Agriculture & Environment Research Unit
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Establishing a field-based evidence base for the impact of agri-environment options on soil carbon and climate change mitigation – phase 1

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1.0. Introduction

1.1. Background

Voluntary agri-environment schemes in one form or another have been in existence in England since the mid-1980s. These schemes were a response to growing evidence that agricultural intensification was having a negative impact on environmental quality, biodiversity and landscapes (e.g. Benson & Willis, 1988; Green, 1990). The general format of such schemes are to incentivise farmers and other land managers to look after the natural environment in which they work by adopting beneficial and protective practices (Batáry *et al.*, 2015). The earliest scheme, launched in 1985, paid farmers in East Anglia not to drain and plough grazing marshlands and the success of the initiative encouraged government to develop the first Environmentally Sensitive Areas (ESA's) in regions of the country considered to be of landscape, biodiversity and cultural importance. By 1991 it was clear that these types of approaches worked well and consequently a national scheme called 'Countryside Stewardship' (CSS) was launched that aimed to protect important habitats and features that were outside the ESAs (Ovenden *et al.*, 1998; Swash, 1997).

In 2003 a review of CSSs and ESAs were undertaken and one of its conclusions was that whilst the schemes could be considered highly successful at protecting important areas of wildlife, landscape and historic value across England, they had been less successful at maintaining and restoring high-quality wildlife habitats and landscape features (Defra, 2003). The review recommended that the most successful elements of both schemes were combined into a single new scheme. Around the same time a report by the Policy Commission on the Future of Farming and Food (PCFFF, 2002) concluded that current schemes were too 'narrow and deep' in their focus and that these should be complimented with a scheme that is 'broad and shallow'. Taking this and the 2005 review recommendations into consideration a revised scheme, to replace the previous initiatives, was launched in 2005 (Dobbs & Pretty, 2008; Natural England, 2009).

This revised 2005 scheme continued with the main priority of protecting biodiversity and their habitats as well as maintaining and protecting landscapes and the historic environment. However, it also included added emphasis on protecting natural resources (soils and water) and promoting environmental education. Completely new to the scheme were the secondary objectives of flood management and conserving genetic resources (Natural England, 2009). A further revision was introduced in 2013 (Natural England 2013ab) which added climate change mitigation and adaptation. Smith (2012) estimates the mitigation potential of UK agriculture overall to be approximately 1 - 2 Mt CO_2e yr^{-1}, with potential reductions mainly due to improved crop nitrogen management coupled with optimal livestock manure management and application strategies.

Structurally the scheme had three tiers. The first, Entry Level Stewardship (ELS), addressed the need for a 'broad and shallow' approach. This operated on a points-based system where applicants selected options from a 'menu' with each option worth a number of points. Once the applicant had selected sufficient points they would be accepted into the scheme under a 5-year agreement and paid a flat rate based on the farm size. The second tier was a modified version of ELS for organic farming (Organic Entry Level Stewardship (OELS)) that paid a higher flat rate, recognising the added costs associated with maintaining organic certification. The third tier, Higher Level Stewardship (HLS), was designed to reward higher environmentally-sound farming practices and those more targeted towards land with the greatest environmental value. It included, for example, maintenance and restoration of semi-natural grassland and practices to minimise soil erosion. Agreements were for a longer period (i.e. 10-years) and payments depended on the type of management being adopted. Under HLS there were also opportunities for capital grants, for example, for historic building restoration, fencing and water body creation (Natural England, 2009).

Like preceding agri-environment schemes there is ample evidence of success particular with respect to protecting populations of farmland birds (e.g. Bright *et al.*, 2015; McHugh *et al.*, 2016) and pollinating insects (e.g. Couvillon *et al.*, 2014; Wood *et al.*, 2015). Nevertheless, the need to continuously review and modify these types of schemes has been embedded in the scheme philosophy since their inception in 1991 and so in 2013 the 2005 Scheme was also reviewed (e.g. Mountford *et al*., 2013) and this process led to the introduction of a new scheme in 2016 called Countryside Stewardship (CS). The new scheme is designed to be much more focused towards key issues and key areas with the ability to be targeted towards addressing local needs and priorities, these being defined in 'Statement of Priorities' which are specific to one of 159 National Character Areas. The scheme is open to all eligible farmers and land managers through a targeted, competitive application process with the overall aim, like that of previous schemes, of delivering significant benefits to wildlife and environmental quality. Despite generic similarities the new scheme does differ from the previous 2005 version in a number of ways. Changes have been introduced in part to try and tackle specific ongoing environmental issues but also, as total scheme funding is limited, to ensure maximum benefit is achieved.

