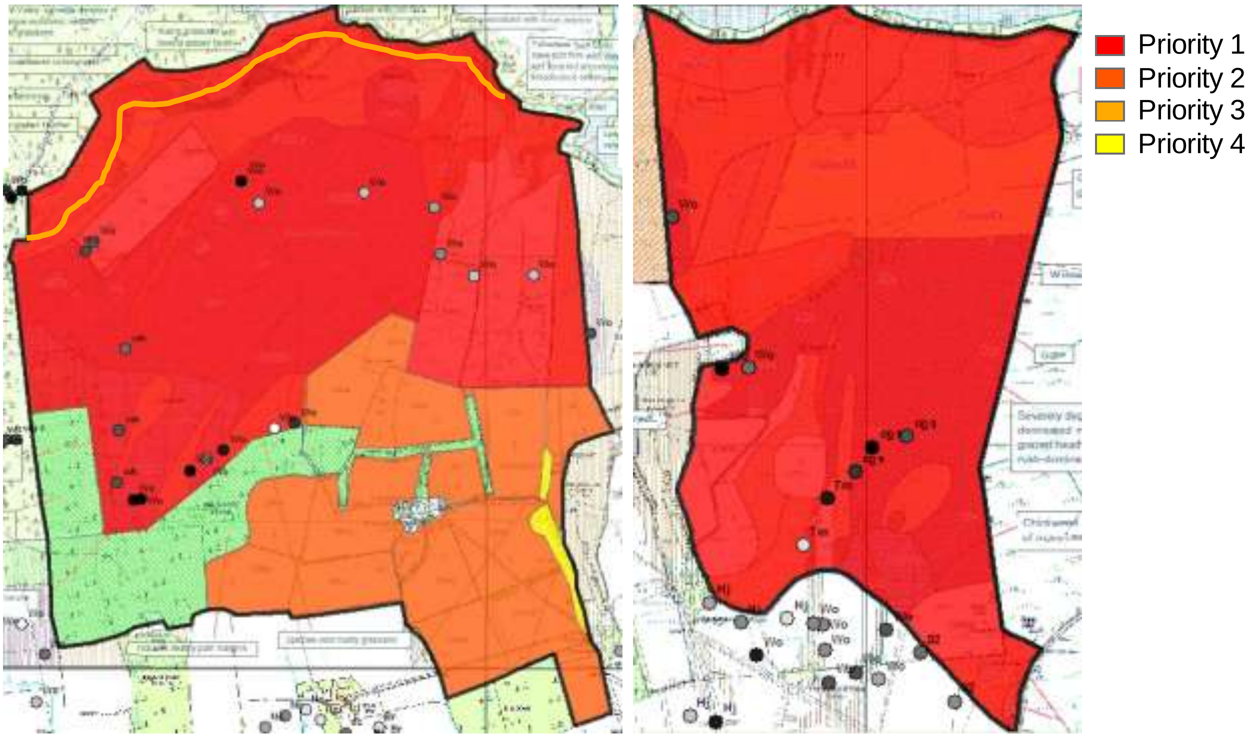


Figure GL3. Priority areas identified on Greenleighton.

1. Priority soil series cgs, K, Tm, wh and Wo. Priority habitat blanket bog, flush, mire and unimproved acid grassland Marshy grassland and semi-improved acid grassland on high priority soil series indicative of degraded moorland habitat. Marshy grassland to the north SOC of series Wo mainly below the mean for marshy grassland on the estate and below the UK mean for series Wo. ItempP (not sampled) bisects area of blanket bog and marshy grassland.
2. Probable high priority soil series Wo (area not sampled). Current land use IpermP and ItempP, restoration of moorland carries a moderate to high displacement risk in this area.
3. Priority habitat watercourse. Prevention of stock access with fencing / maintenance of existing fencing to reduce risk of erosion and compaction.
4. Priority habitat calcareous grassland / neutral grassland. Restoration as necessary to increase species richness.

5.11.4. HLS Options

Options for much of the tenancy are related to moorland although agriculturally improved areas include improved permanent pasture and rough permanent pasture. Areas of broadleaved woodland exist on the periphery however the additional planting of woodland has not been recommended because of the high SOC on much of the site. Table GL3 summarises by priority area (in descending order 1 to 4) options with the potential to have the greatest impact.

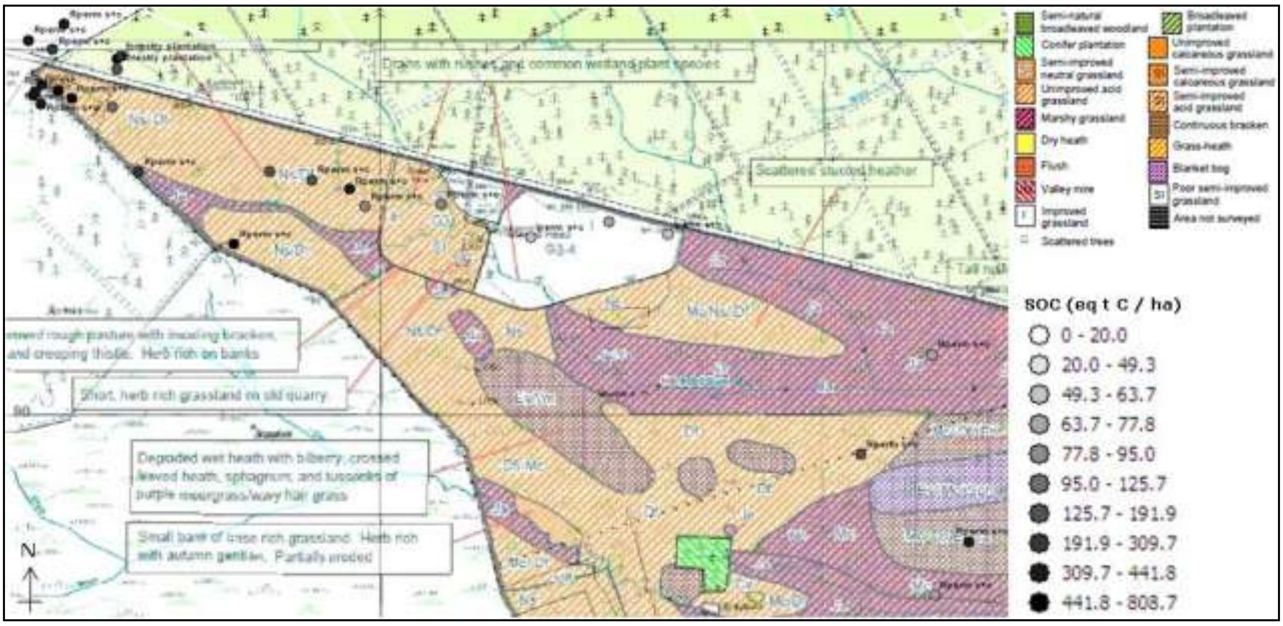
Table GL3. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of priority HLS options for implementation in areas specified in Figure GL1.

	Code / Option		Dis^p Risk	ha	SOC	Bio^mas	Σ	SOC	Bio^mas	Σ
					10 years			20 years		
1	HL10	Restoration of moorland	low	475.0	443.3	0	443.3	1076.6	0	1076.6
1	HL15	Seasonal livestock exclusion supplement	low		Facilitates option HL10					
2	HL10	Restoration of moorland	mod-high	106.3	99.2	0	99.2	240.8	0	240.8
2	HL15	Seasonal livestock exclusion supplement	mod-high		Facilitates option HL10					
3	HJ11	Maintenance of watercourse fencing	mod	2870m	0.3	0.9	1.2	0.6	0.9	1.5
4	HK7	Restoration of species-rich, semi-natural grassland	low	3.1	1.7	2.5	4.1	3.3	2.5	5.8

Dis^p Risk: Displacement Risk
ha: estimated area (ha) where option may be implemented
Σ: Total increase in C

5.12. Harwood Head

5.12.1. Site description



This tenancy is mainly moorland with areas of wet heath (M15, *Trichophorum cespitosus - Erica tetralix*), local patches of blanket mire, marshy grassland (M23a, *Juncus effuses / acutiflorus-Galium palustre* rush-pasture, *Juncus acutiflorus* sub-community), and unimproved acid grassland. A number of sites are in locations just outside the area covered by the Biological Survey (1999). Most sample sites are concentrated in the north-westerly tip where the SOC is generally higher than most other tenancies. The NVC community M15 is indicative of generally acidic and nutrient-poor peats, and peaty mineral soils both of which are C rich. Local increases in peat depth are indicated where the vegetation grades from wet heath to mire. Community M23a indicates moist moderately acidic to neutral peaty and mineral soils. Previous drainage has dried out some areas of wet C rich habitats, overgrazing with cattle may have caused poaching and erosion. The area is currently undergoing restoration.

5.12.2. Baseline carbon

The mean SOC for each soil series and land use relative to the mean for the soil series and land use for the Wallington Estate is given in Tables HH1 and HH2. The SOC for individual sample sites relative to the mean for soil series and land use, and soil series overall for the Wallington Estate are displayed in Figures HH1a and HH1b respectively. The SOC for individual sample sites relative to the NSRI UK mean for soil series is given in Figure HH1c.

Table HH1. Mean SOC for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / -	Max SOC tenancy	Max SOC estate	Max SOC estate <1.5
IpermP	K	49.9	49.9	0.0	49.9	49.9	
	wh	66.4	66.4	0.0	66.4	66.4	
	Wo	59.0	79.9	-20.9	59.0	165.7	

No colour if within + or –0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

Table HH2. Mean SOC with values in excess of 1.5 greater than the mean removed for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / - (<1.5)	Max SOC tenancy	Max SOC estate
IpermP	Wo	59.0	73.3	-14.3	59.0	117.7

No colour if within + or –0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

- Priority habitats: wet heath and unimproved acid grassland sample sites dominated by priority soil series Wo with some Wh and K. Marshy grassland to the east mainly series K. Although above the UK mean the SOC of series Wo on wet heath is subject to large spatial variability in close proximity.
- IpermP: single sample site for three soil series, K and wh (peat) that is only present on IpermP on this tenancy, Wo is below the mean for the estate. All three are listed as high priority soil series, wh in particular; restoration of priority habitat on this field would be preferable since the degradation of high SOC soil series appears to have occurred although there is potential for the restoration in the long term of high SOC. Sheep are grazed for 12 months and the field accommodates those sheep removed from the priority habitats described previously (and so contributes to the preservation of high SOC elsewhere on the tenancy) but substitution of a lower priority soil series for use as IpermP would be preferable.

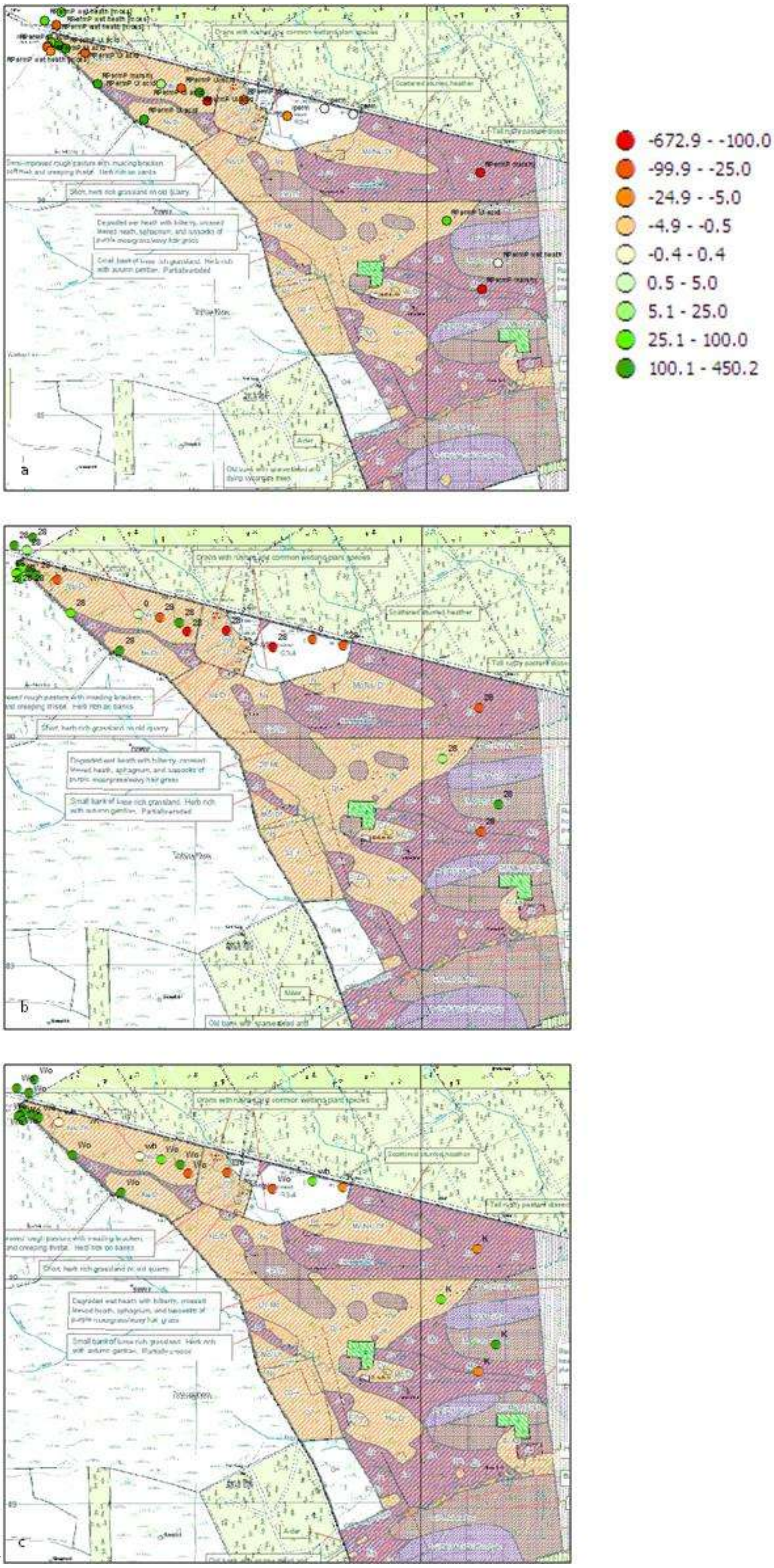


Figure HH1.

a) SOC (t C ha^{-1} eq to 20 cm) of individual sample sites within the tenancy relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the given land use of the Wallington Estate.

b) SOC (t C ha^{-1} eq to 20 cm) relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the whole Wallington Estate.

c) SOC (t C ha-1 eq to 20 cm) relative to the projected mean SOC (t C ha-1 eq to 20 cm) of the NSRI UK soil series

5.12.3. Priority areas

The priority areas are summarised in Figure HH3. Areas of highest priority are labelled Priority 1 then follow in descending order of importance.

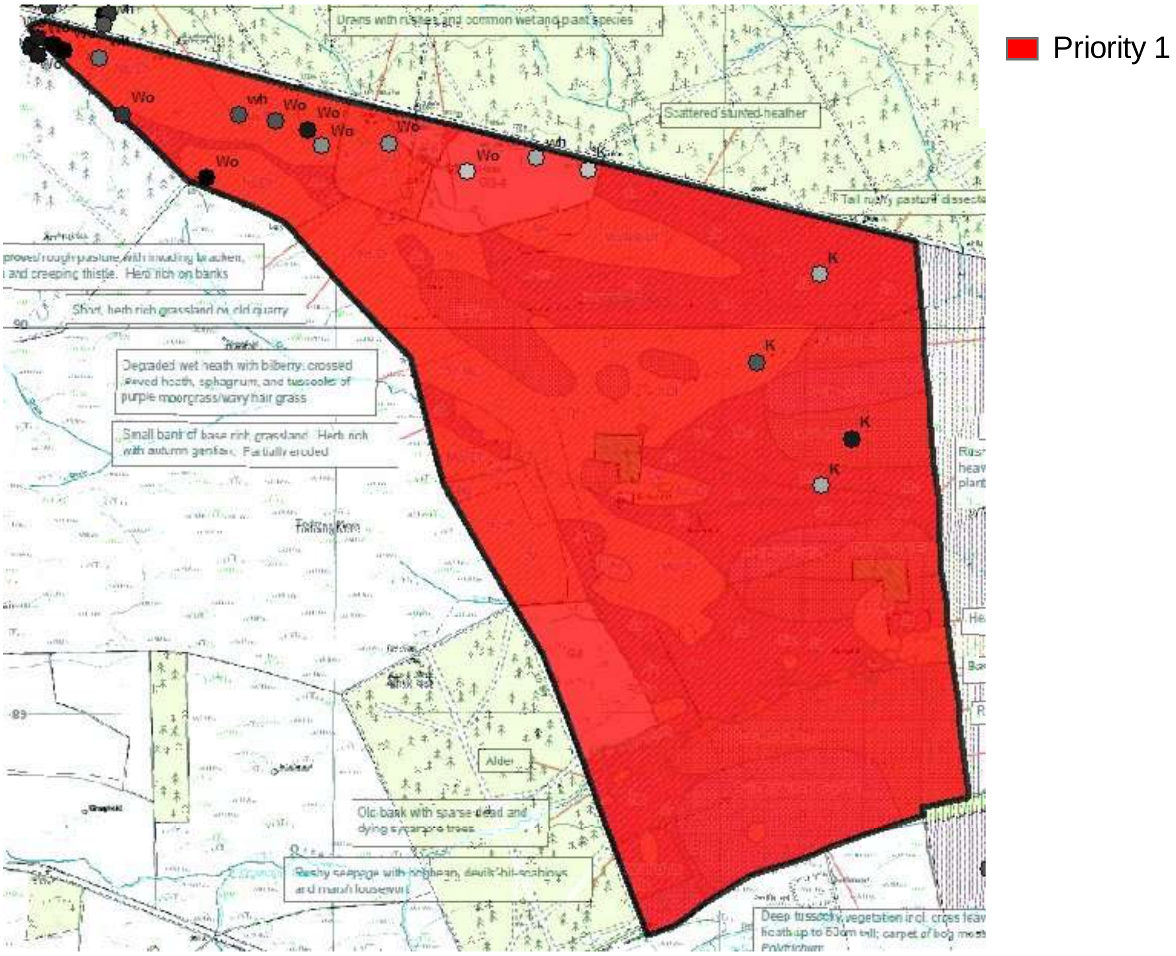


Figure HH3. Priority areas identified on Harwood Head.

1. Priority habitat blanket bog / unimproved acid grassland / wet heath. High priority soil series K, wh and Wo. Marshy grassland on high priority soil series indicative of degraded priority moorland habitat. The Biological Survey (1999) identifies management should aim to create 'a mosaic of moorland communities dominated by wet heath, grading where natural drainage dictates to mire and drier heathland communities with grasslands and marshy communities in places which are naturally less acidic'. Restoration of original wet heath habitats and mire would be conducive with the preservation and restoration of the habitats with the largest and deepest SOC. Series Wo on unimproved acid grassland has the highest consistent SOC for this land use on the tenancy and the SOC of most sample sites are above the UK mean. The area is grazed by both sheep (May – July) and cattle (July – August) but not simultaneously and at low stocking rates (0.2 LU ha^{-1}

maximum). This would appear to be an effective stocking calendar for this land use and soil series relative to other grazing management on the Wallington Estate. The restoration has been ongoing for several years and from the perspective of increasing SOC for the series Wo, appears to have been successful (although the original baseline SOC pre restoration is unknown). Options that specify maintenance and restoration of moorland should be implemented as appropriate. Field of IPermP to the north contains wh (peat) and Wo and should preferably be restored to moorland habitat. Stock grazed in this area (during closed periods on the moorland area) would be preferably grazed on non high priority soil series on the Fairnley tenancy. Field of IpermP to the south-west not sampled but probable priority soil series. Restoration of moorland recommended. During non grazing periods stock it would be preferable to be grazed on non high priority soil series on the Fairnley tenancy.

5.11.4. HLS Options

Table HH3 summarises by priority area options with the potential to have the greatest impact.