Overall there has been a modification to the operating structure. In the new 2016 scheme the grants previously available in the 2005 scheme (i.e. those that were available under the 2005 HLS) mostly continue but benefit from an additional new type of capital grant available which seeks to deliver very specific environmental outcomes. These include, for example, grants for small-scale restoration of boundary features, like hedgerows and stonewalls and there are also opportunities for funding to address local water quality, tree health and woodland creation. All grants of this type are available to farmers and land managers regardless of whether or not they have a CS agreement.

The new CS consists of a Mid-Tier and Higher Tier. The Mid-Tier is open to applications from all, but with access restricted to the most competitive applications. The Mid-Tier scheme aims to address widespread environmental issues, such as reducing diffuse water pollution or improving the farmed environment from farmland birds and pollinators. The Higher-Tier is for areas or projects where management is seen as complex such as that required to create woodland, for habitat restoration or for the protection of priority species such as the grey partridge, yellow hammer and brown hare (Bright *et al*., 2015; Field *et al*., 2011; Ewald *et al*., 2010; Reynolds *et al*., 2010). There is no separate organic strand: instead, a suite of organic land options are available within both the Mid-Tier and the Higher Tier. Further, previously separate grant streams such as the Woodland Grant Scheme (WGS) and Catchment Sensitive Farming (CSF) are all now administered and rationalised through CS.

From the applicants' perspective, perhaps the most significant difference is that the 2016 scheme is much more competitive. Only applicants that include the organic options are guaranteed acceptance but this is still subject to funding availability. Mid-tier and higher-tier management options are not associated with 'points' as they were previously but instead, applicants are evaluated against how well the overall proposal addresses local issues and national priorities as defined in the relevant 'statement of priorities' and only the best applications are successful. These tend to be those that offer benefits to wild pollinator species, improve water quality or those that reduce flood risk (Gov UK, 2015). Consequently, even at the entry level not all applicants will be successful. However, those that are not paid a flat rate but payments are based on the potential to achieve environmental benefits of the applicants' proposals.

The new scheme encourages the uptake of bundles of options, or combinations to produce positive environmental benefits particularly those that support national agri-environmental policy. For example the 'Wild pollinator and farm wildlife package' seeks to provide food and nesting sites for wild pollinators all year round by, for example, sowing nectar flower mixes and managing hedgerows. It therefore supports both Defra's National Pollinator Strategy and the EU Birds Directive as well as seeking to contribute towards other, wider environmental objectives such as protecting ecosystem services, climate change adaptation and water quality.

Another feature of the new scheme is that there is no longer a whole farm agreement but farmers and other land managers who participate will have to meet cross-compliance and other baseline management standards to qualify.

1.2. Aims and objectives

In 2008 and 2011, Defra research projects BD2302 and BD5007 investigated the current and potential climate change mitigation effects of the Environmental Stewardship (ES) scheme (2005-2014). This study seeks to update these findings in the context of the latest CS, launched in 2015. This involves (1) reviewing stewardship options and baseline scenarios to be used; (2) reviewing the latest literature and data relating to agricultural greenhouse gas emissions and carbon sequestration associated with CS options and associated land use management practices; (3) calculating the net impact of CS options on greenhouse gas emissions; and (4) scaling up the emissions using uptake statistics.

2.0. Baseline scenarios and options review

2.1. Introduction

The baseline management scenario provides a reference point against which any changes in land use through the implementation of Environmental Stewardship (ES) or CS agreements may be compared and the net increase or decrease in greenhouse gas (GHG) emissions quantified. A management scenario states all processes involved with the growing of the crop to include application of crop protection and fertilisers products (product, active ingredient, nutrient composition and application rate ha^{-1}); field operations (type of implement, depth of operation and frequency); livestock (type, rates and grazing period); management of manures; and addition of organic amendments (farmyard manure, incorporation of crop residues) (Defra, 2003; Lewis *et al.*, 2010; Tzilivakis *et al.*, 2005ab; Warner *et al.*, 2008, 2010, 2011ab). It also accounts for environmental factors such as (but are not limited to) soil type, topography, temperature and rainfall that may impact on loss of N to de-nitrification and N_2O emissions or CH_4 from manure storage. The existing baseline scenarios in BD2302 and BD5007 will be reviewed and the inputs and management interventions modified in response to changes in current practice, e.g. updates to the fertiliser recommendations stipulated in the revised version of the Nutrient Management Guide (RB209) (AHDB, 2017).

2.2. Workshop

The baseline management scenarios (Warner *et al.* 2008; 2011b) were revised in response to current agricultural practice (ABC, 2017; AHDB, 2017; BSFP, 2017; Nix, 2017; NVZ Guidelines, 2013) and product approval (PPDB, 2017). Scenarios for CS options were constructed with reference to the Natural England mid and higher tier management handbooks (Natural England, 2017ab) and the Natural England list of approved herbicide active ingredients (Natural England, 2017c). The scenarios were revised further in response to discussion during the workshop at Defra, Nobel House, London on 21st November 2017 (see Appendices). The key outputs from the workshop are summarised below:

Grassland baselines and options

- Nitrogen fertiliser recommendations for grassland to continue using the average data published in the British Survey Fertiliser Practice updated to figures published in the 2016 version as opposed to the more field specific recommendations in RB209
- Lowland temporary grassland most likely to be stockless and grown for silage (reference to be made to the legume and herb rich ley survey due in early 2018)
- The number of cuts on silage land considered too high, to be reduced from four to two and supplementary nutrient application rates to be adjusted accordingly
- Semi-improved and unimproved grassland beef or sheep present in equal likelihood, both will be used for the baseline scenarios unless specified in the option management requirements
- Stocking rates, housing period and supplementary feed agreed as per existing baselines, to be adjusted in response to Nix (2017) and ABC (2017) as required
- Organic temporary grassland to use a weighted average to determine stocking rates based on income foregone calculations
- Due to five year agreements it is unlikely that stock will be added to the farm if they are not present already i.e. any option requiring grazing will not be implemented, unlikely to change from sheep to cattle (options where cattle are required will already have cattle present), may change from cattle to sheep (potential financial benefit)

- Option GS3 (Ryegrass seed-set as winter food for birds) may mow twice, remove later nitrogen application (30 kg N ha^{-1}) due to being allowed to set seed
- Options GS9 (Management of wet grassland for breeding waders) and GS10 (Management of wet grassland for wintering waders and wildfowl) to use water meadow grazed by cattle instead of sheep in order to increase sward diversity and reduce the risk of the trampling of eggs
- Options GS9 (Management of wet grassland for breeding waders) and GS10 (Management of wet grassland for wintering waders and wildfowl) to reduce stocking rates to 0.1 livestock units, precise rate in response to the target species of bird (e.g. for snipe '*a mosaic of vegetation heights with short to medium swards (less than 5 cm to 15 cm) covering 30% to 40%, and medium to tall swards (15 cm to 50 cm) covering up to 70% of the area, in scattered tussocks/clumps with open areas between them*'), reduce option grazing period from 0.8 to 0.5 of the year
- The herbicide active ingredient fluroxypyr used to control creeping thistle and docks on grassland by weedwiping is no longer on the Natural England list of approved herbicides, an approved alternative is amidosulfuron (Table 2.1)
- Option HS9 (Restricted depth crop establishment to protect archaeology under an arable rotation) uptake on both temporary grassland and arable land
- Option GS16 (Rush infestation control supplement) baseline will most likely to be sheep grazing as it will be on wet grassland with the need to avoid poaching, rush encroachment less likely to be an issue where cattle are grazed although it remains a possibility
- Option GS17 (Lenient grazing supplement) livestock moved elsewhere on the farm, no net reduction in stocking rates
- Option SW2 (4m to 6m buffer strip on intensive grassland) mostly renewals (existing buffer strip)
- The herbicide active ingredient glyphosate used to treat tree stumps not on the Natural England list of approved herbicides, suitable as a brush application direct to the stump
- Option SW8 (Management of intensive grassland adjacent to a watercourse) likely to be implemented on an existing mixed farm, may be mown solely or grazed
- Option WD5 (Restoration of wood pasture and parkland) 25 – 50 trees ha^{-1} given as an indicator of successful establishment, use the 50 trees ha^{-1} figure (year 1 only)
- Option WD6 (Creation of wood pasture) guidance stipulates the presence of up to 300 trees ha^{-1}, most likely to be 200 ha^{-1} (year 1 only)
- Option UP1 Enclosed rough grazing refer to FERA monitoring to determine area subject to burning