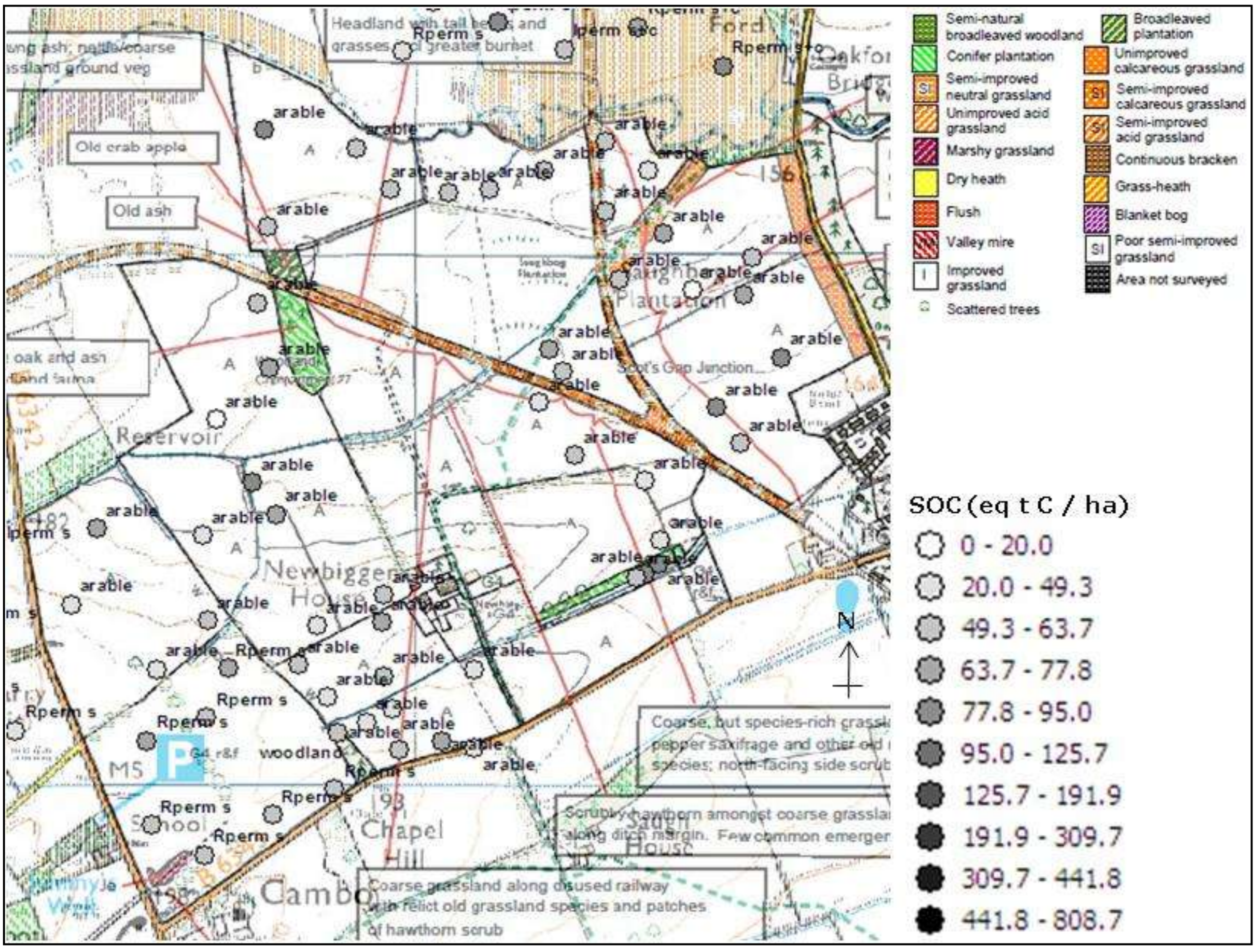
Table HH3. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of priority HLS options for implementation in areas specified in Figure HH1.

	Code / Option		Dis^{p} Risk	ha	SOC	Bio^{mas}	Σ	SOC	Bio^{mas}	Σ
					10 years			20 years		
1	HL10	Restoration of moorland	low	240.5	224.5	0	224.5	545.1	0	545.1
1	HL15	Seasonal livestock exclusion supplement	low		Facilitates option HL10					

Dis^{p} Risk: Displacement Risk
ha: estimated area (ha) where option may be implemented
Σ: Total increase in C

5.13. Newbiggin

5.13.1. Site description



A predominantly arable tenancy with an area of rough permanent pasture grazed by sheep to the south-west. Features of interest (Biological Survey, 1999) includes mature trees, 10-20 m wide strips of unimproved neutral grassland with vegetation characteristic of 'old meadow' to the east (MG1 coarse grassland), and relict ancient woodland. A small area of marshy grassland is present in the south-west corner.

5.13.2. Baseline carbon

The mean SOC for each soil series and land use relative to the mean for the soil series and land use for the Wallington Estate is given in Tables NB1 and NB2. The SOC for individual sample sites relative to the mean for soil series and land use, and soil series overall for the Wallington Estate are displayed in Figures NB1a and NB1b respectively. The SOC for individual sample sites relative to the NSRI UK mean for soil series is given in Figure NB1c.

Table NB1. Mean SOC for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / -	Max SOC tenancy	Max SOC estate	Max SOC estate <1.5
Arable	Br	58.7	51.7	7.0	71.4	71.4	71.4
	Dk	59.3	58.2	1.2	82.1	82.1	68.6
	Eo	65.6	57.3	8.3	79.2	79.2	79.2
	gJ	57.7	57.7	0.0	88.7	88.7	88.7
	tL	46.9	46.9	0.0	67.9	67.9	67.9
RpermP	Hj	53.4	82.3	-28.9	59.3	314.7	59.3
	tL	64.3	64.3	0.0	67.2	67.2	67.2

No colour if within + or –0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

Table NB2. Mean SOC with values in excess of 1.5 greater than the mean removed for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / -	Max SOC tenancy	Max SOC estate
RpermP	Hj	53.4	62.9	-9.5	59.3	59.3

No colour if within + or –0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

- Arable: SOC above the mean for the estate and land use for series Br, Dk and Eo; two year grass / clover ley per 4 year rotation and residues incorporated (not required for cattle bedding and no temporary grassland to which to apply FYM). Dominance of samples above or below the mean dependent on individual fields, several a mixture of both highlighting within field spatial variation; arable fields to the north SOC mainly below the mean. Maximum SOC for arable land of the five soil series on the estate are present on this tenancy suggesting arable land is close to its maximum equilibrium for this land use.

- RpermP: SOC for priority series Hj below the mean, samples within field to the south of the tenancy consistently below the mean suggesting degraded soil conditions.

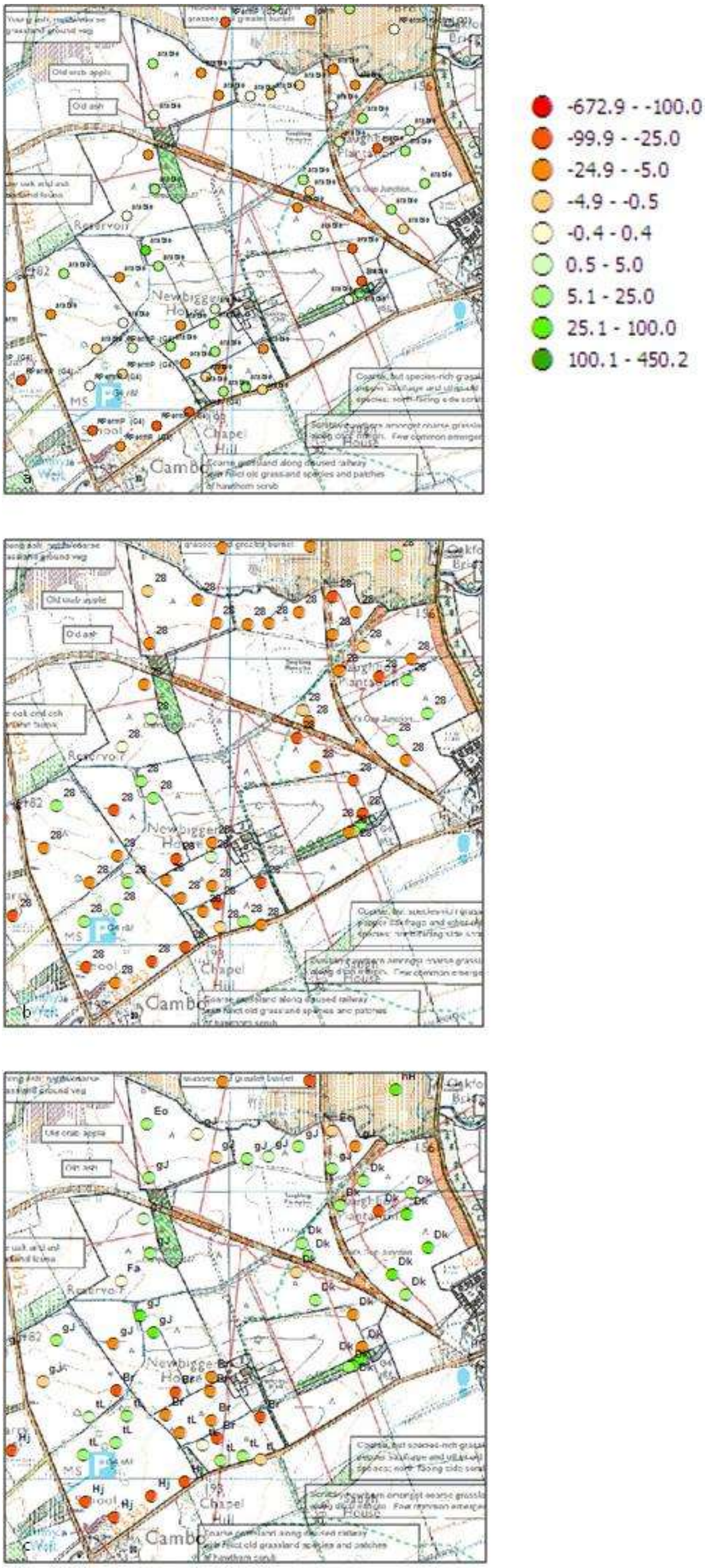


Figure NB1.

a) SOC (t C ha^{-1} eq to 20 cm) of individual sample sites within the tenancy relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the given land use of the Wallington Estate.

b) SOC (t C ha^{-1} eq to 20 cm) relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the whole Wallington Estate.

c) SOC (t C ha-1 eq to 20 cm) relative to the projected mean SOC (t C ha^{-1} eq to 20 cm) of the NSRI UK soil series.

5.12.3. Priority areas

The priority areas are summarised in Figure NB3. Areas of highest priority are labelled Priority 1 then follow in descending order of importance.

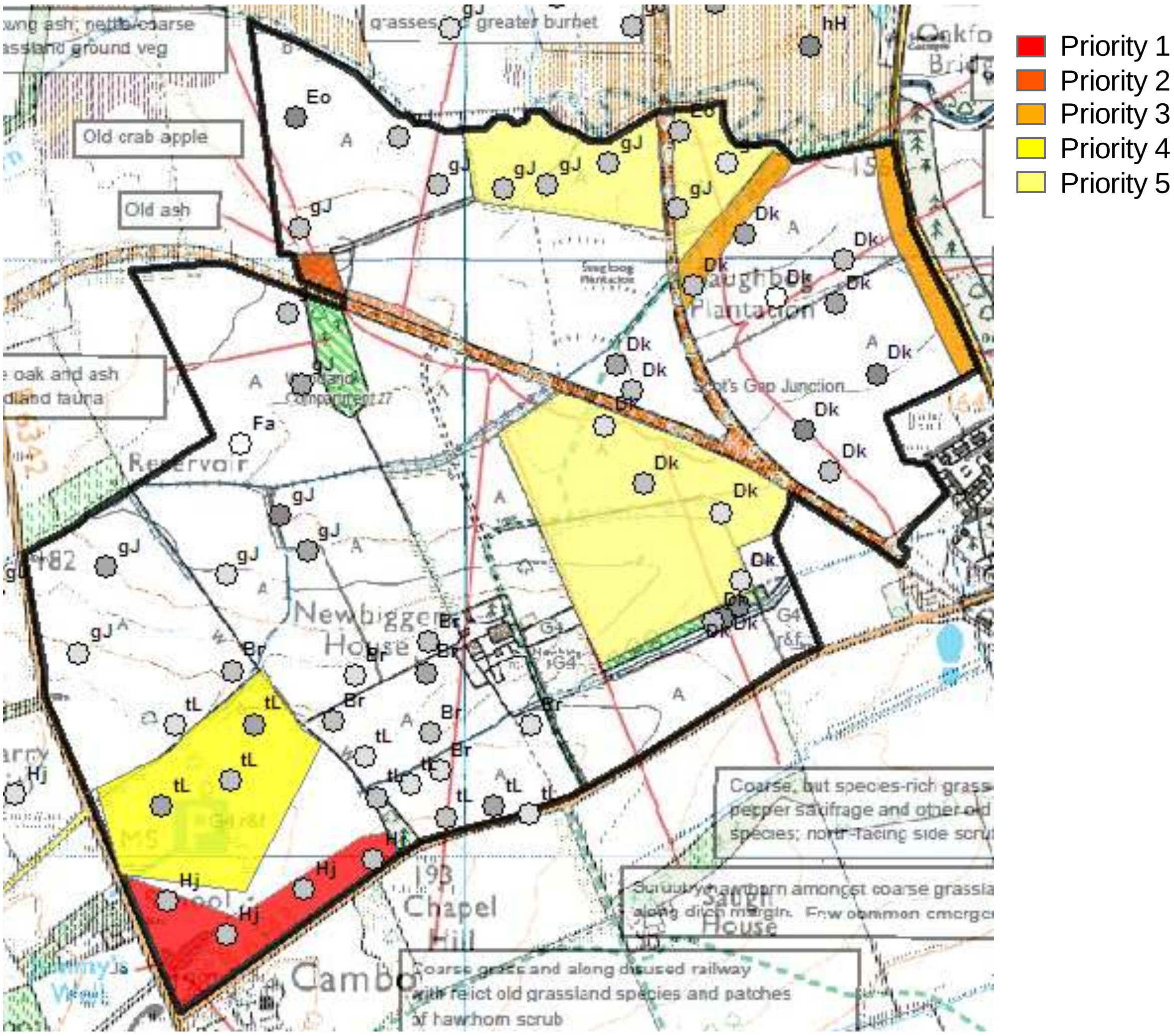


Figure NB3. Priority areas identified on Newbiggin Farm.

1. Priority soil series Hj. Area of marshy grassland along southern edge to be extended within the area indicated as far as possible. Seasonal removal of stock during the winter.
2. Priority habitat broadleaved woodland on non-high priority soil series. Occasional mature oak and young ash stand, maintenance and restoration as necessary.
3. Priority habitat calcareous grassland. Restoration as required to improve species diversity, also recommended by the Biological Survey (1999).
4. Restoration / creation of wood pasture where non priority soil series on RPermP. These options would extend the area of existing old ash trees within field and in

the field boundary and be conducive with new planting recommended in this area by the Biological Survey (1999). Alternatively, silvipasture may be trialled in this area.

5. Areas of low SOC on arable land and soil series at Wallington, soil series overall and relative to the UK. Although mainly arable, the presence of livestock offers the opportunity to create and graze grass leys that reduce tillage frequency and is already undertaken on the tenancy. HLS options that may improve it are limited to the establishment of winter cover between harvest of the second winter oats crop and sowing the grass/clover ley in the spring (1 year in 4). The mean SOC for the tenancy is roughly 15 t C ha^{-1} lower than the maximum sample value for each series and would suggest potential to increase SOC further. The use of winter cover crops to avoid bare soil before the spring sowing of clover leys is recommended.

5.12.4. HLS Options

Table NB3 summarises by priority area (in descending order 1 to 5) options with the potential to have the greatest impact.

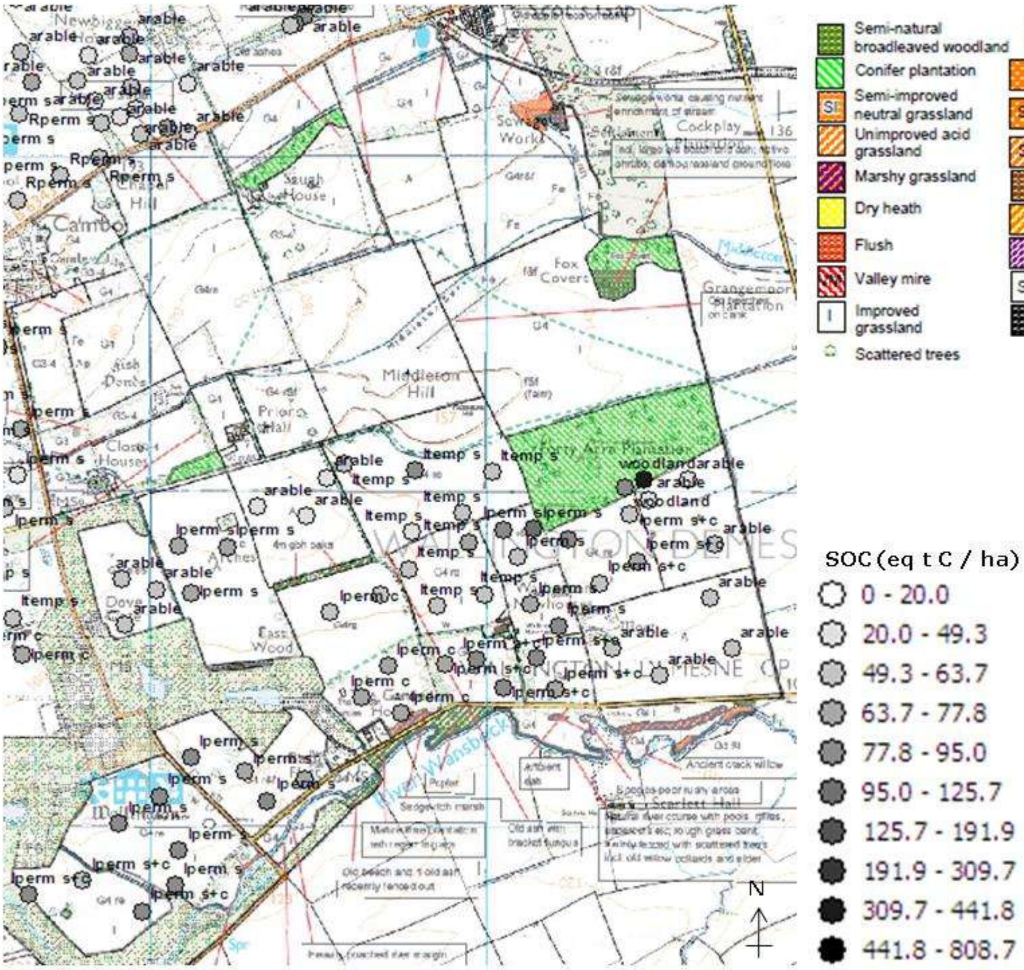
Table NB3. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of priority HLS options for implementation in areas specified in Figure NB1.

	Code / Option		Dis^{p} Risk	ha	SOC	Bio^{mas}	Σ	SOC	Bio^{mas}	Σ
					10 years			20 years		
1	HK19	Raised water levels (lowland grassland)	low	4.5	23.8	0.9	24.7	47.7	0.9	48.6
2	HJ7	Seasonal livestock removal on grassland with no input restriction	low	4.5	1.5	0	1.5	3.0	0	3.0
2	HC8	Restoration of woodland	low	0.4	0.02	1.1	1.1	0.04	2.1	2.2
3	HK7	Restoration of species-rich, semi-natural grassland	low	2.8	1.5	2.2	3.7	2.9	2.2	5.1
4	HC13	Restoration of wood pasture and parkland	low	7.9	4.2	26.7	30.9	4.2	48.9	53.1
5	HJ13	Winter cover crop	low	19.8	18.1	0	18.1	36.2	0	36.2

Dis^{p} Risk: Displacement Risk
ha: estimated area (ha) where option may be implemented
Σ: Total increase in C

5.14. Prior Hall

5.14.1. Site description



A mixed farm consisting of arable, improved permanent grassland grazed by sheep and sheep and cattle, and temporary pasture grazed by sheep. A number of conifer plantations are present, and a small area of semi-natural broadleaved woodland. A large number of field boundary trees are identified as a key feature of interest by the Biological Survey (1999), and areas characteristic of wood pasture. To the south-east is an area of poorly draining marshy grassland. The river banks are highlighted as being at risk to erosion, accelerated livestock access.

5.14.2. Baseline carbon

The mean SOC for each soil series and land use relative to the mean for the soil series and land use for the Wallington Estate is given in Tables PH1 and PH2. The SOC for individual sample sites relative to the mean for soil series and land use, and soil series overall for the Wallington Estate are displayed in Figures PH1a and PH1b respectively. The SOC for individual sample sites relative to the NSRI UK mean for soil series is given in Figure PH1c.

Table PH1. Mean SOC for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / -	Max SOC tenancy	Max SOC estate	Max SOC estate <1.5
Arable	Br	48.8	51.7	-2.9	60.6	71.4	71.4
	Dk	48.3	82.1	-33.8	48.4	82.1	82.1
	Nc	59.8	51.6	8.2	62.2	68.6	68.6
ItempP	Br	77.0	64.8	12.2	90.4	176.1	96.9
	Dk	55.2	64.7	-14.6	67.0	86.4	86.4
IpermP	Br	67.1	70.8	-3.7	75.4	138.7	97.3
	Dk	79.1	79.1	0.0	98.8	98.8	98.8
	gJ	78.8	70.0	8.8	93.1	102.5	102.5
	Nc	80.7	75.1	5.5	94.4	132.5	98.2

No colour if within + or –0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

Table PH2. Mean SOC with values in excess of 1.5 greater than the mean removed for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / -	Max SOC tenancy	Max SOC estate
Arable	Br	48.8	51.7	-2.9	60.6	71.4
	Dk	48.3	82.1	-33.8	48.4	82.1
	Nc	59.8	51.6	8.2	62.2	68.6
ItempP	Br	77.0	58.8	18.2	90.4	96.9
	Nc	55.2	69.8	-14.6	67.0	86.4
IpermP	Br	67.1	68.2	-1.1	75.4	97.3
	Dk	79.1	79.1	0.0	98.8	98.8
	gJ	78.8	70.0	8.8	93.1	102.5
	Nc	80.7	73.7	7.0	94.4	98.2

No colour if within + or –0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

- Arable: below the estate mean for this land use for series Br and Dk; individual fields containing series Br to the north one with samples above the mean, one below the mean suggesting difference in management practice at the field level; a 3 or 5 year grass ley has been used previously as an alternative to a winter oilseed rape break crop on those fields with above mean SOC (i.e. not all individual fields have had the same rotation history).
- ItempP: series Br above the estate mean for this land use although limited to two sample sites and skewed by a single site with high SOC, series Dk below the mean overall although over 50% of individual sample sites are above the mean; not reseeded in the past 18 years.
- IpermP: SOC of series Nc is above the mean for the estate and land use overall however variation exists between fields; above the mean on two fields below on the other. The main difference in management practice at the time of sampling was the field with SOC below the mean grazed by cattle only, the other by sheep (lower SOC may be due to soil compaction although the Nc series has been classed as low compaction risk).