Habitat specific baselines and options

- Salt marsh baseline to reduce stocking rates from 0.15 / 0.3 to 0.05 / 0.1 for sheep and cattle respectively
- Sand dune baseline may include previously ungrazed areas where grazing at low stocking rates is introduced (assume no net increase in stocking rates)
- Reed bed to include occasional cutting or grazing at the edge
- Options WT6 (Management of reedbed), WT8 (Management of fen) and WT10 (Management of lowland raised bog) to continue using a restoration and maintenance scenario (as proportions based on uptake data) despite the amalgamation of the two in the CS higher tier management specifications
- Option AB8 (Flower-rich margins and plots) in bush orchards implemented along the periphery (no change to tree biomass, only understory)
- Option AB12 (Supplementary winter feeding for farmland birds) in bush orchards implemented as a replacement of the grass strip between tree rows (no trees are removed)

Arable baselines and options

- Arable baselines to be adjusted to reflect the proportion of farms implementing non-inversion tillage (32% estimated by Townsend *et al.*, 2016)
- Organic arable rotation to include the incorporation of farmyard manure (proportional reduced tillage not applied to this scenario)
- Option OP5 (undersown cereal) to be maintained for at least 2 years, will often be grown as part of a longer term ley
- Option AB14 (Harvested low input cereal) decrease the number of crop protection applications i.e. herbicides, decrease nitrogen application to 25 kg N ha^{-1}
- Option GS4 (Legume and herb-rich swards) apply herbicide as a spot spray instead of weedwipe, restablish 3 times during the 5 year option agreement (no payment for second year of third establishment period)
- Option SW12 (Making space for water) allows for the periodic inundation of potentially large areas on marginal land typically adjacent to SSSI's, apply herbicide as a spot spray instead of weedwipe, sow as grassland and manage as low input hay or silage

Further detail for all option management scenarios to be obtained from the detailed management prescriptions available to advisors, supplied by Natural England.

Table 2.1: Crop protection active ingredients from the BD2302 and BD5007 baseline management and option management scenarios, and their current EU and Natural England (2017) approval status

Active ingredient	Function	EU approval status	Alternative
Amidosulfuron (75% w/w)	Herbicide - broad-leaved weeds	current + NE approved herbicide	
Clodinafop propargyl (240 g ha^{-1})	Herbicide - wild oats	current + NE approved herbicide	
Azoxystrobin (250 g ha^{-1})	Fungicide	current	
Captan (80% w/w)	Fungicide - scab, *Gloeosporium* rot	current	
Carboxin (200 g ha^{-1})	Fungicide - seed treatment winter wheat	current	
Chlormequat (700 g ha^{-1})	Growth regulation	current	
Chlorpyrifos (480 g ha^{-1})	Insecticide - leatherjackets	current	
Cypermethrin (100 g ha^{-1})	Insecticide - flea beetle	current	
Epoxiconazole (125 g ha^{-1})	Fungicide - septoria, rusts	current	
Fenoxycarb (25% w/w)	Insecticide	current	
Fluazifop-P-butyl (125 g ha^{-1})	Herbicide - post emergence grass weed control	current	
Fluroxypyr (200 g ha^{-1})	Herbicide - weedwipe of docks, annual dicots	[a]current	Amidosulfuron
Glyphosate (360 g ha^{-1})	Dessicant - oilseed crops	current	
Glyphosate (360 g ha^{-1})	Herbicide - manual tree stump application	[a]current	*suitable for tree stump application*
Methiocarb (3% w/w)	Molluscicide - slugs	current	
Penconazole (100 g ha^{-1} 10.6% w/w)	Fungicide - powdery mildew	current	
Pendimethalin (400 g ha^{-1})	Herbicide - grass weeds	[a]current	Diclofop-methyl + fenoxaprop-P-ethyl
Pirimicarb (50% w/w)		current	
Quinoxyfen (500 g ha^{-1})	Fungicide - mildew	current	
Tebuconazole (250 g ha^{-1})	Fungicide - stem canker, light leaf spot	current	

Active ingredient	Function	EU approval status	Alternative
Tralkoxydim (250 g ha^{-1})	Herbicide	current	
Trinexapac-ethyl (250 g ha^{-1})	Growth regulator	current	
Beta-cyfluthrin (100 g ha^{-1})	Insecticide - seed treatment oilseed crops flea beetle (20 ml kg^{-1} seed)	extended 31/10/2018	
Deltamethrin (25 g ha^{-1})	Insecticide - seed weevil, pod midge	extended 31/10/2018	
Iprodione (167 g ha^{-1})	Fungicide - sclerotinia	extended 31/10/2018	
Thiophanate-methyl (167 g ha^{-1})	Fungicide - sclerotinia	extended 31/10/2018	
Thiram (200 g ha^{-1})	Seed treatment - winter wheat	extended 30/04/2018	
Trifloxystrobin (125 g ha^{-1})	Fungicide - septoria and rusts	extended 31/07/2018	
Carbendazim (125 g ha^{-1})	Fungicide - stem canker	not approved	Prothioconazole or tebuconazole
Flusilazole (250 g ha^{-1})	Fungicide - stem canker	not approved	Prothioconazole or tebuconazole
Imidacloprid (100 g ha^{-1})	Insecticide - seed treatment flea beetle (20 ml kg^{-1} seed)	not approved	Lambda-cyhalothrin
Picoxystrobin (250 g ha^{-1})	Fungicide - septoria	not approved	Trifloxystrobin
Triazoxide (20 g ha^{-1})	Fungicide - seed treatment spring barley	not approved	Prothioconazole + fluoxastrobin
Trifluralin (480 g ha^{-1})	Herbicide - post-drill, pre-emergence	not approved	Prosulfocarb + S-metolachlor

Note: [a] Fluroxypyr and Pendimethalin no longer approved for use as a herbicide by Natural England

Table 2.2: Comparison of fertiliser recommendations between RB209 in 2010 and 2017, and the British Survey of Fertiliser Practice in 2010 and 2016 (from Tables GB1.1 and GB2.1)

Crop	Product	BSFP average field rate (kg ha^{-1})			[ab]RB209 (kg ha^{-1})		
		2010	**2016**	***change***	**2010**	**2016**	***change***
winter wheat	N	195	192	*-3*	220	220	*0*
	P_2O_5	60	60	*0*	60	60	*0*
	K_2O	72	71	*-1*	45	45	*0*
spring barley (feed)	N	104	106	*2*	140	140	*0*
	P_2O_5	50	50	*0*	45	45	*0*
	K_2O	64	68	*4*	35	35	*0*
winter oilseed rape	N	200	184	*-16*	30 + 190	30 + 190	*0*
	P_2O_5	60	58	*-2*	50	50	*0*
	K_2O	67	67	*0*	40	40	*0*
top fruit	N	74	107	*33*	60 to 130	60 to 130	*0*
	P_2O_5	33	81	*48*	20	20	*0*
	K_2O	46	107	*61*	80	80	*0*
forage maize	N	64	57	*-7*	100	100	*0*
	P_2O_5	56	50	*-6*	55	55	*0*
	K_2O	79	67	*-12*	175	175	*0*
leafy forage crops	N	76	78	*2*	90	75	*-15*
	P_2O_5	55	38	*-17*	25	25	*0*
	K_2O	59	45	*-14*	50	50	*0*
grass <5 years old	N	126	124	*-2*	[e]240	[c]130	
	P_2O_5	32	30	*-2*	20	20	*0*
	K_2O	47	43	*-4*	0	0	*0*
silage – not grazed	N	140	138	*-2*	[g]80 + 25	[g]80 + 50	
	P_2O_5	34	30	*-4*	40 + 25	40 + 25	*0*
	K_2O	51	50	*-1*	80 + 90	80 + 90	*0*
grass >5 years old	N	92	88	*-4*	[f]0 to 90	[d]30	