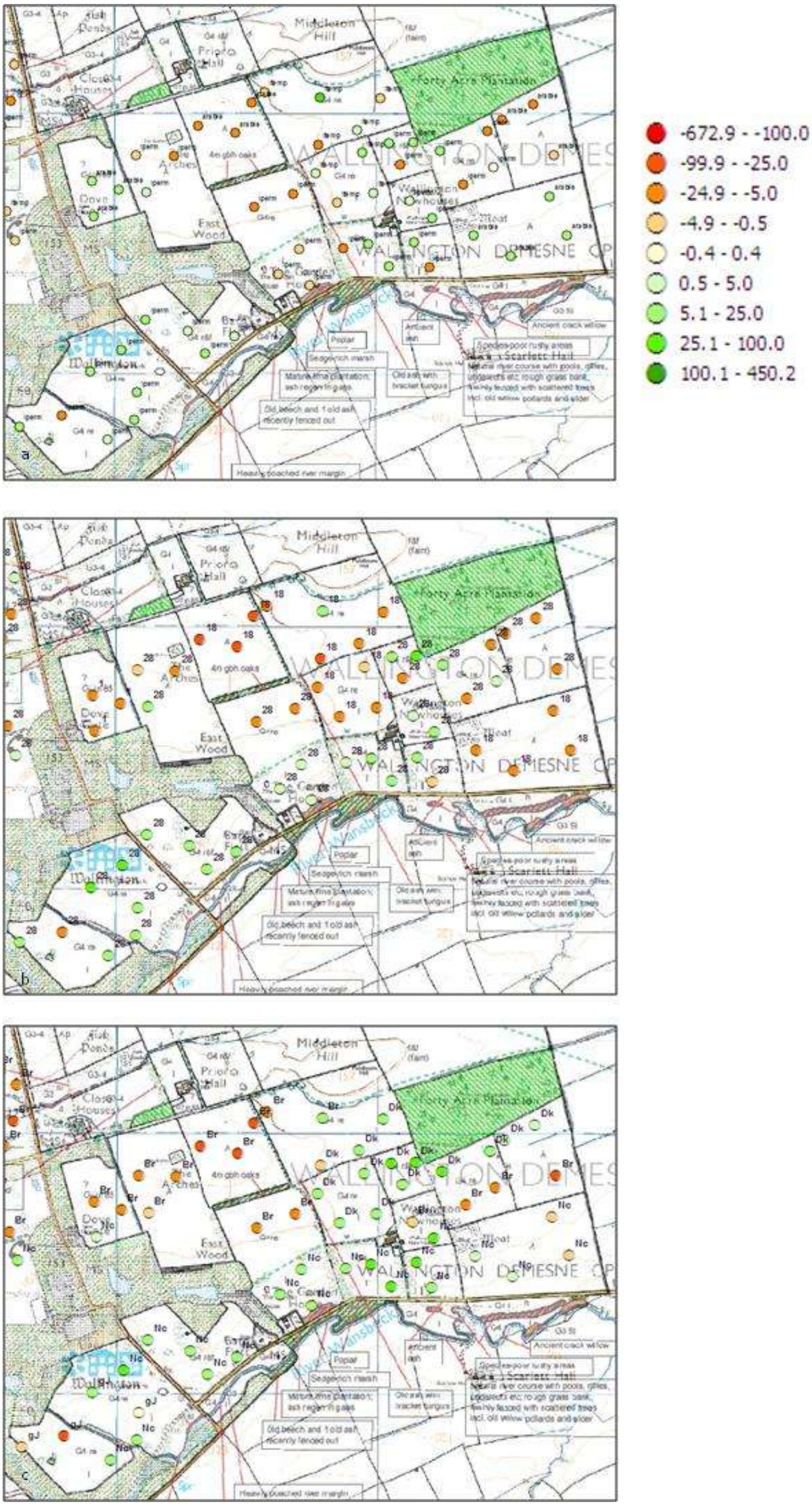


Figure PH1.

a) SOC (t C ha^{-1} eq to 20 cm) of individual sample sites within the tenancy relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the given land use of the Wallington Estate.

b) SOC (t C ha^{-1} eq to 20 cm) relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the whole Wallington Estate.

c) SOC (t C ha^{-1} eq to 20 cm) relative to the projected mean SOC (t C ha^{-1} eq to 20 cm) of the NSRI UK soil series.

5.14.3. Priority areas

The priority areas are summarised in Figure 3. Areas of highest priority are labelled Priority 1 then follow in descending order of importance.

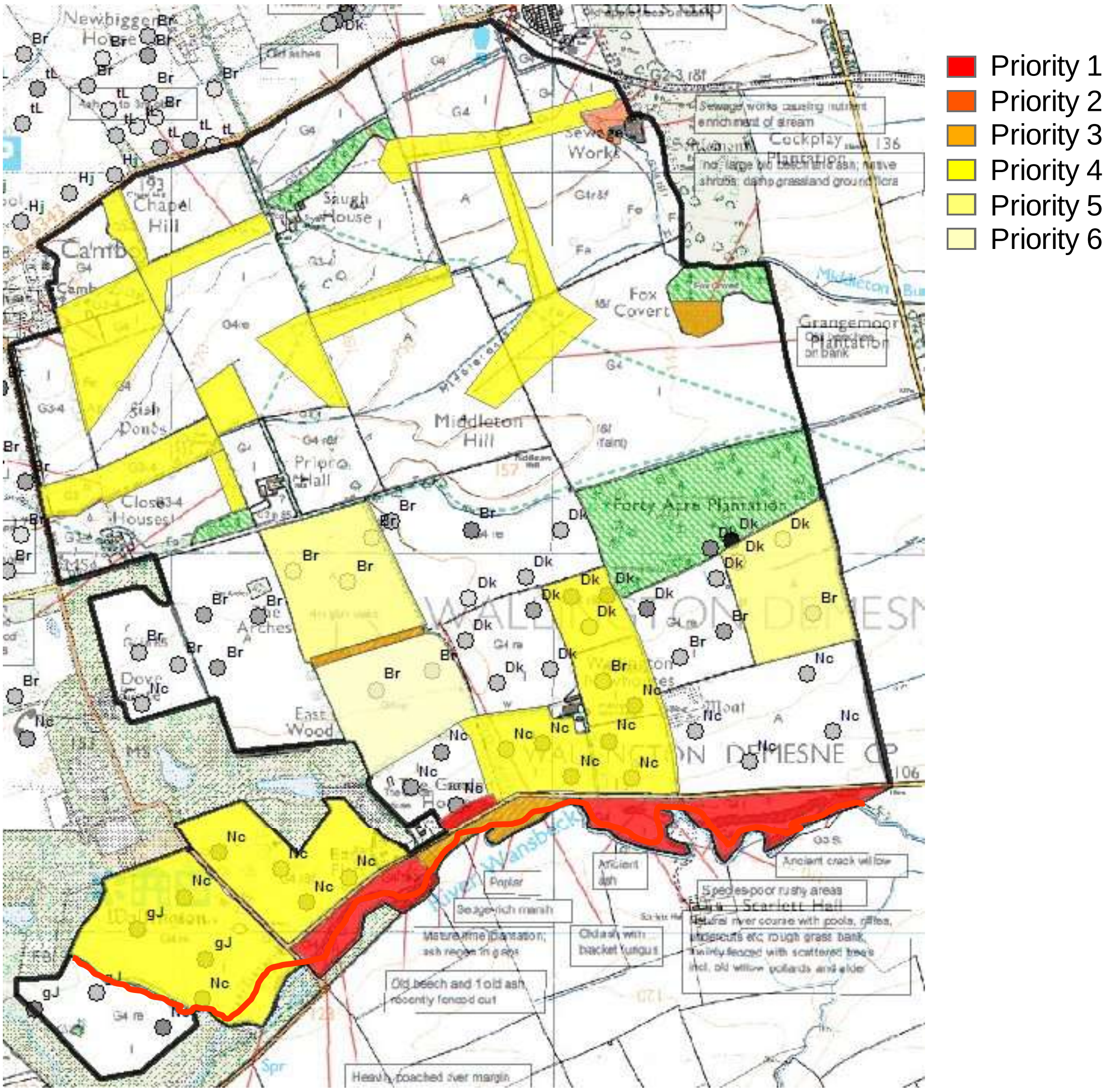


Figure PH3. Priority areas identified on Prior Hall farm.

The fields to the north of the tenancy are not sampled and therefore the soil series and SOC is unknown. Options have been recommended in these areas based on the presence of, or potential for restoration of priority habitats on assumed non high priority soil series.

1. Priority habitat marshy grassland on non high priority soil series to the south of the tenancy with potential expansion as practicable, forming a buffer zone around

priority watercourse habitat. They would benefit from seasonal livestock removal during the winter.

2. Priority habitat watercourse. Prevention of livestock access as necessary to reduce erosion and compaction.
3. Priority habitat broadleaved woodland on non high priority soil series. Represents a small area on the tenancy. Maintenance or restoration as required, option Maintenance of woodland is recommended at the interface where woodland is adjacent to cultivated land (northern length of the strip in the central eastern part of the tenancy).
4. Potential to restore / create priority habitat wood pasture incorporating the large numbers of mature trees in the boundary and within field areas. There is potential to extend these areas with new plantings.
5. Low SOC on cultivated land. Below the estate mean for this land use for series Br and Dk; individual fields containing series Br to the north one with samples above the mean, one below the mean suggesting difference in management practice at the field level; a 3 or 5 year grass ley has been used previously as an alternative to a winter oilseed rape break crop on those fields with above mean SOC (i.e. not all individual fields have had the same rotation history). The inclusion of a grass / clover ley is recommended on fields within priority 5.
6. Low SOC on IPermP. This field is listed in the Biological Survey (1999) as being temporary grassland and will have been cultivated in the past. The conversion to permanent grassland will have allowed an increase in SOC, the rate of which may be enhanced by removal of stock during the winter or trialling of silvipasture.

5.14.4. HLS Options

The options on marshy grassland, unimproved acid grassland, watercourses, improved temporary grassland, improved permanent grassland outside SDAs and boundary features are applicable. Table PH3 summarises by priority area (in descending order 1 to 6) options with the potential to have the greatest impact.

Table PH3. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of priority HLS options for implementation in areas specified in Figure PH1.

	Code / Option		Dis^p Risk	ha	SOC	Bio^{mas}	Σ	SOC	Bio^{mas}	Σ
					10 years			20 years		
1	HK19	Raised water levels	low	11.1	59.0	118.1	2.2	2.2	61.3	120.3
1	HJ7	Seasonal livestock removal on grassland with no input restriction	low		Facilitates option HK19					
2	HJ11	Maintenance of watercourse fencing	mod	2650m	0.3	0.5	0.8	0.8	1.1	1.4
3	HC8	Restoration of woodland	low	3.0	0.2	0.3	8.3	16.6	8.4	16.9
3	HC4	Maintenance of woodland edges	mod	0.2	1.2	2.4	0.4	0.4	1.6	2.9
4	HC13	Restoration of wood pasture and parkland	high	27.1	14.4	14.4	91.0	166.8	105.4	181.2
6	HJ7	Seasonal livestock removal on grassland with no input restriction	low	9.5	3.2	6.4	0	0	3.2	6.4

Dis^p Risk: Displacement Risk
ha: estimated area (ha) where option may be implemented
Σ: Total increase in C

5.14.5. Non-HLS Options

The potential impact of suggested non HLS options on marshy grassland and cultivated land are summarised in Table PH4. Short rotation coppice assumes harvest every 10 years, the equilibrium for biomass is reached after an average of 5 years.

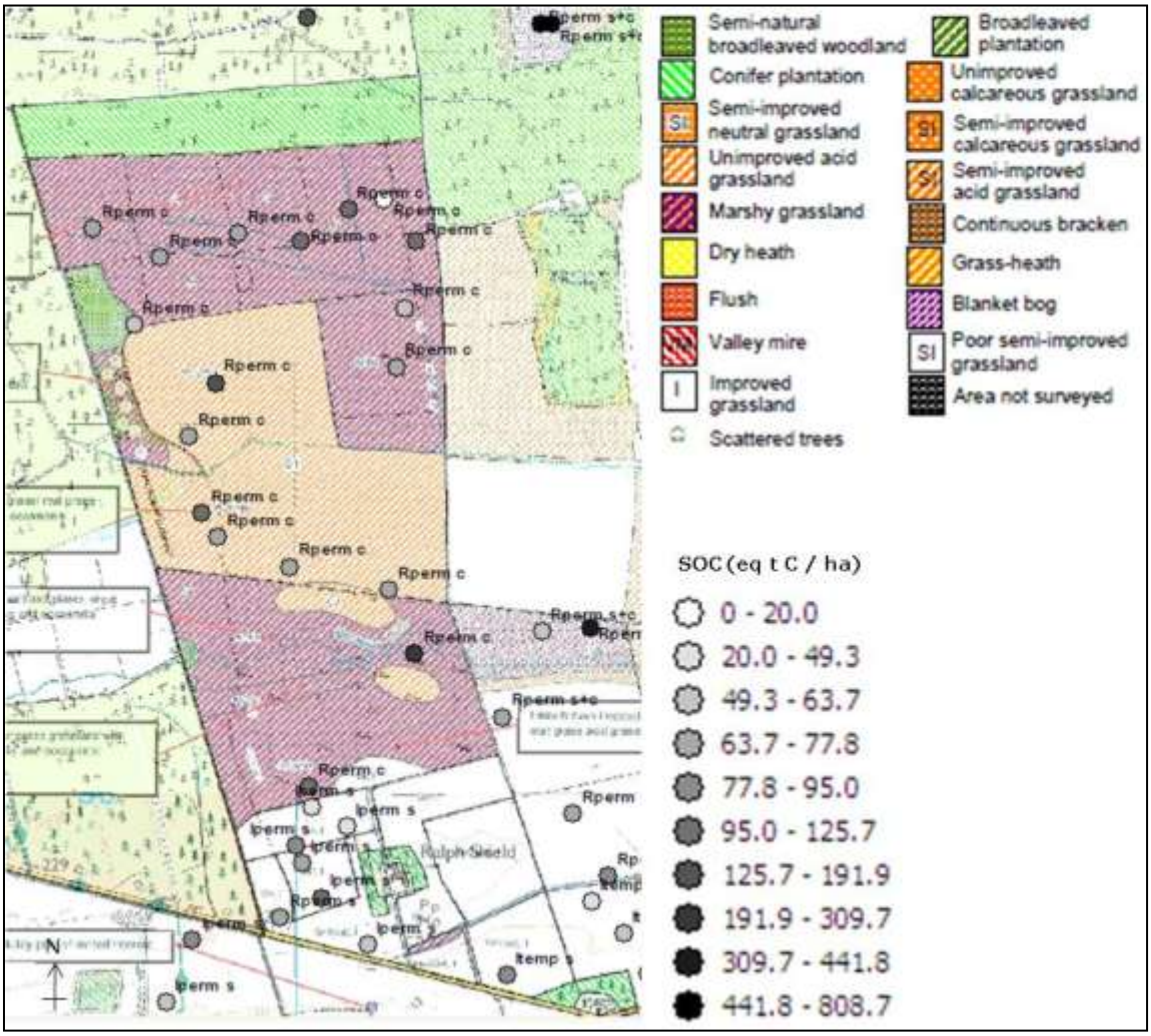
Table PH4. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of potential non HLS options for implementation in areas specified in Figure DH3.

	Option	Dis^p Risk	ha	SOC	Bio^{mas}	Σ	SOC	Bio^{mas}	Σ
				10 years			20 years		
1	Palludiculture	low	11.1	59.0	232.5	291.5	118.1	464.9	583.0
1	Silvipasture	low	9.5	2.5	124.7	127.3	5.0	257.0	262.1

The use of short rotation coppice willow as a biofuel is cited by Smith et al. (2000) to have an additional energy substitution value of 2.1 t C ha^{-1} $year^{-1}$, equivalent to 232 and 465 t C after 10 and 20 years respectively if the marshy grassland areas are fully exploited.

5.15. Ralph Shield

5.15.1. Site description



At the time of sampling the northern area was grazed by cattle (the tenant stated however that they no longer keep cattle), the areas of rough and improved permanent pasture (MG6, *Cynosurus cristatus- Lolium perenne*) adjacent to farm buildings are grazed by sheep. Temporary grassland is located in the south-west corner. The tenancy is dominated by degraded acid moorland to the north (Biological Survey, 1999). Relict old wood pasture is present to the west, with large areas of marshy grassland (M25, *Molinia caerulea - Potentilla erecta* mire) and unimproved acid grassland (U5, *Nardus stricta - Galium saxatile*). The area has been subject to drainage and reseeding operations (Biological Survey, 1999). A large number of drainage ditches were noted in the north-eastern corner extending south-west.

The improved permanent pasture is cut for silage although not annually, it received FYM produced by the cattle grazed on the unimproved areas to the north of the tenancy, but this has been reduced since cattle were taken off the tenancy. It receives small quantities of inorganic NPK. The two sample sites of low SOC are present on areas where vehicle traffic is evident along the edge and / or where livestock movement is frequent (close to gates).

5.15.2. Baseline carbon

The mean SOC for each soil series and land use relative to the mean for the soil series and land use for the Wallington Estate is given in Tables RS1 and RS2. The SOC for individual sample sites relative to the mean for soil series and land use, and soil series overall for the Wallington Estate are displayed in Figures RS1a and RS1b respectively. The SOC for individual sample sites relative to the NSRI UK mean for soil series is given in Figure RS1c.

Table RS1. Mean SOC for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / -	Max SOC tenancy	Max SOC estate	Max SOC estate <1.5
ItempP	gJ	82.3	66.6	15.7	82.3	82.3	82.3
IpermP	Br	82.4	70.8	11.5	107.5	138.7	97.3
	Wo	62.6	79.9	-17.3	82.9	165.7	117.7
RpermP	Br	70.7	78.3	-7.6	70.7	214.2	109.8
	gJ	74.0	74.4	-0.4	88.9	110.7	110.7

No colour if within + or −0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

Table RS2. Mean SOC with values in excess of 1.5 greater than the mean removed for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / - (<1.5)	Max SOC tenancy	Max SOC estate
IpermP	Br	57.2	68.2	-11.0	57.2	97.3
	Wo	62.6	73.3	-10.7	82.9	117.7
RpermP	Br	70.7	69.5	1.2	70.7	109.8

No colour if within + or −0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

- ItempP: series gJ (one site) above the mean for land use; is cut rotationally (may just be grazed during certain years) and received FYM when cattle were grazed on the tenancy (cattle are no longer present), the last reseed date is unknown. For this series and land use the maximum SOC on the estate has been reached.

- IpermP: series Br above the mean for this land use on the estate (two sample points) with scope to increase relative to the maximum, the remainder of samples are high priority series Wo (mainly to the north of the farmhouse directly adjacent to the marshy grassland) that is below the mean for the estate and UK.
- RpermP: Series Br (one sample site) is below the mean for the land use and estate, and the UK.

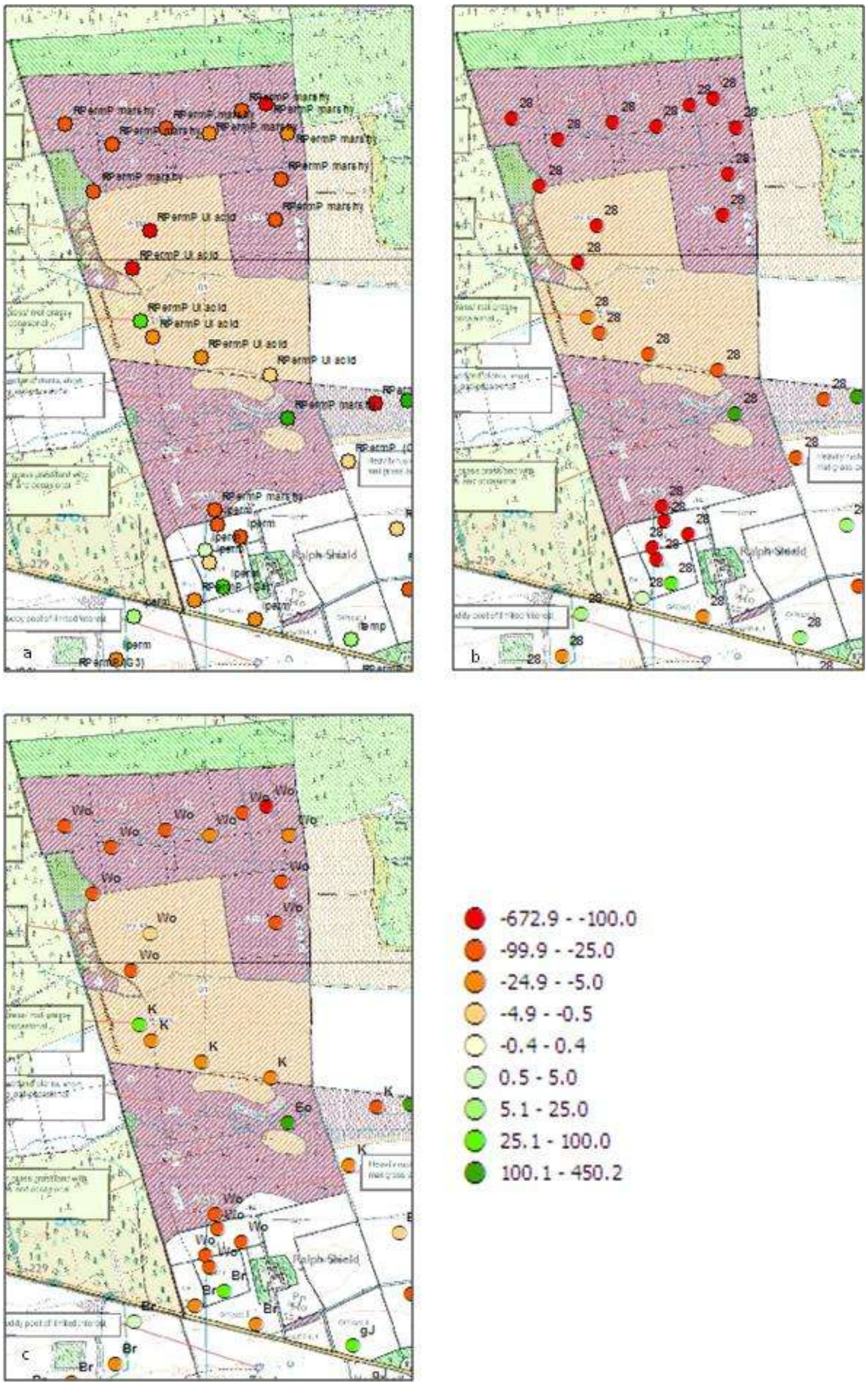


Figure RS1.

a) SOC (t C ha^{-1} eq to 20 cm) of individual sample sites within the tenancy relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the given land use of the Wallington Estate.

b) SOC (t C ha^{-1} eq to 20 cm) relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the whole Wallington Estate.

c) SOC (t C ha^{-1} eq to 20 cm) relative to the projected mean SOC (t C ha^{-1} eq to 20 cm) of the NSRI UK soil series

5.15.3. Priority areas

The priority areas are summarised in Figure RS3. Areas of highest priority are labelled Priority 1 then follow in descending order of importance.