Crop	**Product**	**BSFP average field rate (kg ha^{-1})**			**[ab]RB209 (kg ha^{-1})**		
		2010	**2016**	***change***	**2010**	**2016**	***change***
	P_2O_5	22	22	*0*	20	20	*0*
	K_2O	27	27	*0*	0	0	*0*
ryegrass grown for seed	N	-	-	-	160	160	*0*
	P_2O_5	-	-	-	30	30	*0*
	K_2O	-	-	-	90	90	*0*
cattle FYM to grassland	t ha^{-1}	17	15	*-2*			

Note: [a]RB209: SNS 1 medium / mineral soils, P index 2, K index 2-, straw incorporated; [b]RB209: grassland average growth class; [c]indicative yield 7 - 9 t DM ha^{-1}; [d]indicative yield 4 - 5 t DM ha^{-1}; [e]intensively grazed beef cattle. [f]extensive / moderate grazing beef cattle or sheep; [g]two cuts

Average fertiliser rates have in most cases decreased since 2010 except for top fruit. The scenarios where BSFP data is used have been updated to the 2017 values accordingly.

Table 2.3: Review of intensive livestock stocking rates and supplementary feed consumption published in Nix and the Agricultural Budgeting Costings book in 2013 and 2017

System	**Unit**	**ABC (2013)**	**Nix (2013) - low**	**Nix (2013) - average**	**Nix (2013) - high**
Lowland beef cattle	Head			Spring 1.80; Autumn 1.65	Spring 2.20; Autumn 2.00
	Concentrates (kg per head)	steer 300, heifer 260		Spring £42.00, 210 kg; Autumn £73.00, 365 kg	Spring £35.00, 175 kg; Autumn £66.00, 300 kg
	Silage (t fresh weight per head)	steer 3.7, heifer 3.4			
		ABC (2017)	**Nix (2017) - low**	**Nix (2017) - average**	**Nix (2017) - high**
Lowland beef cattle	Head			Spring 1.80; Autumn 1.65	Spring 2.20; Autumn 2.00
	Concentrates (kg per head)	steer 350, heifer 300		Spring £36.00, 180 kg; Autumn £62.00, 310 kg	Spring £30.00, 150 kg; Autumn £57.00, 285 kg
	Silage (t fresh weight per head)	steer 3.7, heifer 3.4			

Note: Low, moderate and high denotes performance

Any changes noted between years, for example the increase in concentrates within the diet of lowland beef cattle (Table 2.3) have been used to update the baseline scenarios as required. This has also been applied for any changes observed in Tables 2.4 to 2.6.

Table 2.4: Review of stocking rates and supplementary feed: Lowland

System	**Unit**	**ABC (2013)**	**Nix (2013) - low**	**Nix (2013) - average**	**Nix (2013) - high**
Lowland sheep	Head (ewe + lambs)	Spring lambing: 11 ewes (1.55 LPE); Early lambing: 14 ewes (1.38 LPE); Organic spring lambing 9 ewes (1.50 LPE)	7.5 ewes (1.30 LPE)	10 ewes (1.57 LPE)	11 ewes (1.74 LPE)
	Concentrates (kg per head)	Spring lambing: **47.8 kg** (40 kg per	£19.80, 99 kg	£14.70, 74 kg	£13.20, 66 kg

System	Unit	ABC (2013)	Nix (2013) - low	Nix (2013) - average	Nix (2013) - high
		ewe, 5 kg per lamb); Housed early **127.6** kg (55 kg per ewe, 55 kg per lamb); Organic spring lambing 52.5 kg (30 kg per ewe, 15 kg per lamb)			
	Silage (t fresh weight per head)		0.38 t FW		
Lowland beef cattle	Head	**Spring 1.55;** **Autumn 1.40**; Organic spring 1.0		Spring: 1.80; Autumn 1.65	
	Concentrates (kg per head)	Spring: 110 kg per cow, 60 kg per calf; Autumn: 170 kg per cow, 120 kg per calf; Organic: 150 kg per cow, 90 kg per calf		Spring: £42.00, **210 kg**; Autumn £73.00, **365 kg**	
	Silage (t fresh weight per head)				