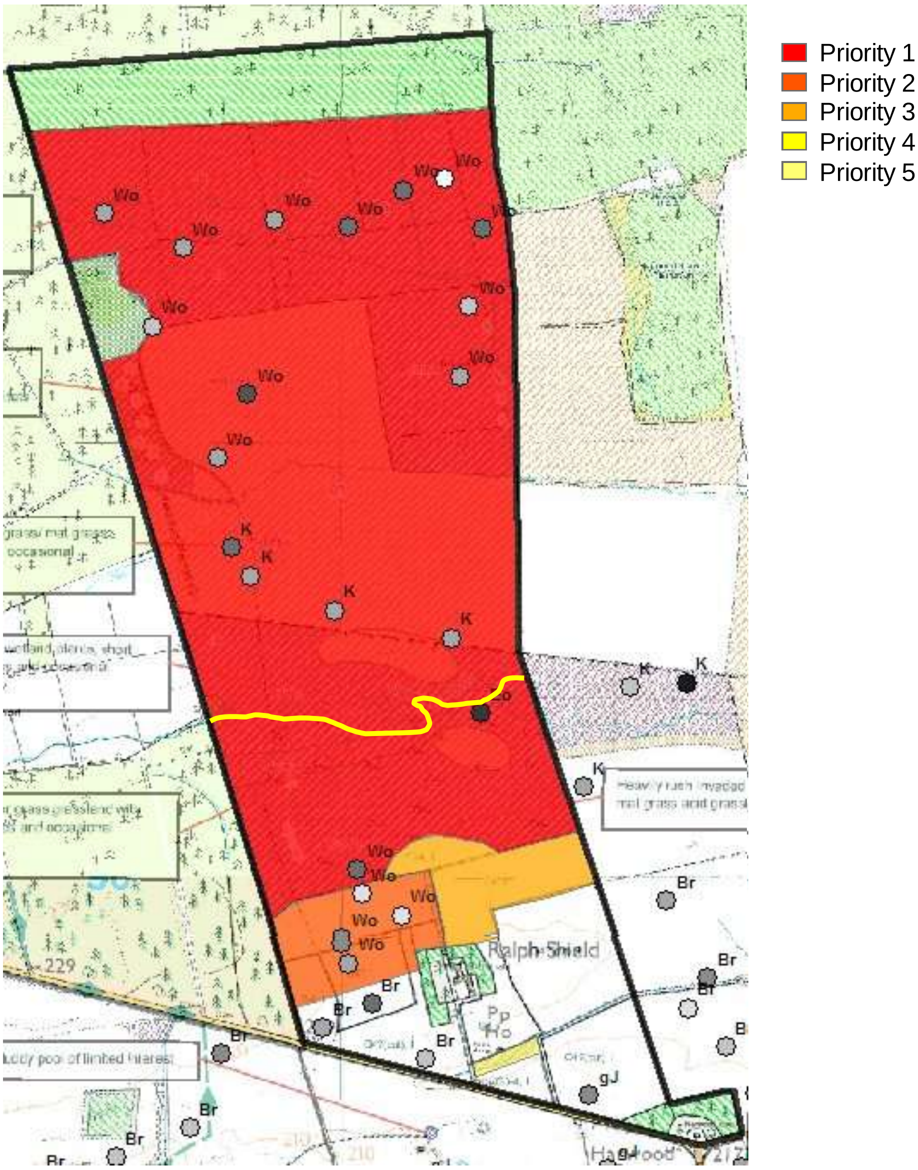


Figure RS3. Priority areas identified on Ralph Shield.

1. High priority soil series K and Wo present on U5 NVC community (degraded moorland). The highest unimproved acid grassland SOC for series Wo is located on Harwood Head and as a consequence the SOC for this land use on this tenancy tends to be lower than average for the estate and land use. Series Wo and K on the unimproved acid grassland and marshy grassland to the north are below the UK mean and restoration of the these degraded moorland habitats offers potential to increase SOC to levels observed at Harwood Head.

2. High priority soil series Wo on IPermP. Restoration of moorland is possible however the area is fenced from the main area and is managed as IPermP. Close proximity to the farmhouse may limit the viability of this option.
3. Probable high priority soil series Wo on IPermP (not sampled). Recommended options the same for priority 2.
4. Priority habitat watercourse. Fencing to prevent stock access as deemed necessary (cattle have been removed from the tenancy, erosion and compaction risk is now lower).
5. Marshy grassland on non high priority soil series. Maintenance of / extension of the marshy area as practicable. This area offers potential for growing short-rotation willow coppice.

5.15.4. HLS Options

The options on marshy grassland, unimproved acid grassland, watercourses, improved temporary grassland, improved permanent grassland outside SDAs and boundary features are applicable. Table RS3 summarises by priority area (in descending order 1 to 5) options with the potential to have the greatest impact.

Table RS3. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of priority HLS options for implementation in areas specified in Figure RS1.

	Code / Option		**Dis^{p} Risk**	**ha**	**SOC**	**Bio^{mas}**	**Σ**	**SOC**	**Bio^{mas}**	**Σ**
					10 years			**20 years**		
1	HL10	Restoration of moorland	low	149.3	139.3	0	139.3	338.3	0	338.3
1	HL15	Seasonal livestock exclusion supplement	low		Facilitates option HL10					
2	HL10	Restoration of moorland	low	7.8	7.3	0	7.3	17.8	0	17.8
2	HL15	Seasonal livestock exclusion supplement	low		Facilitates option HL10					
3	HL10	Restoration of moorland	low	6.7	6.2	0	6.2	15.1	0	15.1
3	HL15	Seasonal livestock exclusion supplement	low		Facilitates option HL10					
4	HJ11	Maintenance of watercourse fencing	mod	971.0	0.1	0.3	0.4	0.2	0.3	0.5
5	HK19	Raised water levels	low	0.5	2.9	0.1	3.0	5.8	0.1	5.9

Dis^{p} Risk: Displacement Risk
ha: estimated area (ha) where option may be implemented
Σ: Total increase in C

5.15.5. Non-HLS Options

The potential impact of suggested non HLS options on marshy grassland and cultivated land are summarised in Table RS4. Short rotation coppice assumes harvest every 10 years, the equilibrium for biomass is reached after an average of 5 years.

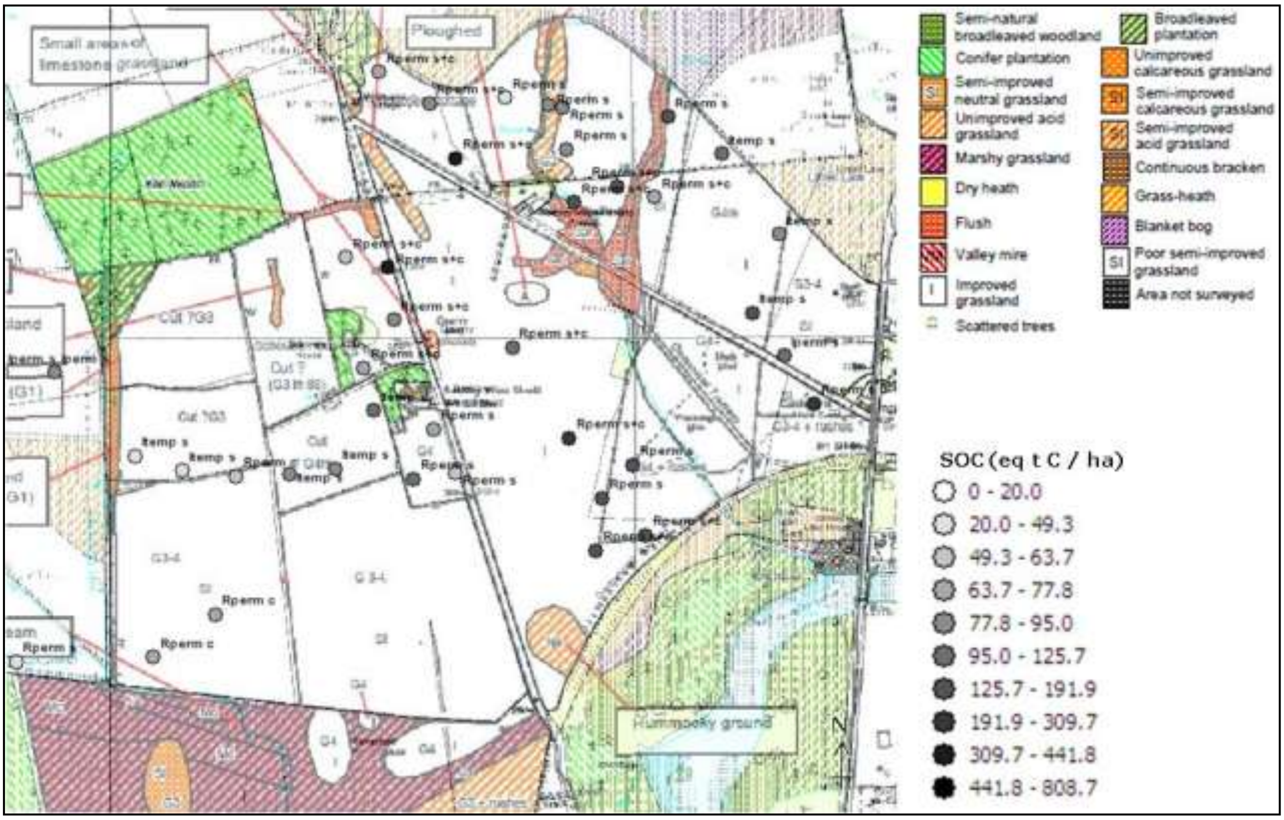
Table RS4. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of potential non HLS options for implementation in areas specified in Figure DH3.

	Option	Dis^{p} Risk	ha	SOC	Bio^{mas}	Σ	SOC	Bio^{mas}	Σ
				10 years			20 years		
5	Palludiculture	low	0.5	2.9	11.3	14.2	5.8	22.7	28.4

The use of short rotation coppice willow as a biofuel is cited by Smith et al. (2000) to have an additional energy substitution value of 2.1 t C ha^{-1} $year^{-1}$, equivalent to 11 and 23 t C after 10 and 20 years respectively if the marshy grassland areas are fully exploited.

5.16. Rothley West Shield

5.16.1. Site description



Rough permanent pasture is grazed by sheep or cattle only, and by sheep and cattle. Temporary pasture is grazed by sheep. Hay meadows are present to the west of the tenancy (transitional between MG1, *Arrhenatherum elatius* and MG3, *Anthoxanthum odoratum - Geranium sylvaticum* characteristic of hay meadows), with marshy grassland and unimproved acid grassland to the south (not sampled).

5.16.2. Baseline carbon

The mean SOC for each soil series and land use relative to the mean for the soil series and land use for the Wallington Estate is given in Tables RWS1 and RWS2. The SOC for individual sample sites relative to the mean for soil series and land use, and soil series overall for the Wallington Estate are displayed in Figures RWS1a and RWS1b respectively. The SOC for individual sample sites relative to the NSRI UK mean for soil series is given in Figure RWS1c.

Table RWS1. Mean SOC for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / -	Max SOC tenancy	Max SOC estate	Max SOC estate <1.5
ItempP	92	124.0	124.0	0.0	172.1	172.1	82.2
	Br	95.5	64.8	30.7	114.9	176.1	96.9
IpermP	92	121.6	121.6	0.0	121.6	121.6	121.6
RpermP	92	154.6	154.6	0.0	191.9	191.9	191.9
	Br	101.4	78.3	23.2	214.2	214.2	109.8
	Hj	105.6	82.3	23.3	314.7	314.7	113.1
	Wo	195.1	110.2	84.9	322.1	322.1	92.2

No colour if within + or −0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

Table RWS2. Mean SOC with values in excess of 1.5 greater than the mean removed for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / - (<1.5)	Max SOC tenancy	Max SOC estate
ItempP	92	82.2	82.2	0.0	82.2	82.2
	Br	85.9	58.8	27.0	88.5	96.9
RpermP	Br	73.2	69.5	3.7	98.1	109.8
	Hj	76.3	62.9	13.4	113.1	113.1
	Wo	152.7	69.7	83.0	226.8	92.2

No colour if within + or −0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

- ItempP: series 92 (only found on this tenancy) is above the UK mean however this series is classed as 'man made' and may be indicative of deeply cultivated organic soils potentially losing SOC through intermittent cultivation.
- IpermP: series 92 (only found on this tenancy) above the UK mean – see RpermP

- RpermP: series Wo to the north above the mean for land use (observations during farm visits identified small pools of sphagnum moss in the area) and sample to the south was amongst *Juncus* species suggesting wet soil conditions; series Hj to the north east has potentially high SOC (those samples with high individual SOC were among *Juncus* species implying wet soil conditions);

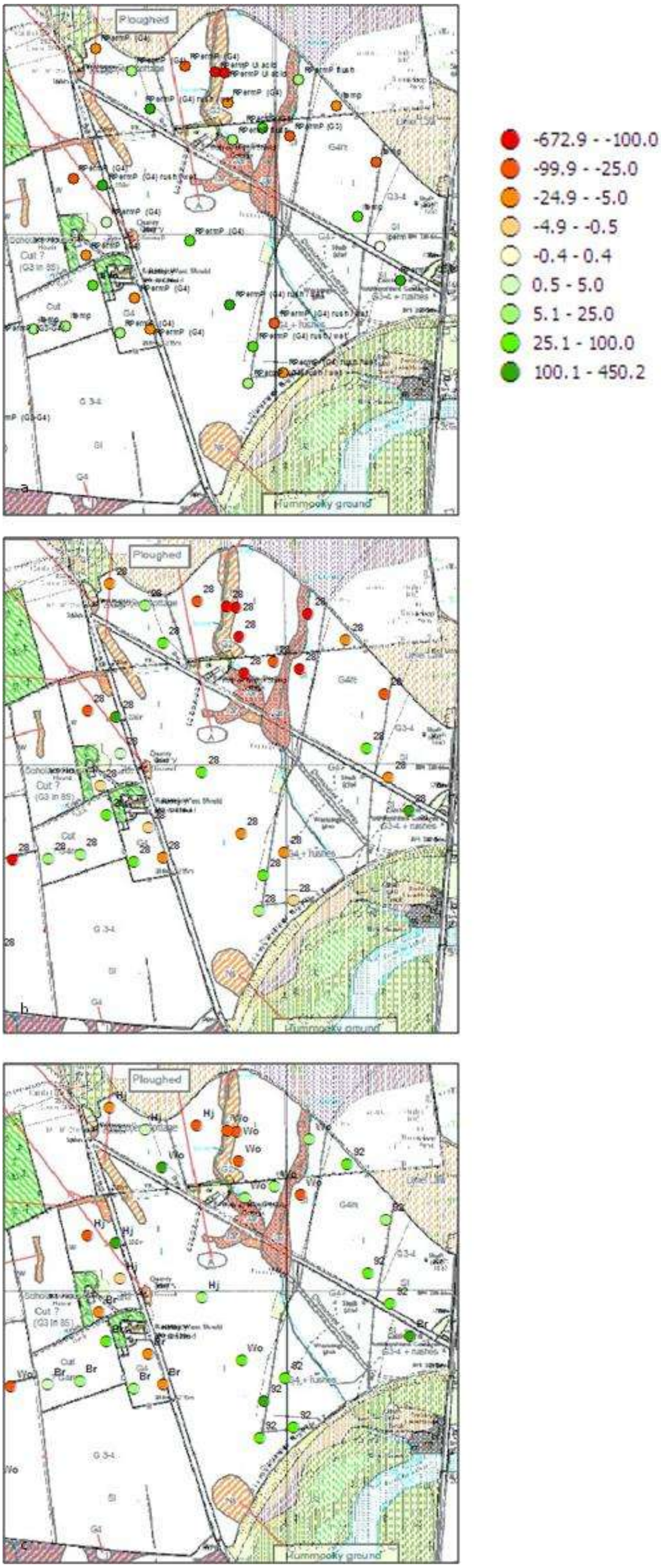


Figure RWS1.

a) SOC (t C ha^{-1} eq to 20 cm) of individual sample sites within the tenancy relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the given land use of the Wallington Estate.

b) SOC (t C ha^{-1} eq to 20 cm) relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the whole Wallington Estate.

c) SOC (t C ha^{-1} eq to 20 cm) relative to the projected mean SOC (t C ha^{-1} eq to 20 cm) of the NSRI UK soil series.

5.16.3. Priority areas

The priority areas are summarised in Figure 3. Areas of highest priority are labelled Priority 1 then follow in descending order of importance.

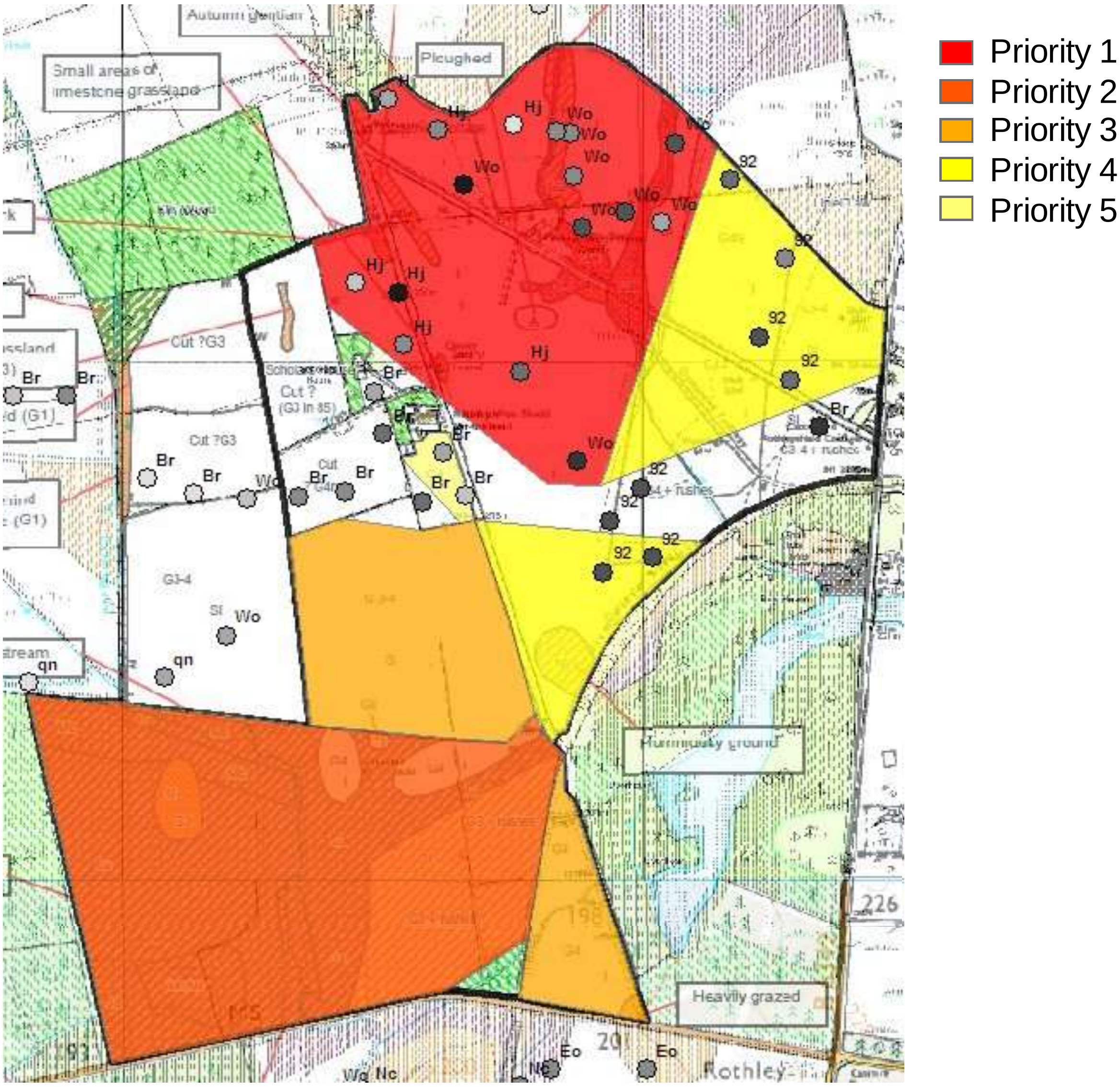


Figure RWS3. Priority areas identified on.

1. High priority soil series Hj and Wo. Priority habitats unimproved acid grassland (below the mean for the estate) and flush (above the estate mean for this land use) to the north on soil series Wo which is below the mean for the UK (suggests degraded soil, noted that it is separated from larger areas of unimproved acid grassland by a stone wall implying reseeded with grass previously). Observations during farm visits identified small pools of sphagnum moss in the area and *Juncus* species suggesting wet soil conditions, but also degraded moorland habitat. The restoration of wet heath and mire communities on wetter ground recommended by

the Biological Survey (1999) is conducive with increased coverage by habitats typically with high SOC (i.e. the restoration of soil conditions that allow accumulation of large quantities of SOC). Options to restore moorland habitat to the north of the tenancy offers potential to increase the SOC of a potentially high C containing high priority soil series. There are however dwellings present in these areas and modification to site hydrology via HLS options must take these into consideration. Priority should then be given to avoidance of further drainage and maintenance of existing wet soil conditions.

2. Potential (not sampled so unconfirmed) high priority soil series Wo (Wo present on Dyke Head fields to the north and Donkin Rigg to the south; series K on Gallows Hill to the east). The presence of semi-improved acid grassland and marshy grassland on potentially high priority soil series is indicative of degraded moorland habitat. The restoration of moorland as for priority 1 is applicable to this area.
3. Improved grassland with potential high priority soil series Wo (not sampled so unconfirmed). The absence of habitat indicative of degraded moorland as in (2) above renders these areas lower in confidence to recommend moorland restoration options.
4. Potential degraded high priority soil series. Soil series 92 (only found on this tenancy) is above the UK mean however it may be indicative of deeply cultivated organic soils in which SOC is currently being lost where present on ItempP through intermittent cultivation. Conversion to permanent grassland would be preferable.
5. Low SOC for series and land use, and compared to UK mean. Close proximity to farmhouse allows easy access to stock during the winter and potential for overwintering if moorland restoration is undertaken elsewhere and stock are removed. It is small in size.

5.16.4. HLS Options

Table RWS3 summarises by priority area (in descending order 1 to 5) options with the potential to have the greatest impact.

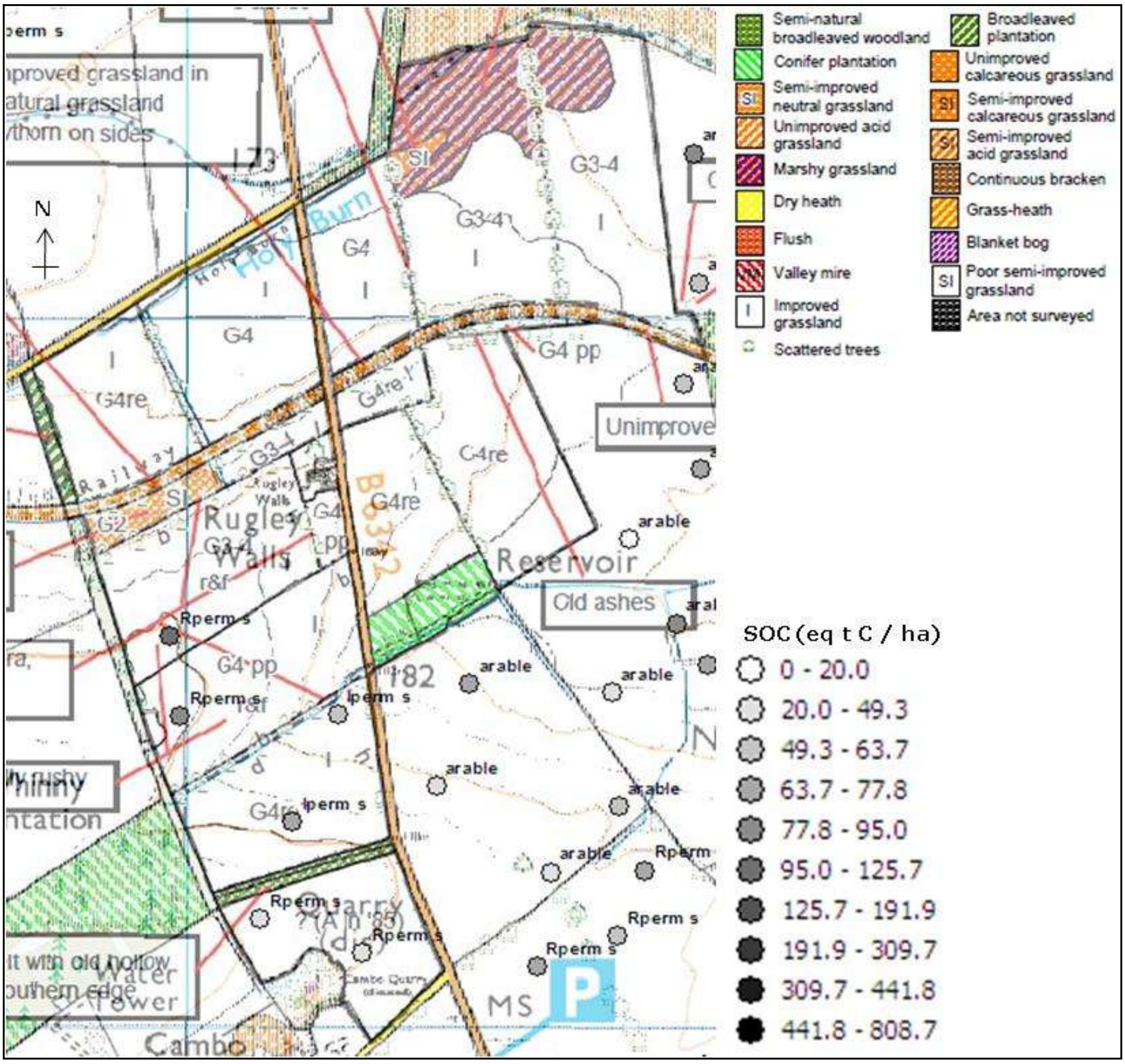
Table RWS3. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of priority HLS options for implementation in areas specified in Figure RWS1.

	Code / Option		Dis^p Risk	ha	SOC	Bio^mas	Σ	SOC	Bio^mas	Σ
					10 years			20 years		
1	HL10	Restoration of moorland	low	41.8	39.0	0	39.0	94.8	0	94.8
1	HL15	Seasonal livestock exclusion supplement	low		Facilitates option HL10					
2	HL10	Restoration of moorland	low	51.2	47.7	0	47.7	115.9	0	115.9
2	HL15	Seasonal livestock exclusion supplement	low		Facilitates option HL10					
3	HL10	Restoration of moorland	low	22.1	20.6	0	20.6	50.1	0	50.1
3	HL15	Seasonal livestock exclusion supplement	low		Facilitates option HL10					
4	HK2	Permanent grassland with low inputs (outside SDAs)	high	34.9	81.5	27.9	109.4	163.0	27.9	191.0

Dis^p Risk: Displacement Risk
ha: estimated area (ha) where option may be implemented
Σ: Total increase in C

5.17. Rugley Walls

5.17.1. Site description



Land use consists of rough permanent and improved permanent pasture grazed by sheep. Areas of marshy grassland are present to the north (not sampled), with conifer and broadleaved plantations, and a mature belt of oak and ash trees to the south.

5.17.2. Baseline carbon

The mean SOC for each soil series and land use relative to the mean for the soil series and land use for the Wallington Estate is given in Tables RW1 and RW2. The SOC for individual sample sites relative to the mean for soil series and land use, and soil series overall for the Wallington Estate are displayed in Figures RW1a and RW1b respectively. The SOC for individual sample sites relative to the NSRI UK mean for soil series is given in Figure RW1c.

Table RW1. Mean SOC for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / -	Max SOC tenancy	Max SOC estate	Max SOC estate <1.5
IpermP	gJ	63.9	70.0	-6.1	69.7	102.5	102.5
RpermP	gJ	99.2	74.4	24.8	110.7	110.7	110.7
	Hj	41.9	82.3	-40.4	45.5	314.7	113.1

No colour if within + or −0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

Table RW2. Mean SOC with values in excess of 1.5 greater than the mean removed for soil series and agricultural land use on the tenancy relative to that land use for the whole Wallington Estate, and maximum SOC sampled on the tenancy and the estate.

Land use	Soil series	Mean SOC tenancy	Mean SOC estate	+ / - (<1.5)	Max SOC tenancy	Max SOC estate
RpermP	Hj	41.9	62.9	-21.1	45.5	113.1

No colour if within + or −0.5 t C ha^{-1} equivalent. Where <1.5 refers to values in excess of 1.5 times the mean removed.

- IpermP: series gJ below the mean for the estate in this land use; grazed by sheep only however potential stock to congregate along the boundary with the watercourse to the north of the field.
- RpermP: SOC of series gJ above the mean for this land use on the estate and the highest SOC of any sample site of gJ on RpermP on Wallington; high priority series Hj in the field of rough permanent pasture grazed by sheep to the south-west has greater potential to increase SOC compared to series gJ.

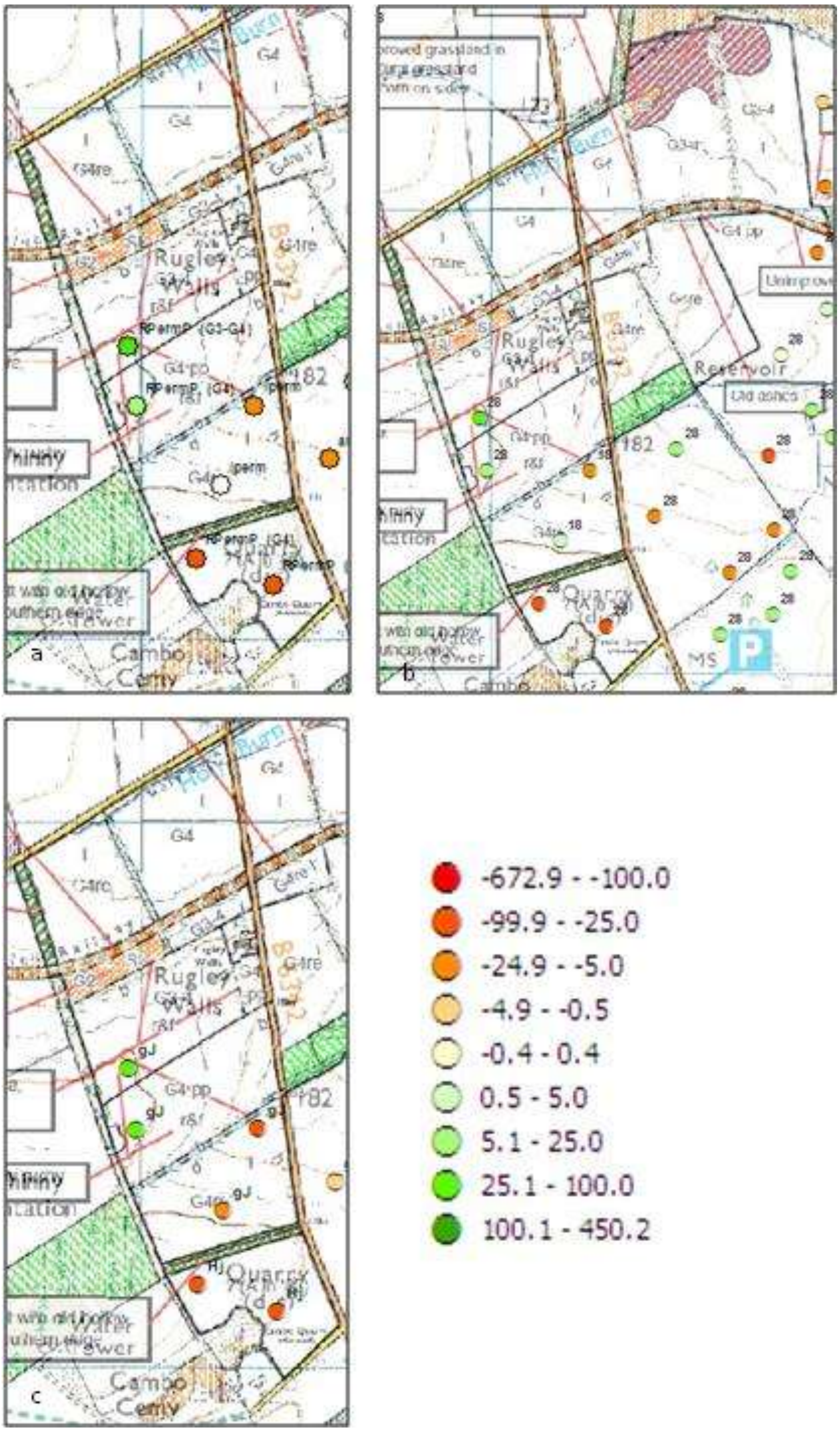


Figure RW1.

a) SOC (t C ha^{-1} eq to 20 cm) of individual sample sites within the tenancy relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the given land use of the Wallington Estate.

b) SOC (t C ha^{-1} eq to 20 cm) relative to the mean SOC (t C ha^{-1} eq to 20 cm) of the soil series for the whole Wallington Estate.

c) SOC (t C ha^{-1} eq to 20 cm) relative to the projected mean SOC (t C ha^{-1} eq to 20 cm) of the NSRI UK soil series

5.17.3. Priority areas

The priority areas are summarised in Figure RW3. Areas of highest priority are labelled Priority 1 then follow in descending order of importance.

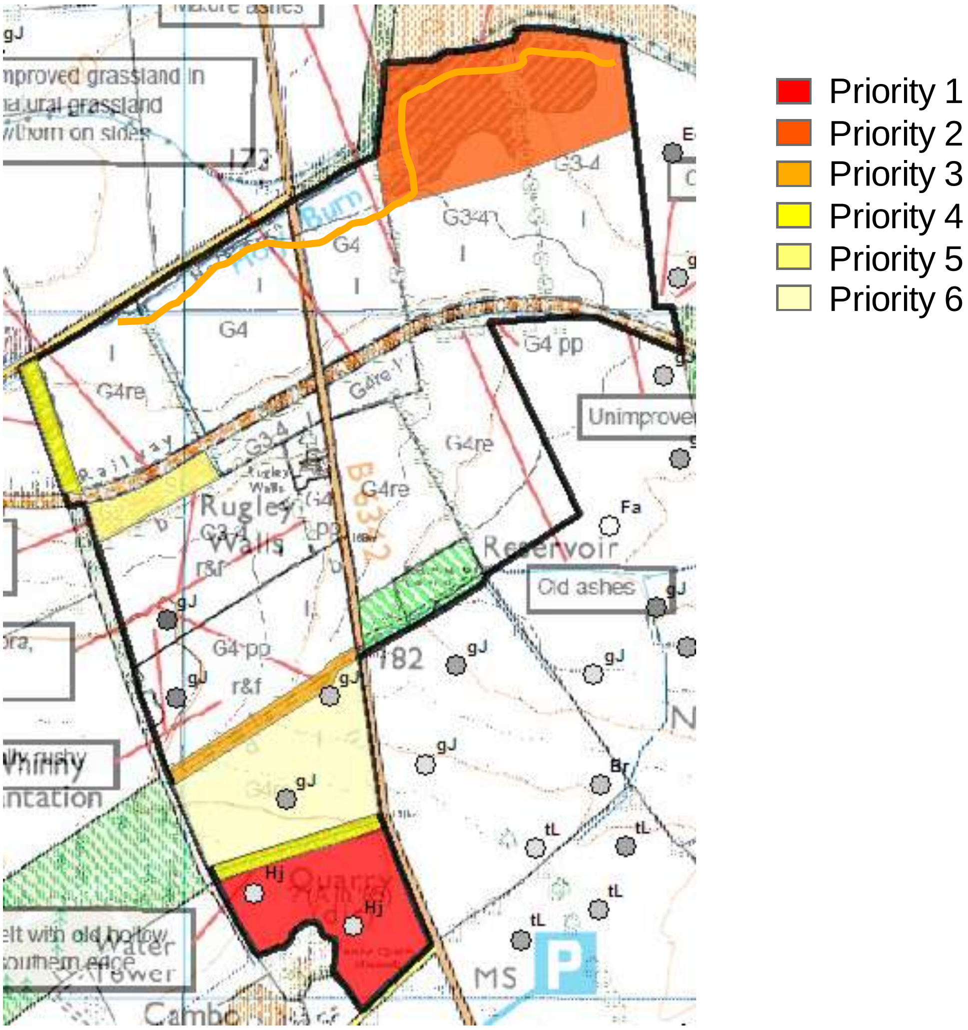


Figure RW3. Priority areas identified on Rugely Walls.

1. Priority soil series Hj in the field of rough permanent pasture grazed by sheep in the south-west. Described as arable in 1985 (Biological Survey, 1999) and has therefore been subject to frequent cultivation previously (as opposed to impact of current management practice). It would also imply slow recovery of C stocks proceeding conversion to permanent pasture. The field slopes steeply rendering options to raise water levels impractical. Options to mitigate compaction risk such as winter stock removal are recommended instead.
2. Priority habitat marshy grassland to the north (not sampled but assumed as a non high priority soil series). Existing marshy areas should be preferably maintained and extended where possible. The Biological Survey (1999) states allowance of

drains to fall into disrepair as a potential means to achieve this objective. This area offers the opportunity to grow water tolerant woody biomass crops such as willow.

3. Priority habitat watercourse. The fields adjacent are grazed by sheep only however there is potential to congregate along boundary and cause compaction and erosion. The fencing of as necessary / maintenance of existing fencing of the area is required.
4. Priority habitat broadleaved woodland (mature oak, ash and beech in strips within field and boundaries adjacent to permanent grassland). Maintenance or restoration as necessary.
5. Semi-improved neutral grassland with potential for restoration to species rich grassland (Biological Survey, 1999).
6. Low SOC for series gJ on IpermP. Listed as reseeded in the Biological Survey (1999) suggesting SOC is increasing now the area is permanent grassland. Options to facilitate recovery include winter stock removal or potential trialling of silvipasture.

5.17.4. HLS Options

The options on marshy grassland, watercourses, improved temporary grassland, improved permanent grassland outside SDAs and boundary features are applicable. Table RW3 summarises by priority area (in descending order 1 to 5) options with the potential to have the greatest impact.

Table RW3. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of priority HLS options for implementation in areas specified in Figure RW1.

	Code / Option		Dis^{p} Risk	ha	SOC	Bio^{mas}	Σ	SOC	Bio^{mas}	Σ
					10 years			20 years		
1	HJ7	Seasonal livestock removal on grassland with no input restriction	low	4.3	1.4	0	1.4	2.9	0	2.9
2	HK19	Raised water levels (lowland grassland)	low	6.9	36.8	1.4	38.2	73.6	1.4	75.0
3	HJ11	Maintenance of watercourse fencing	low	610.0	0.1	0.2	0.3	0.1	0.2	0.3
4	HC7	Maintenance of woodland	low	1.2	0.0	0.0	0.0	0.0	0.0	0.0
4	HC8	Restoration of woodland	low	1.2	0.1	3.2	3.3	0.1	6.4	6.6
5	HK7	Restoration of species-rich, semi-natural grassland	mod	0.9	0.5	0.7	1.2	0.9	0.7	1.7

6	HJ7	Seasonal livestock removal on grassland with no input restriction	low	4.9	1.6	0	1.6	3.3	0	3.3

Dis^p Risk: Displacement Risk

ha: estimated area (ha) where option may be implemented

Σ: Total increase in C

5.17.5. Non-HLS Options

The potential impact of suggested non HLS options on marshy grassland and cultivated land are summarised in Table RW4. Short rotation coppice assumes harvest every 10 years, the equilibrium for biomass is reached after an average of 5 years.

Table RW4. Mean estimated C accumulation to 20 cm (t C ha^{-1}) of potential non HLS options for implementation in areas specified in Figure RW3.

	Option	**Dis^p Risk**	**ha**	**SOC**	**Bio^{mas}**	**Σ**	**SOC**	**Bio^{mas}**	**Σ**
				10 years			**20 years**		
1	Palludiculture	low	6.9	36.8	144.9	181.7	73.6	289.8	363.4
6	Silvipasture	low	4.9	1.3	64.0	65.3	2.6	131.9	134.5

The use of short rotation coppice willow as a biofuel is cited by Smith et al. (2000) to have an additional energy substitution value of 2.1 t C ha^{-1} $year^{-1}$, equivalent to 145 and 290 t C after 10 and 20 years respectively if the marshy grassland areas are fully exploited.

6.0. Monitoring

6.1. Soil carbon monitoring

The actions suggested under HLS applicable to Wallington are divided into three groups:

1. Actions upon organic or peat soils - Restoration of moorland; creation of moorland; maintenance of moorland; and moorland rewetting supplement.
2. Actions that would predominantly be upon mineral soils - maintenance of woodland; restoration of woodland; creation of woodland; maintenance of wood pasture and parkland; and creation of wood pasture.
3. Actions that could be upon organo-mineral soils - restoration of rough grazing; restoration of grassland; and enclosed rough grazing.

6.1.1. Summary of recommendations

6.1.1.1. Monitoring

The monitoring plan should proceed via the following steps. More detail is given in sections 6.2 and 6.3.

1. Identify soil type
2. Define indicator to be measured relevant to that soil type (listed under the activity heading in Table 6.1) (e.g. change in % SOC due reversion to pasture or arable land).
3. Establish controls (land left without intervention for comparison using same monitoring methods).

6.1.1.2. Additional core activities

1. Improvement in present baseline be undertaken before any changes in land management
2. Life cycle analysis of any land management changes are considered and agricultural activity monitored throughout within a CALM-ES framework.
3. Statistical analysis and modelling of results should be carried out on an annual basis as part of yearly reporting.

6.1.1.3. Additional supporting activities

1. That an automatic weather station be established within the Estate.

Many of the proposed activities can be conducted by National Trust staff, especially, with respect to actions upon organic soils, however, many of the key indicators cannot be measured or supported without specialist facilities and/or staff. The measurement of %SOC, for example, must be a key indicator of success for this programme and its measurement does require trained staff working in a laboratory and we do not recommend the monitoring programme proceed without measurement of %SOC. The monitoring activities proposed have been divided into two classes of activities – those which could be conducted by National Trust staff and those which will require support from skilled specialist staff. They are summarised in Table 6.1.

Table 6.1. Recommended monitoring activities. Activities highlighted in orange are not deemed suitable to be undertaken by non skilled staff.

Action	Activity	Lead/lag indicator	Control required	Time step	Number replicates	Measurable by National Trust staff
Organic or peat soils	Vegetation survey	Lag	✓	Annual	6	✓
	Depth to water table	Lead	✓	Monthly	6	✓
	Accumulation pins	Lag	✓	6-monthly	24	✓
Mineral soils	% soil organic matter	Lag	✓	Biennial	12	×
	Bulk density	Lag	✓	Biennial	12	×
Organo-mineral soils	Accumulation pins	lag	✓	6-monthly	24	✓
	% soil organic matter	Lag	✓	Biennial	12	×
	Soil profiles	Lag	✓	Biennial	2	✓
Core	Baseline	na	×	Project inception	na	×
	Life cycle analysis	Lead	×	Annual	na	✓
	Statistical analysis	Lag	na	Annual	na	?
	Modelling	Lead	na	Annual	na	×
Supporting	Mapping	na	na	Annual	na	✓
	Environmental drivers	na	na	Monthly	na	✓

6.1.2. Actions to be implemented by National Trust staff

6.1.2.1. Actions upon organic or peat soils

There are almost 4 km^2 of peat soils within the Wallington estate and alongside these soils there are fringing organic soils. Organic soils cannot be treated like mineral soils as they are overwhelmingly organic matter and so measuring the change in its concentration is meaningless as it would not be expected to vary over time. Therefore, organic soils must not be treated like mineral soils. It is assumed that on the Wallington Estate those activities on "moorland" are activities on peat or organic soils.

The following monitoring activities are relevant to organic, and especially peat soils:

1. Vegetation cover – sustainable organic matter accumulation in peat soils is associated with key species, specifically *sphagnum* sp. and sedge species (eg. Eriophorum sp.). Fixed quadrats could be surveyed on an annual basis to assess whether peat forming species are increasing or declining in number. A typical number of fixed quadrats would be 6 per management unit plus 6 in the control unit. Quadrats should be surveyed annually, at the same time each year and normally in summer.
2. Depth to water table – peat soils exist because they can maintain and keep pace with a relatively high standing water table. The depth to water table is easy and cheap to measure at multiple sites. Furthermore, depth to water table is a key measure of peat carbon balance used to model carbon and GHG balance of peat soils. A typical number of dipwells within any management unit would be 6 plus 6 in a suitable control unit. Depth to water table is a lead indictor in [eat soils and should measured monthly throughout the year. *Initial assistance with installation may be required.*
3. Accumulation pins – carbon storage in peat soils cannot be assessed by change in soil organic carbon concentration but it can be assessed by change in depth or thickness of the organic layer. Therefore, accumulation pins can be used and monitored. However, accumulation pins are relatively insensitive as the change in organic layer thickness can be slow and so although cheap, they are needed in large numbers and so a typical number of accumulation pins per management plot is 24, plus 24 on a control unit. Furthermore, they are an insensitive measure of accumulation and so need only be measured twice a year should be treated as a lag indicator. *Initial assistance with installation may be required.*

The following sites are recommended:

1. Greenleighton mire – although this has been partially drained this site would represent a control;
2. Harwood Forest – the majority of the peat soils are still under plantation forestry; and
3. Deforested mire – a section of the Harwood Forest has been clear-felled. Unfortunately, this is a situation where we have no baseline control.

6.1.2.2. Additional core activities

1. Life cycle analysis. Completion of the CALM-ES questionnaire each year of the scheme (at least the questionnaire front end of the product). Where management changes are not covered by completion of the CALM-ES software front end they should be documented separately.

6.1.2.3. Supporting resources

The monitoring above does not in itself provide an estimate of the stock change these measurements need to be supported by:

1. Mapping - the scheme benefits from the existing mapping of the estate as part of Madeleine Bell’s thesis and this will need to be maintained.
2. Environmental drivers. The most important is meteorological data and so a weather station should be established within the Estate. This weather station could be automatic and monitored every month.

6.1.3. Actions to be implemented with additional support from specialist staff

The main action identified that will require use of specialist staff is the measurement of %SOC since there is no simple, accurate, alternative measure of %SOC other than based on either modified versions of the Walkley-Black method or CHN elemental analysis.

The monitoring of streams as a proxy of carbon stocks, for example, use of dissolved organic (DOC) or suspended sediment have some attractive properties, for example they are integrating measures from a catchment and not just one location; they are relatively simple to measure even if a laboratory is required; and they are components of the carbon cycle of any environment. However, they are significant drawbacks that preclude them from exclusion in this programme:

- First, they are an integrating measure and as such could represent all activities within a specific catchment but would be difficult to attribute to any single site or activity, i.e. without knowing where the water came from it would be difficult to know where to attribute any observed results.
- Second, suitable monitoring locations, streams, drains would need to be identified alongside suitable controls – it is not clear that is possible for range of soils and interventions considered.
- Thirdly, DOC and SS have to be measured in a laboratory and so could not be measured by NT staff alone within current facilities.
- Finally, there is no established link between DOC and SS in streams and soil organic carbon stocks. Because of the relative large coverage and amount of DOC concentration in stream water data for the UK the subject of its usefulness as a measure of soil carbon was the subject of a recent Defra research project. This project has shown that DOC data was always dominated by presence of organic soils, and therefore, insensitive to processes on organo-mineral or mineral soils.

Furthermore, DOC export in rivers could only be related to the broad classes of soil type (organic, organo-mineral or mineral) in combination with land use, but not to specific carbon stocks or other activities, and some combinations (eg. arable farming on mineral soils) ahve no significant DOC export. Therefore, we will not be including such options in the subsequent discussion.

6.1.3.1. Actions on mineral soils

In mineral soils, as with organic soils it is possible to measure a complete carbon or greenhouse gas budget, however, this is costly and time consuming. The single most important measure other than the detail of a complete monitored budget would be measuring the soil organic matter concentration. However, %SOC is an insensitive indicator of change but it must be considered a key indicator given the nature of the scheme objectives. Therefore we recommend that control and intervention sites are selected and then surveyed every other year.

The number of controls and replicates must be large and then replicates within each field needs to be of the order of 12 in each management unit with

12 in a suitable control. Wherever possible %SOC should be measured alongside bulk density. Given the nature of the changes being suggested under HLS we would not consider it necessary to measure %SOC below the top 20 cm although a number of soil profiles should be examined as %SOC with depth was under-represented in most studies. One note of caution is not of the monitoring activities recommend in this section for actions on mineral soils are lead indicators.

6.1.3.2. Actions on organo-mineral soils

Because of the land use/soil spatial relationships at Wallington many activities planned for rough grazing will be organo-mineral soils. As a rough estimate there are some 9 km^2 of organo-mineral soils on the Estate. Organo-mineral soils are characterised by a layer of organic matter that is less than 40 cm thick overlying mineral matter and which has no acrotelm/catotelm boundary which means that the organo-layer is seasonally dry. Because they are seasonally dry, water table is less of useful indicator in these soils, because they are not active peat forming key vegetation such as *Sphagnum* spp. are less common and so also less useful, and equally, because their surface layers are predominantly organic matter %SOC may not be a useful measure. Therefore, we recommend a more mixed monitoring approach to these soils where accumulation pins and the digging of soil profiles are used to assess the depth of the surface organic layers and periodic soil sampling and analysis for bulk density and %SOC are used to ensure that the surface layers are retaining organic matter and not becoming more mineral dominated. Therefore, we recommend that accumulation pins are used as described above for the organic soils, that soil profiles are dug every other year in conjunction with a programme of soil sampling as described for mineral soils. One note of caution is none of the monitoring activities recommend in this section for actions on mineral soils are lead indicators. Although National Trust staff could be involved in monitoring of accumulation pins *we do not believe that measurements of %SOC could be made by National Trust staff.*

6.1.3.3. Additional core activities

1. *Baseline.* Further targeted soil sampling of sparsely sampled areas. *Involves the measurement of %SOC.*
2. *Statistical analysis.* The monitoring activities suggested in this report have all been designed to be as statistically robust as practical. In general, the underlying designed of the suggested monitoring activities is a factorial

design with a range of covariates included. Therefore, the statistical modelling of results will be an important component of any programme. We recommend that statistical modelling of results is performed each year as part of an annual reporting process.

3. *Modelling.* It is recommended that modelling of the Estate is done each year as part of an annual reporting process. Also, the models proposed above can be used to project results under a range of scenarios informed by the monitoring within the Estate and therefore can be treated as a lead indicator. It will be necessary to interpret results within a model framework and given the nature of the soils on the Wallington estate two models are needed:
    a. Durham Carbon Model (Suke) – this model is developed for peat soils and has been run for the Wallington estate.
    b. Simeon – this model is developed for mineral soils and land use change and a formulation of it does already exist for the Wallington estate.

6.2. Biodiversity monitoring

6.2.1. Arable land and grassland

Agricultural biodiversity includes species such as collembola, carabid beetles, Staphylinids and Arachnids. Collembola feed on fungal hyphae (Hopkin, 2002) and their presence indicative of increased abundance of microbial biomass. Carabids, Staphylinids and Arachnids are predatory, classed as beneficial species (consume pests) (Warner et al., 2008c) and provide food for farmland birds. They are easy to identify to family level or above which combined with their importance in agro-ecosystems make them prime candidates as indicators for soil surface biodiversity. Earthworms are noted as beneficial to the enhancement of SOC and monitoring of their population also recommended.

6.2.1.1. Surface sampling

It is recommended that the soil surface be sampled using pitfall traps (Figure 6.1).

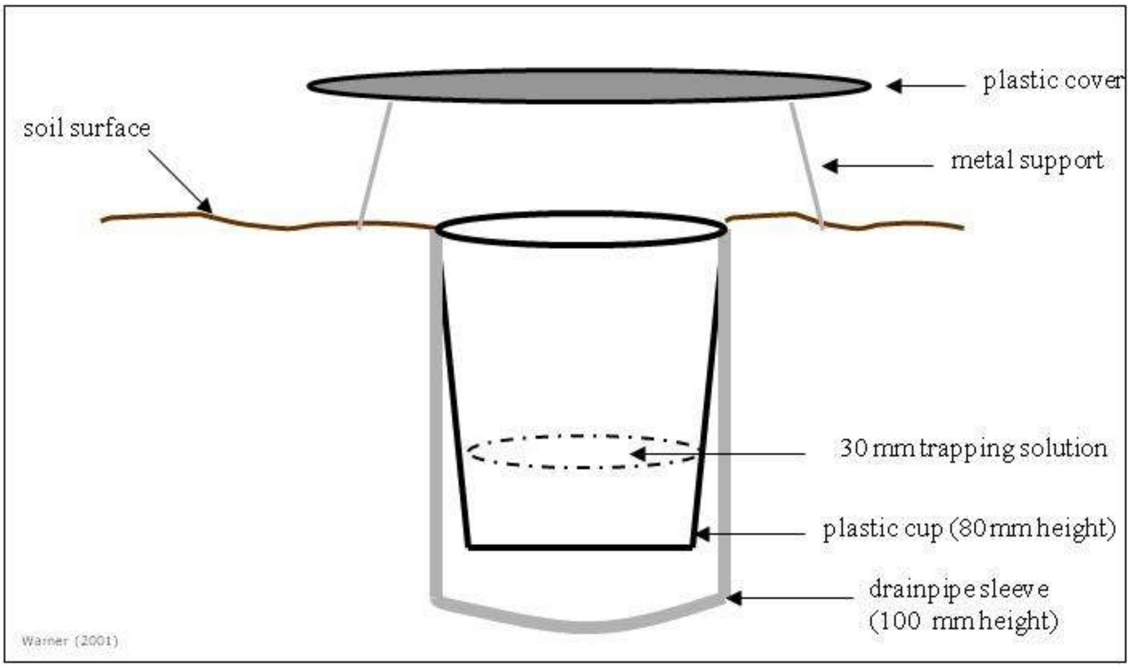


Figure 6.1. Overview of a pitfall trap

Pitfall traps indicate 'activity density' rather than direct population density because the organism must be active on the soil surface to fall into the trap. Sampling must be undertaken when the target species are active but also avoid agricultural operations. The sampling regime at each sampling site of Bell (2010) will involve the following:

1. Three sampling periods one month apart: early May, June and July (maximise species diversity within samples to include spring breeding and autumn breeding carabids).
2. Pitfall traps to be opened for a period of three days for each of the three periods.
3. Sample catch at each sample site to be identified to family as minimum: carabid beetles, staphylinids, arachnids and collembolans. Optional identification beyond family (e.g. genus) depending on available time and experience of staff involved.
4. Data analysis: see section 6.2.3.

6.2.1.2. Subsurface sampling

Vermifuge sampling of earthworms requires application of an irritant solution that drives the earthworm to the soil surface. It is acknowledged that this requires quantities of solution to be transported to some areas not accessible by road vehicles. The recommended size of the sample pit may be reduced as necessary to reduce the volume of solution required. Sampling[1] is recommended as follows:

1. Dig a square pit 30 cm x 30 cm x 10 cm (place soil on a plastic sheet).
2. Pour in a vermifuge solution (50g mustard powder per 10 litres of water).
3. Sift and remove earthworms from soil placed on plastic sheet.
4. Check pit frequently and remove earthworms.
5. Either make counts of earthworms in the field or return to laboratory for later counting.
6. Data analysis: see section 6.2.3.

[1]based on the recommended method of the Earthworm Society of Great Britain.

6.2.2. Priority habitats

Priority habitats such as wet heathland and blanket bog, and habitats potentially indicative of degraded habitats such as unimproved acid grassland are recommended to be monitored via quadrat sampling using vegetation indicator species, specifically the target NVC habitat classifications, indicative of e.g. high quality upland heath / heather moorland. This includes the following NVC plant communities:

1. M18 *Erica tetralix - Sphagnum papillosum* raised and blanket mire
2. M19 *Calluna vulgaris - Eriophorum vaginatum* blanket mire
3. M25 *Molinia caerulea - Potentilla erecta* mire

For these priority habitats the accumulation of SOC is coupled with restoration to high quality habitat (namely the removal of drainage and excessive grazing pressure) and the allowance of formation of desired vegetation.

6.2.3. Data analysis

It is recommended that a spatial analysis statistical program such as Spatial Analysis by Distance IndicEs (SADIE) (Perry, 1995; 1998a,b) is used to quantify the spatial association (the similarity) between the arable and grassland biodiversity data-sets from multiple years.

SADIE describes the spatial characteristics of a set of counts within a given sampling area and quantifies the degree of spatial association between two sets of data for the same sample locations (in this case the counts of invertebrates during different years when sampling has been undertaken) (Perry, 1998b). The null hypothesis tested is that the two populations are distributed independently of one-another (there is neither association nor dissociation between them). Clustering indices (vi or vj) are determined for the two populations and then compared with one another (the indices determined for each sample location are effectively over-laid on eachother). If both dataset 1 and dataset 2 at a given sample point have a positive cluster index value (vi) the two populations are spatially associated and the product (indicative of the degree of association) is positive.

An association or dissociation product is determined for each sample location so that any change in invertebrate populations at individual sample sites may be ascertained (and mapped). This may then be used to assess the impact of individual HLS options at known sample sites. If the counts of a particular species in dataset 1 at a given sample unit have a positive cluster index (vi) and the counts of data-set 2 a negative cluster index (vj), the samples are dissociated and the sample unit product negative. The extent of association or dissociation for the whole estate is determined by the overall correlation co-efficient (X). For two identical data-sets the value of the overall correlation co-efficient is 1 (ie 100% associated). Under the null hypothesis of zero association, the closer (X) is to zero, the less similar the distribution of the two populations is. The association indices at each sample point may be mapped using the product for each sample point pinpointing exactly where biodiversity has changed, and if significant ($p<0.05$).

7.0. Blueprint

This section provides step by step guidance to allow the non expert to identify the most likely SOC baseline categories for a given area of land and target appropriate HLS management accordingly. A series of questions (e.g. current land use, previous land use, period of time in land use, main soil type) are included within a two Tier decision tree process to ascertain whether the SOC is likely to be below average and have potential to accumulate SOC by alteration of management practices or whether equilibrium is at its maximum and no change in management needed.

7.1. Site description

Land use requires classification into the categories identified in Table 7.1. Habitat classification should be supplemented with NVC categories where existing surveys have been undertaken to indicate the status of habitat e..g magnitude of degredation. They are used in conjunction with prioritised soil type (Tier 1) or series (Tier 2) to determine the necessary action.

Table 7.1. Land use classifications and revised land use classifications.

Land use	Soil series priority	Habitat status
Arable	High	Degraded priority
Improved temporary pasture	High	Degraded priority
Improved permanent pasture	High	Degraded priority
Rough permanent grassland	High	Degraded priority
Marshy grassland	High	Degraded priority
Unimproved acid grassland	High	Priority
Semi-improved acid grassland	High	Degraded priority
Blanket bog	High	Priority
Wet heath	High	Priority
Flush	High	Priority
Woodland	High	Degraded priority
Forestry plantation	High	Degraded priority
Arable	Medium / low	Compare with mean SOC to determine status
Improved temporary pasture	Medium / low	Compare with mean SOC to determine status
Improved permanent pasture	Medium / low	Compare with mean SOC to determine status
Rough permanent grassland	Medium / low	Compare with mean SOC to determine status
Marshy grassland	Medium / low	Priority
Unimproved calcareous grassland	Medium / low	Priority
Semi-improved calcareous grassland	Medium / low	Degraded priority
Unimproved neutral grassland	Medium / low	Priority
Semi-improved neutral grassland	Medium / low	Degraded priority
Woodland	Medium / low	Priority
Forestry plantation	Medium / low	Compare with mean SOC to determine status

7.2. Tier 1 (unknown soil carbon and soil series)

A decision tree for the choice of HLS options on National Trust properties where detailed soil sampling programmes such as that undertaken by Bell (2010) are not available, is given in Figure 7.2. Soil series has been replaced with soil type (organic, organo-mineral, clay, silt, loam and sand) identifiable on farm by simple soil tests (for example, the soil texture test given in Figure 7.1).

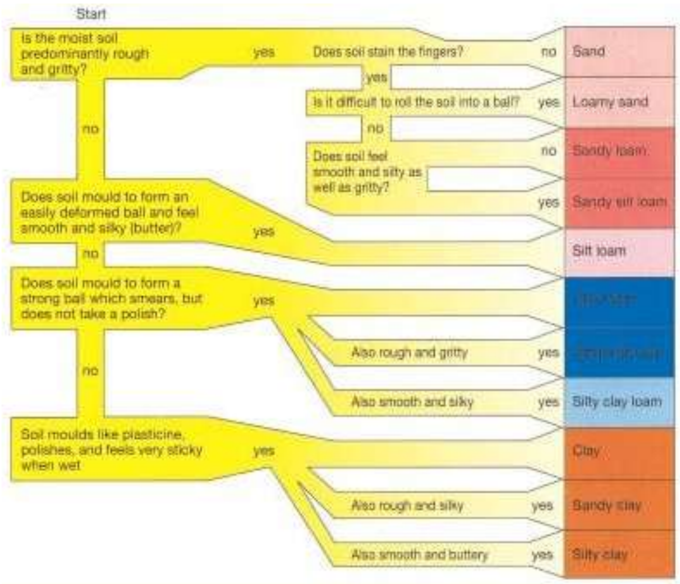
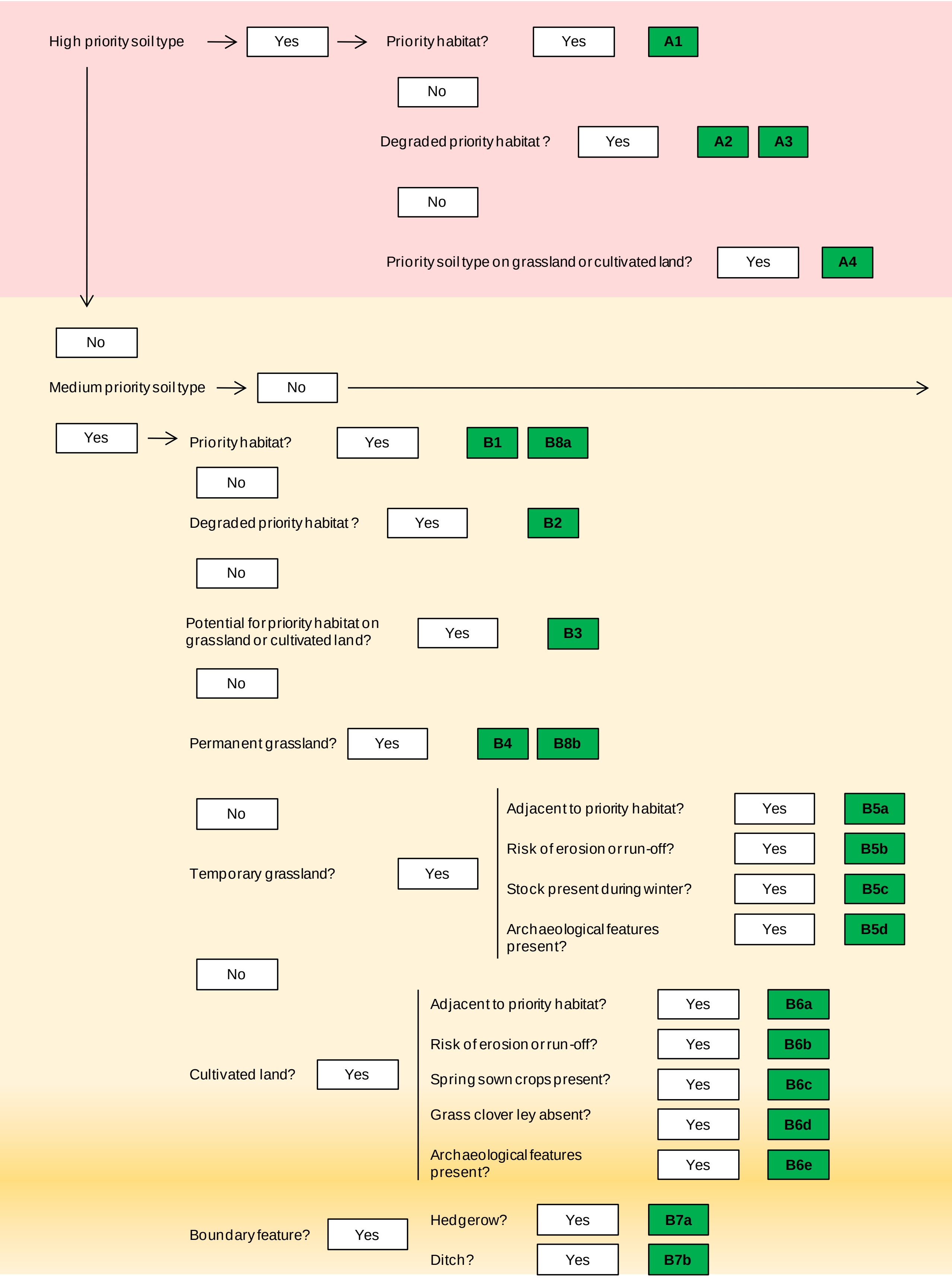


Figure 7.1. Soil texture assessment (from Defra 2005: Controlling soil erosion).

Priority habitat on priority soil types (organic and organo-mineral soils) includes heather moorland, wet heath, bog, fen and watercourses. Degraded priority habitat on priority soils where e.g. drainage has occurred includes remnant moorland habitats, acid grassland and marshy grassland. The presence of trees on priority soil types may result in degradation of organic soils. On medium priority soil types (predominantly clay or silt soils) or low priority soils (predominantly sand or loam soils) priority habitats include watercourses, marshy grassland / rush pastures, woodland and wood pasture. Marshy grassland on medium / low priority soils tends to result from e.g. proximity to a watercourse as opposed to degraded habitat. Clay and silt soils are vulnerable to soil compaction but their small particle size and space between particles enhances water retention capacity, anaerobic conditions and potential for SOC accumulation. They have been classed as medium priority. Sandy soils have greater particle size, air space between particles, enhanced drainage and smaller capacity to accumulate SOC. These soils are categorised as low priority.

The options listed in Tables 7.3 – 7.5 are prioritised by potential for displacement of agricultural production. Higher priority is given to those options that are of lower displacement risk.


High priority soil type
Yes
Priority habitat?
Yes
A1
No
Degraded priority habitat ?
Yes
A2
A3
No
Priority soil type on grassland or cultivated land?
Yes
A4
No
Medium priority soil type
No
Yes
Priority habitat?
Yes
B1
B8a
No
Degraded priority habitat ?
Yes
B2
No
Potential for priority habitat on grassland or cultivated land?
Yes
B3
No
Permanent grassland?
Yes
B4
B8b
No
Temporary grassland?
Yes
Adjacent to priority habitat?
Yes
B5a
Risk of erosion or run-off?
Yes
B5b
Stock present during winter?
Yes
B5c
Archaeological features present?
Yes
B5d
No
Cultivated land?
Yes
Adjacent to priority habitat?
Yes
B6a
Risk of erosion or run-off?
Yes
B6b
Spring sown crops present?
Yes
B6c
Grass clover ley absent?
Yes
B6d
Archaeological features present?
Yes
B6e
Boundary feature?
Yes
Hedgerow?
Yes
B7a
Ditch?
Yes
B7b

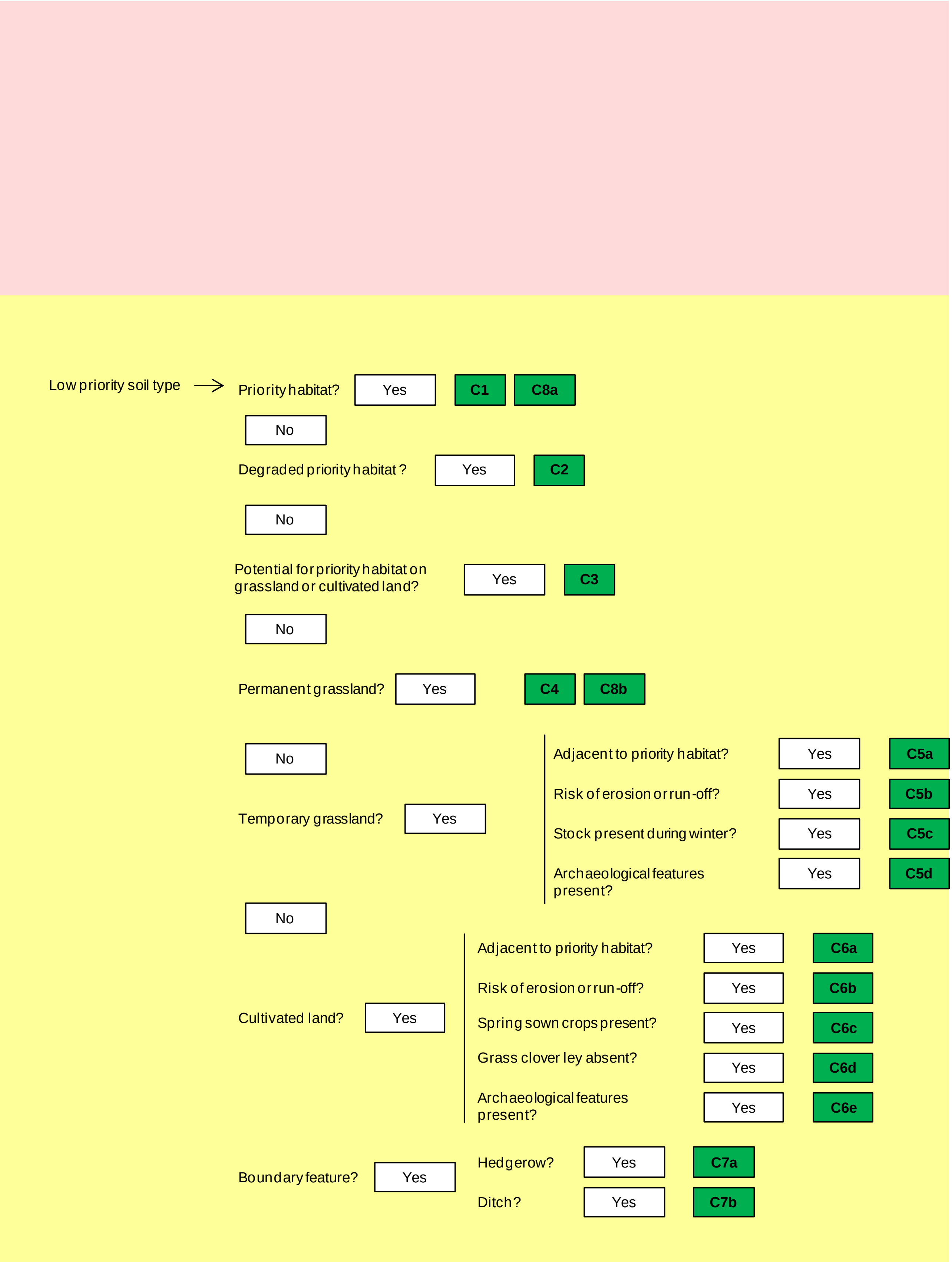


Figure 7.2. Tier 1 option decision tree.

7.3. Tier 2 (known soil carbon and soil series)

Where the existing SOC is known (Tier 2) it requires comparison with the mean data for land use at Wallington (Table 7.2). High priority soil series should be restored to priority habitat as priority. Where the existing soil series and SOC is known for moderate / low priority soil series on agricultural land it should be compared with the values in Table 7.2 to determine status. This is then used in the Tier 2 Decision Tree (Figure 7.2).

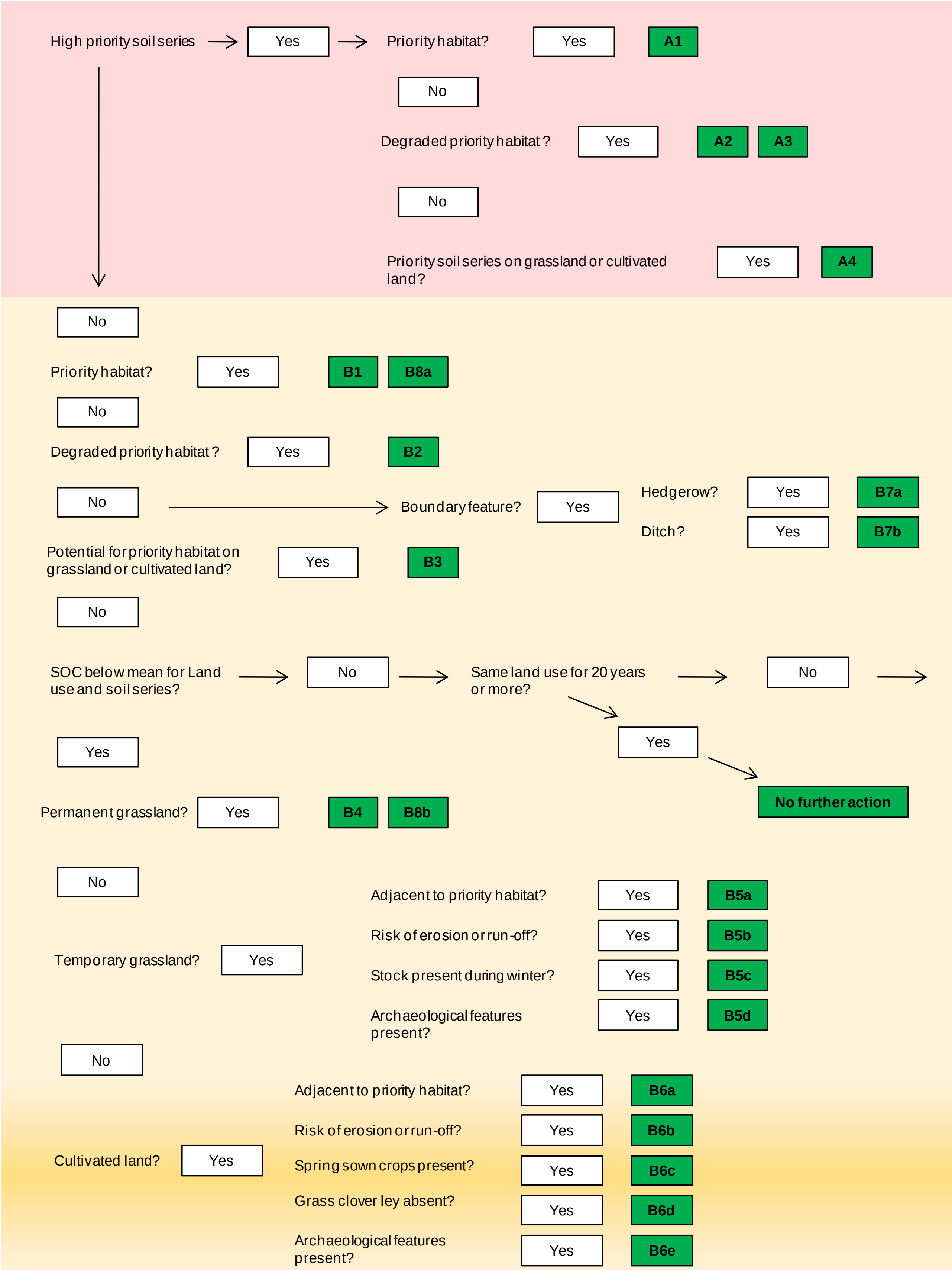
Table 7.2. Priority of soil series present on Wallington (highest to lowest) and mean for land use. NS indicates no sample available, red text one sample.

Soil series	Abb[v]	Wallington mean	Arable mean	ItempP mean	IpermP mean	RpermP mean	Priority
Winter Hill	wh	peat	Remove from land use – restore priority habitat				high
Cragside	cgs	388.8					high
Wilcocks	Wo	243.4					high
Thrunton	Tm	222.2					high
Kielder	K	133.0					high
Withnell	wm	265.8					high
Heapy	Hj	82.3					high
Brickfield	Br	69.7	51.7	64.8	70.8	81.5	moderate
Wigton Moor	ww	103.4	NS	NS	NS	103.4	moderate / high
Disturbed / man-made	92	139.0	NS	124.0	121.6	154.6	moderate
Waltham	Wa	65.6	NS	66.3	57.6	67.1	moderate / high
Dunwell	dz	116.4	NS	NS	116.4	NS	moderate
Nercwys	Nc	69.3	51.6	64.7	75.1	73.2	moderate
Sulham	sj	14.9	NS	14.9	NS	NS	moderate / high
Rivington	Rc	85.1	NS	85.1	NS	NS	low
	MI	123.4	NS	NS	111.9	NS	low
Enborne	Eo	81.2	57.3	52.0	NS	85.5	low
Greyland	gJ	66.8	57.7	66.6	70.0	75.1	low
Neath	nh	70.6	NS	NS	NS	70.6	low
Dunkeswick	Dk	69.8	58.2	55.2	79.1	NS	low
Ticknall	tL	54.9	46.9	NS	52.1	64.1	low
Quorndon	qn	46.2	NS	NS	NS	46.2	low

Where mean UK data from the NSRI dataset is available it can be used to determine if the estate overall has low SOC for a particular series. If identified as such then action to increase SOC may be required even if above the mean for land use and for the estate overall.

The spatial scale with which the mean may be compared (field level, tenancy level, estate level) is dependent on the number of samples. A minimum of 12 samples is required per land area for comparison between areas. For valid spatial statistics to be undertaken as per the monitoring programme, a statistical package such as SADIE requires a minimum of 36 sample points (Perry, 1998a b). It is appreciated that this will not viable for all land uses due to cost and sampling effort required. Samples may be aggregated wherever possible (e.g. three fields if sampling contains 12 samples per field) for use of spatial statistics.

The codes listed in green boxes in Figure 7.3 refer to the potential options available listed in section 7.3.


High priority soil series
Yes
Priority habitat?
Yes
A1
No
Degraded priority habitat ?
Yes
A2
A3
No
Priority soil series on grassland or cultivated land?
Yes
A4
No
Priority habitat?
Yes
B1
B8a
No
Degraded priority habitat ?
Yes
B2
No
Boundary feature?
Yes
Hedgerow?
Yes
B7a
Ditch?
Yes
B7b
Potential for priority habitat on grassland or cultivated land?
Yes
B3
No
SOC below mean for Land use and soil series?
No
Same land use for 20 years or more?
No
Yes
No further action
Yes
Permanent grassland?
Yes
B4
B8b
No
Adjacent to priority habitat?
Yes
B5a
Temporary grassland?
Yes
Risk of erosion or run-off?
Yes
B5b
Stock present during winter?
Yes
B5c
Archaeological features present?
Yes
B5d
No
Adjacent to priority habitat?
Yes
B6a
Risk of erosion or run-off?
Yes
B6b
Cultivated land?
Yes
Spring sown crops present?
Yes
B6c
Grass clover ley absent?
Yes
B6d
Archaeological features present?
Yes
B6e

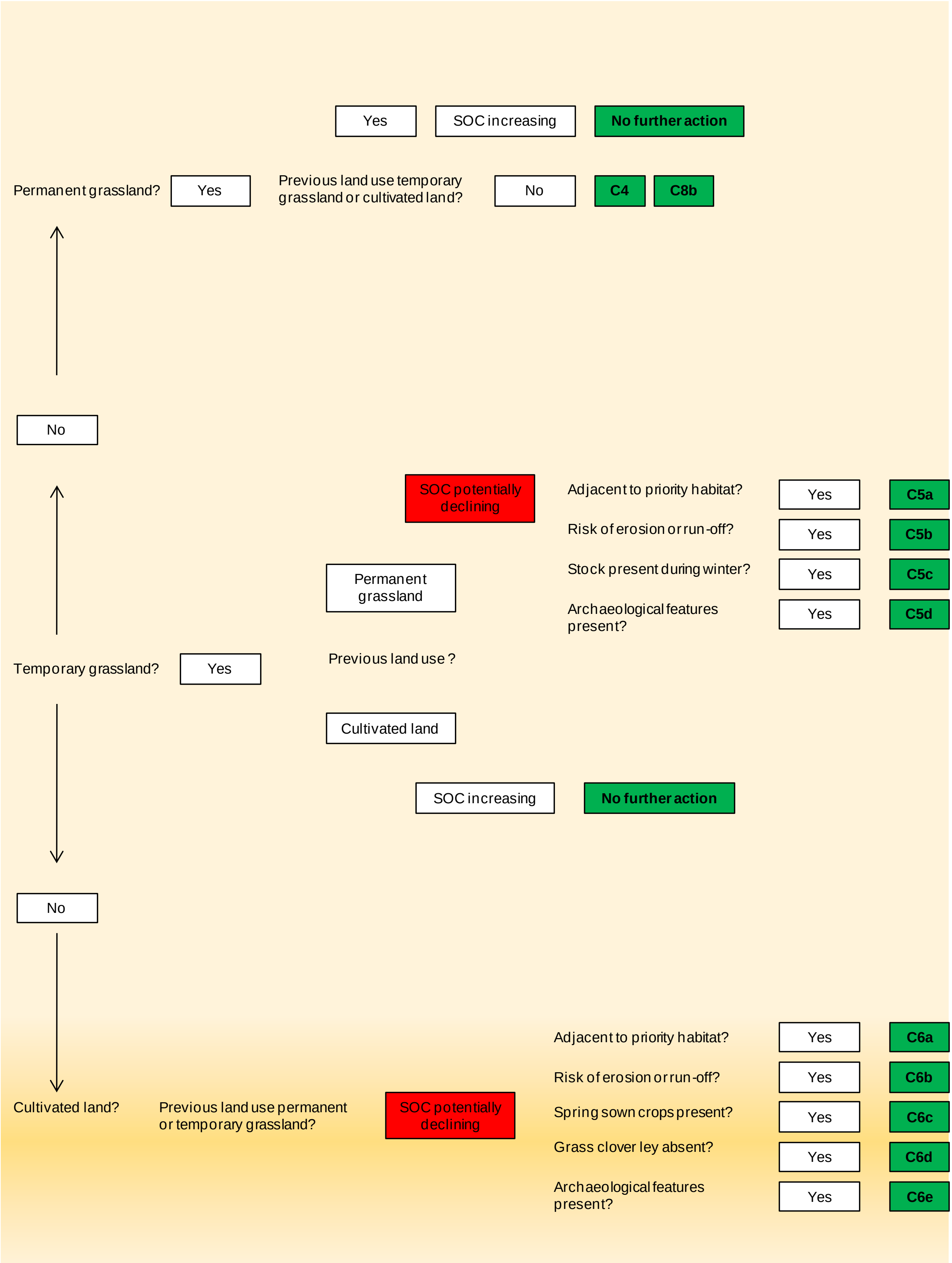


Figure 7.3. Tier 2 option decision tree.

7.5. HLS options

The codes in green boxes in the decision trees refer to the options in Tables 7.2 – 7.4.

Table 7.3. Options on high priority soils.

Code	Option	
Priority habitat maintenance options		
HL9	Maintenance of moorland	A1
HL7	Maintenance of rough grazing for birds	A1
HL5	Enclosed rough grazing	A1
HL6	Unenclosed moorland rough grazing	A1
HK15	Maintenance of grassland for target features	A1
HQ6	Maintenance of fen	A1
Priority habitat restoration options		
HL10	Restoration of moorland	A2
HL13	Moorland rewetting supplement	A2
HL8	Restoration of rough grazing for birds	A2
HQ7	Restoration of fen	A2
Priority habitat protection options		
HJ11	Maintenance of watercourse fencing	A3
HJ9	12 m buffer strips for watercourses on cultivated land	A3
HE10	6 m buffer strips on intensive grassland next to a water course	A3
Priority habitat creation options		
HL11	Creation of moorland	A4
HQ8	Creation of fen	A4
HO4	Creation of lowland heathland from improved grassland	A4

Where:

Low displacement risk
Moderate displacement risk
High displacement risk

Table 7.4. Options on medium priority soils.

Code	Option	
Priority habitat maintenance options		
HL4	Management of rush pastures in SDAs	B1
HC7	Maintenance of woodland	B1
Priority habitat restoration options		
HC8	Restoration of woodland	B2
HC13	Restoration of wood pasture and parkland	B2
HK7	Restoration of species-rich, semi-natural grassland	B2
HC4	Maintenance of woodland edges	B2
Priority habitat creation options		
HC14	Creation of wood pasture	B3
HK8	Creation of species-rich, semi-natural grassland	B3
HK17	Creation of grassland for target features	B3
HC9	Creation of woodland inside the SDAs	B3
HC10	Creation of woodland outside the SDAs	B3
Permanent grassland		
HJ7	Seasonal livestock removal on grassland with no input restriction	B4
HL15	Seasonal livestock exclusion supplement	B4

HL2	Permanent grassland with low inputs in SDAs	B4
HL3	Permanent grassland with very low inputs in SDAs	B4
Improved temporary pasture - Priority habitat protection options		
HC2	Protection of in-field trees - grassland	B5a
HC4	Maintenance of woodland edges	B5a
HC6	Ancient trees in intensively managed grass fields	B5a
HE4	2 m buffer strips on intensive grassland	B5a
HE5	4 m buffer strips on intensive grassland	B5a
HE6	6 m buffer strips on intensive grassland	B5a
HE11	Enhanced strips for target species on intensive grassland	B5a
Improved temporary pasture - Risk of erosion or run-off		
HJ6	Preventing erosion or run-off from intensively managed improved grassland	B5b
HK18	Haymaking supplement	B5b
HK2	Permanent grassland with low inputs (outside SDAs)	B5b
HK3	Permanent grassland with very low inputs (outside SDAs)	B5b
Improved temporary pasture - Stock present during winter		
HJ7	Seasonal livestock removal on grassland with no input restriction	B5c
HL15	Seasonal livestock exclusion supplement	B5c
Improved temporary pasture - Archaeological features present		
HD5	Management of archaeological features on grassland	B5d
Arable - Priority habitat protection options		
HC5	Ancient trees in arable fields	B6a
HE1	2 m buffer strips on cultivated land	B6a
HE2	4 m buffer strips on cultivated land	B6a
HE3	6 m buffer strips on cultivated land	B6a
HE8	Buffering in-field ponds in arable land	B6a
HE10	Floristically enhanced grass buffer strips (non-rotational)	B6a
Arable - Risk of erosion or run-off		
HF7	Beetle banks	B6b
HJ5	In-field grass areas to prevent erosion and run-off	B6b
HJ3	Arable reversion to unfertilised grassland to prevent erosion or run-off	B6b
HJ4	Arable reversion to grassland with low fertiliser input to prevent erosion or run-off	B6b
Arable - Spring sown crops in rotation		
HJ13	Winter cover crops	B6c
HG1	Under sown spring cereals	B6c
Arable – Absence of grass/clover ley		
HF12	Enhanced wild bird seed mix plots (non-rotational)	B6d
HF12	Enhanced wild bird seed mix plots (rotational)	B6d
HF14	Unharvested, fertiliser-free conservation headland	B6d
Arable - Archaeological features present		
HD3	Reduce cultivation depth on land where there are archaeological features	B6e
HD8	Maintaining high water levels to protect archaeology	B6e
HD2	Take archaeological features currently on cultivated land out of cultivation	B6e
Boundary - Hedgerow		
HR	Hedgerow restoration including laying, coppicing and gapping up	B7a
PH	Hedgerow planting – new hedges	B7a
HC24	Hedgerow tree buffer strips on cultivated land	B7a
HC25	Hedgerow tree buffer strips on grassland	B7a
Boundary - Ditch		
HB14	Management of ditches of very high environmental value	B7b
Non-HLS options – Marshy ground		
	Palludiculture	B8a
Non-HLS options – Improved permanent grassland		
	Silvipasture	B8b

Table 7.5. Options on low priority soils.

Code	Option	
Priority habitat maintenance options		
HL4	Management of rush pastures in SDAs	C1
HC7	Maintenance of woodland	C1
Priority habitat restoration options		
HC8	Restoration of woodland	C2
HC13	Restoration of wood pasture and parkland	C2
HK7	Restoration of species-rich, semi-natural grassland	C2
HC4	Maintenance of woodland edges	C2
Priority habitat creation options		
HC14	Creation of wood pasture	C3
HK8	Creation of species-rich, semi-natural grassland	C3
HK17	Creation of grassland for target features	C3
HC9	Creation of woodland inside the SDAs	C3
HC10	Creation of woodland outside the SDAs	C3
Permanent grassland		
HJ7	Seasonal livestock removal on grassland with no input restriction	C4
HL15	Seasonal livestock exclusion supplement	C4
HL2	Permanent grassland with low inputs in SDAs	C4
HL3	Permanent grassland with very low inputs in SDAs	C4
Improved temporary pasture - Priority habitat protection options		
HC2	Protection of in-field trees - grassland	C5a
HC4	Maintenance of woodland edges	C5a
HC6	Ancient trees in intensively managed grass fields	C5a
HE4	2 m buffer strips on intensive grassland	C5a
HE5	4 m buffer strips on intensive grassland	C5a
HE6	6 m buffer strips on intensive grassland	C5a
HE11	Enhanced strips for target species on intensive grassland	C5a
Improved temporary pasture - Risk of erosion or run-off		
HJ6	Preventing erosion or run-off from intensively managed improved grassland	C5b
HK18	Haymaking supplement	C5b
HK2	Permanent grassland with low inputs (outside SDAs)	C5b
HK3	Permanent grassland with very low inputs (outside SDAs)	C5b
Improved temporary pasture - Stock present during winter		
HJ7	Seasonal livestock removal on grassland with no input restriction	C5c
HL15	Seasonal livestock exclusion supplement	C5c
Improved temporary pasture - Archaeological features present		
HD5	Management of archaeological features on grassland	C5d
Arable - Priority habitat protection options		
HC5	Ancient trees in arable fields	C6a
HE1	2 m buffer strips on cultivated land	C6a
HE2	4 m buffer strips on cultivated land	C6a
HE3	6 m buffer strips on cultivated land	C6a
HE8	Buffering in-field ponds in arable land	C6a
HE10	Floristically enhanced grass buffer strips (non-rotational)	C6a
Arable - Risk of erosion or run-off		
HF7	Beetle banks	C6b
HJ5	In-field grass areas to prevent erosion and run-off	C6b
HJ3	Arable reversion to unfertilised grassland to prevent erosion or run-off	C6b
HJ4	Arable reversion to grassland with low fertiliser input to prevent erosion or run-off	C6b
Arable - Spring sown crops in rotation		
HJ13	Winter cover crops	C6c

HG1	Under sown spring cereals	C6c
Arable – Absence of grass/clover ley		
HF12	Enhanced wild bird seed mix plots (non-rotational)	C6d
HF12	Enhanced wild bird seed mix plots (rotational)	C6d
HF14	Unharvested, fertiliser-free conservation headland	C6d
Arable - Archaeological features present		
HD3	Reduce cultivation depth on land where there are archaeological features	C6e
HD8	Maintaining high water levels to protect archaeology	C6e
HD2	Take archaeological features currently on cultivated land out of cultivation	C6e
Boundary - Hedgerow		
HR	Hedgerow restoration including laying, coppicing and gapping up	C7a
PH	Hedgerow planting – new hedges	C7a
HC24	Hedgerow tree buffer strips on cultivated land	C7a
HC25	Hedgerow tree buffer strips on grassland	C7a
Boundary - Ditch		
HB14	Management of ditches of very high environmental value	C7b
Non-HLS options – Marshy ground		
	Palludiculture	C8a
Non-HLS options – Improved permanent grassland		
	Silvipasture	C8b

8.0. References

Avery, B.W. (1980). Soil Classification for England and Wales. (Higher categories). Harpenden, UK.

Bell, M. J. and Worrall, F. (2009). Estimating a region's soil organic carbon baseline: The undervalued role of land management. Geoderma 152, 74-84.

Biological Survey (1999). Wallington Estate Biological Evaluation. National Trust.

Brentrup, F. and Pallière, C. (2008) Greenhouse gas emissions and energy efficiency in European nitrogen fertiliser production and use. The International Fertiliser Society Proceedings, 639.

Bradley, R.I., Milne, R. Bell, J. Lilly, A., Jordan, C. & Higgins, A. 2005. A soil carbon and land use database for the United Kingdom. Soil Use and Management 21, 363–369.

Carey, P.D., Wallis, S., Chamberlain, P.M., Cooper, A., Emmett, B.A., Maskell, L.C., McCann, T., Murphy, J., Norton, L.R., Reynolds, B., Scott, W.A., Simpson, I.C., Smart, S.M., Ullyett, J.M., 2008. Countryside Survey: UK Results from 2007. NERC/Centre for Ecology & Hydrology, 105pp. CEH Project Number: C03259.

Cerri, C. C., Bernoux, M., Cerri, C. E. P. and Feller, C. (2004) Carbon cycling and sequestration opportunities in South America: the case of Brazil. Soil Use Management, 20, 248–254

Conant, R. T., Paustian, K. and Elliott, E. T. (2001) Grassland Management and Conversion into Grassland: Effects on Soil Carbon. Ecological Applications, 11, 343-355

Conant, R. T., Paustian, K., Del Grosso, S. J. and Parton, W. J. (2005) Nitrogen pools and fluxes in grassland soils sequestering carbon. Nutrient Cycling Agroecosystems, 71, 239–248

Cooper, E.A. (1997). Summary Descriptions of National Vegetation Classification: Grassland and Montane Communities - UK Nature Conservation Series v. 14. Joint Nature Conservation Committee.

Cowell, S.J. and Clift, R. (2000) A methodology for assessing soil quantity and quality in life cycle assessment. Journal of Cleaner Production, 8(4), 321-331.

Department for Environment, Food and Rural Affairs (Defra), 2005a. Entry Level Stewardship Handbook. PB10355. February 2005.

Department of the Environment and Rural Affairs (Defra). 2007. Annex XIII - Environmental Stewardship scheme. Income foregone calculations for Environmental Stewardship available on www.defra.gov.uk/erdp/docs/national/annexes/annex-xiii/default.htm.Dawson and Smith, 2007

Dawson, J.J.C. and Smith, P. (2007) Carbon losses from soil and its consequences for land-use management. Science of the Total Environment, 382, 165–190.

Dyson, K. E., Thomson, A. M., Mobbs, D. C., Milne, R., Skiba, U., Clark, A., Levy, P. E., Jones, S. K., Billett, M. F., Dinsmore, K. J., van Oijen, M., Ostle, N., Foereid, B., Smith, P., Matthews, R. W., Mackie, E., Bellamy, P., Rivas-Casado, M., Jordan, C., Higgins, A., Tomlinson, R. W., Grace, J., Parrish, P., Williams, M., Clement, R., Moncrieff, J. and Manning, A. (2009) Inventory and projections of UK emissions by sources and removals by sinks due to land use, land use change and forestry. Ed: K.E. Dyson. Annual Report, July 2009. Department for the Environment, Food and Rural Affairs Climate, Energy and Ozone: Science and Analysis Division Contract GA01088

European Commission (EC) (2005) Soil ATLAS of Europe. European Soil Bureau Network, 111.

European Environment Agency (2010) http://www.eea.europa.eu/data-and-maps/figures/the-natural-susceptibility-fo-soils. Date accessed 12th October 2010.

Falloon P, Powlson D, Smith P. 2004. Managing field margins for biodiversity and carbon sequestration: a Great Britain case study. Soil Use and Management 20. 240-247

Freeman, C., Ostle, N., and Kang, H. (2001) An enzymic 'latch' on a global carbon store. Nature, 409, 149

Freibauer, A. (2003) Regionalised inventory of biogenic greenhouse gas emissions from European agriculture. European Journal of Agronomy, 19, 135-160

Freibauer, A., Rounsevell, M., Smith, P. and Verhagen, A. (2004) Carbon sequestration in the agricultural soils of Europe, Geoderma, 122, 1–23.

Gibson, H.S., Worrall, F. Burt, T.P. and Adamson, J.K. (2009). DOC budgets of drained peat catchments: implications for DOC production in peat soils. Hydrological Processes 23, 1901–1911.

Hopkin, S.P. (2002). Collembola. University of Reading.

Hopkins, D.W., Waite, I.S., McNicols, J.W., Poulton, P.R., MacDonald, A.J., O'Donnell, A.G. (2009). Soil organic carbon contents in long-term experimental grassland plots in the UK (Palace Leas and Park Grass) have not changed consistently in recent decades. Global Change Biology 15, 1739–1754.

IPCC (2006) 2006 Guidelines for National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa

Jackson, J., Choudrie, S., Thistlethwaite, G., Passant, N., Murrells, T., Watterson, J., Mobbs, D., Cardenas, L., Thomson, A. and Leech, A. (2009) UK Greenhouse Gas Inventory, 1990 to 2007: Annual Report for submission under the Framework Convention on Climate Change. ISBN 0-9554823-8-0.

http://www.airquality.co.uk/reports/cat07/0905131425_ukghgi-90
07_main_chapters_Issue2_UNFCCC_CA_v5_Final.pdf

Johnston, A. E. (2008) Resource or waste: the reality of nutrient cycling to land. The International Fertiliser Society Proceedings, 630

Kechavarzi, C., Dawson, Q., Bartlett, M., Leeds-Harrison, P.B. (2010). The role of soil moisture, temperature and nutrient amendment on CO2 efflux from agricultural peat soil microcosms. Geoderma 154, 203–210.

King, J.A., Bradley, R.I., Harrison, R. & Carter, A.D. 2004. Carbon sequestration and saving potential associated with changes to the management of agricultural soils in England. Soil Use and Management 20, 394-402.

Kuipers H. and van De Zande, J.C. (1994) Quantification of traffic systems in crop production. In: Soane, B. D. and Ouwerkerk, C. (eds) Soil compaction in crop production. Amsterdam: Elsevier, 1994:417–45.

Louwagie, G., Gay, S. H., Burrell, A. (2009). Sustainable Agriculture and Soil Conservation (SoCo). Final report. EUR 23820 EN – 2009. DG Agriculture and Rural Development, European Commission.

Marriott, C.A., Fisher, J.M., Hood, K., Pakeman, R.J. (2010). Impacts of extensive grazing and abandonment on grassland soils and productivity. Agriculture, Ecosystems & Environment 139, 476-482.

Milne R., Brown T.A., 1997. Carbon in the vegetation and soils on Great Britain. Journal of Environmental Management 49, 413–433.Milne, R. & Mobbs, D.C. (editors). 2006. UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry Activities. DEFRA Contract EPG 1/1/160

Moorby, J. M., Chadwick, D. R., Scholefield, D., Chambers, B. J. and Williams, J. R. (2007) A review of best practice for reducing greenhouse gases. Defra project report AC0206.

Mudgal, S. and Turbé, A. (2010) Soil biodiversity: functions, threats and tools for policy makers. [Contract 07.0307/2008/517444/ETU/B1]. European Commission DG ENV. Final report February 2010.

National Trust (2010). Defra Multi-Objective Flood Management Demonstration Project Inception Phase - Process Report. January 2010. Penny Anderson Associates Limited.

Natural England, 2010. HLS Handbook 3rd edition.

Ostle, N. J., Levy, P. E., Evans, C. D. and Smith, P. (2009) UK land use and soil carbon sequestration. Land Use Policy, 26, S274-S283

Perry, J.N. (1995). Spatial Analysis by Distance Indices. Journal of Animal Ecology 64, 303-314.

Perry, J.N. (1998a). Measures of Spatial Pattern for Counts. Ecology 79, 1008-1017.

Perry, J.N. (1998b). Measures of spatial pattern and spatial association for insect counts. In, Population and Community Ecology for Insect Management and Conservation. Eds J. Baumgartner, P. Brandmayr & B. F.J. Manly. Balkema, Rotterdam. Proceedings of the Ecology and Population Dynamics Section of the 20th International Congress of Entomology, Florence, Italy, 25-31August 1996. ISBN90 5410 9300.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R. and Blair, R. (1995) Environmental and Economic Costs of Soil Erosion and Conservation Benefits. Science (Washington D C) 267(5201), 1117-1123.

Ravindranath, N. H. and Ostwald, M. (2008). Carbon Inventory Methods: Handbook for Greenhouse Gas Inventory, Carbon Mitigation and Roundwood Production Projects (Advances in Global Change Research). Springer (30 Nov 2007).

Renard, K. G., Foster, G. R., Weesies, G. A., Yoder, D. C. (1997) Predicting soil erosion by water. A guide to conservation planning with the universal soil loss equation (RUSLE). Agricultural Handbook 70

Rochette, P., Gregorich, E.G., 1998. Dynamics of soil microbial biomass C, soluble organic C, and CO2 evolution after three years of manure application. Canadian Journal of Soil Science 78, 283–290.

Schils, R., Kuikman, P., Liski, J., van Oijen, M., Smith, P., Webb, J., Alm, J., Somogyi, Z., van den Akker, J., Billett, M., Emmett, B., Evans, C., Lindner, M., Palosuo, T., Bellamy, P., Alm, J., Jandl, R. and Hiederer, R. (2008) Review of existing information on the interrelations between soil and climate change. ClimSoil. Final Report for Contract number 070307/2007/486157/SER/B1

Smith, P. (2004) Soils as carbon sinks: the global context. Soil Use and Management, 20, 212-218

Smith, P. (2005) An overview of the permanence of soil organic carbon stocks: influence of direct human-induced, indirect and natural effects. European Journal of Soil Science, 56, 673–680

Smith, K. A. and Conen, F. (2004) Impacts of land management on fluxes of trace greenhouse gases. Soil Use Management, 20, 255–263

Smith, J. U., Bradbury, N. J. and Addiscott, T. M. (1996) SUNDIAL: A PC-based system for simulating nitrogen dynamics in arable land. Agronomy Journal, 88, 38-43

Smith, P., Powlson, D. S., Smith, J. U., Falloon, P. and Coleman, K. (2000a) Meeting the UK's climate change commitments: options for carbon mitigation on agricultural land. Soil Use and Management, 16, 1-11

Smith, P., Powlson, D. S., Smith, J. U., Falloon, P. and Coleman, K. (2000b) Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture. Global Change Biology, 6, 525-539

Smith, P., Milne, R., Powlson, D. S., Smith, J. U., Falloon, P. and Coleman, K. (2000c) Revised estimates of the carbon mitigation potential of UK agricultural land. Soil Use and Management, 16, 293-295

Smith, P. (2004b) Engineered biological sinks on land. In The global carbon cycle. Integrating humans, climate, and the natural world (eds C. B. Field and M. R. Raupach), pp. 479–491. Washington, DC: Island Press

Smith, P., Martino, D., Cai, Z., Gwary D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S. (2007). Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture. Agriculture, Ecosystems and Environment, 118. 6-28.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M. and Smith, J. (2008a) Greenhouse gas mitigation in agriculture. Philosophical Transactions Royal Society of London Biological Sciences, 363, 789-813

Smith, W. N., Grant, B. B, Desjardins, R. L., Qian, B., Hutchinson, J. and Gameda, S. (2008b) Potential impact of climate change on carbon in agricultural soils in Canada 2000-2099. Climatic Change, 93, 313-333

Soussana, J. F., Loiseau, P., Viuchard, N., Ceschia, E., Balesdent, J., Chevallier, T., Arrouays, D. (2004) Carbon cycling and sequestration opportunities in temperate grasslands. Soil Use Management, 20, 219–230

Steber, A., Brooks, K., Perry, C.H., Kolka, R. (2007). Surface compaction estimates and soil sensitivity in Aspen stands of the Great Lakes States. Northern Journal of Applied Forestry 24, 276-281.

Thomas, C. (2004) Feed into Milk (FiM): a New Applied Feeding System for Dairy Cows. Nottingham University Press, UK.

van Camp, L., Bujarrabal, B., Gentile, A.R., Jones, R.J.A., Montanarella, L., Olazábal, C. and Selvaradjou, S.K. (2004). Reports of the Technical Working Groups Established under the Thematic Strategy for Soil Protection. EUR 21319 EN/1-Working Group on Research.

van den Akker, J.J.H. and Schjønning, P., 2004. Subsoil compaction and ways to prevent it. In: Schjønning, P., Elmholt, S. and Christensen, B.T. (eds.). Management Soil Quality: Challenges in modern agriculture, CABI Publishing, CAB International, Wallingford, Oxon, UK. pp. 163-184.

Warner DJ (2001) The Potential of Carabidae in the Control of Insect Pests of Winter Oilseed Rape. PhD Thesis. University of Hertfordshire, UK, in collaboration with Rothamsted Research, Harpenden, UK.

Warner, D. J., Tzilivakis, J. and Lewis, K. A. (2008a) Research into the current and potential climate change mitigation impacts of environmental stewardship. Final report for Department for Environment, Food and Rural Affairs (Defra) project BD2302

Wichtmann, W. and Joosten, H. (2007) Paludiculture: peat formation and renewable resources from rewetted peatlands. IMCG Newsletter 2007/3, 24-28

Williams, A. G., Audsley, E. and Sandars, D. L. (2006) Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities. Main Report. Defra Research Project IS0205. Bedford: Cranfield University and Defra

Wischmeier, W. H. and Smith, D. D. (1978) Predicting rainfall erosion losses: a guide to conservation planning. Agricultural Handbook No 537. US Dept of Agricultural Science and Education. Agricultural Research