System	Unit	ABC (2017)	Nix (2017) - low	Nix (2017) - average	Nix (2017) - high
Lowland sheep	Head (ewe + lambs)	Spring lambing: **10** ewes (1.5 LPE); Early lambing: 12 ewes (1.42 LPE); Organic spring lambing **9** ewes (1.50 LPE)	8.0 ewes (1.29 LPE)	**10** ewes (1.5 LPE)	11 ewes (1.69 LPE)
	Concentrates (kg per head)	Spring lambing: **75.0** kg (60 kg per ewe, 10 kg per lamb); Housed early **131.0** kg (65 kg per ewe, 50 kg per lamb); Organic spring lambing **52.5** kg (30 kg per ewe, 15 kg per lamb)	£13.00, 65 kg	£13.00, 65 kg	£12.00, 60 kg
	Silage (t fresh weight per head)				
Lowland beef cattle	Head	Spring: 1.50; Autumn 1.60; Organic **1.0**		Spring: **1.80**; Autumn 1.65	

	Concentrates (kg per head)	Spring 200 kg per cow, 50 kg per calf; Autumn 250 kg per cow, 100 kg per calf; Organic: **150** kg per cow, **90** kg per calf		Spring £36, **180** kg; Autumn £62, **310** kg	
	Silage (t fresh weight per head)				

Note: Low, moderate and high denotes performance; LPE lambs per ewe

Table 2.5: Review of stocking rates and supplementary feed: Upland

System	**Unit**	**ABC (2013)**	**Nix (2013) - low**	**Nix (2013) - average**	**Nix (2013) - high**
Upland sheep	Head (ewe + lambs)	9.5 ewes (1.45 LPE)	4.0 ewes (1.24 LPE)	**9.0 ewes** (1.42 LPE)	10.0 ewes (1.61 LPE)
	Concentrates (kg per head)	45 kg	£22.34, 112 kg (60 kg per ewe, 10 kg per lamb)	£16.60, **83 kg** (60 kg per ewe, 10 kg per lamb)	£13.24, 66 kg (60 kg per ewe, 10 kg per lamb)
	Silage (t fresh weight per head)				
Upland beef cattle	Head			Spring 1.6; Autumn 1.25	Spring 1.9; Autumn 1.5
	Concentrates (kg per head)			Spring £46, 230 kg; Autumn £76, 380 kg	Spring £39, 195 kg; Autumn £69, 345 kg
	Silage (t fresh weight per head)				
System	**Unit**	**ABC (2017)**	**Nix (2017) - low**	**Nix (2017) - average**	**Nix (2017) - high**
Upland sheep	Head (ewe + lambs)	9.5 ewes (1.47 LPE)	4.0 ewes (1.19 LPE)	**9.0** ewes (1.42 LPE)	10.0 ewes (1.58 LPE)
	Concentrates (kg per head)	**40** kg	£15.00, 75 kg (59 kg per ewe, 10 kg per lamb)	£10.00, **50 kg** (40 kg per ewe, 6 kg per lamb)	£6.00, 30 kg (24 kg per ewe, 2 kg per lamb)
	Silage (t fresh weight per head)				
Upland beef cattle	Head			Spring **1.6**; Autumn 1.25	Spring 1.9; Autumn 1.5
	Concentrates (kg per head)			Spring £38, **190** kg; Autumn £63, **315** kg	Spring £32, 160 kg; Autumn £58, 290 kg
	Silage (t fresh weight per head)				

Note: Low, moderate and high denotes performance; LPE lambs per ewe

Table 2.6: Review of stocking rates and supplementary feed: Upland LFA

System	**Unit**	**ABC (2013)**	**Nix (2013) - low**	**Nix (2013) - average**	**Nix (2013) - high**
Upland LFA sheep	Head (ewe + lambs)		4.0 ewes (1.24 LPE)		
	Concentrates (kg per head)	**45** kg	£22.34, 112 kg		

	Silage (t fresh weight per head)				
Upland LFA beef cattle	Head	Spring calving 1.15 cows; Autumn 1.0 cows		Spring 1.6; Autumn 1.25	
	Concentrates (kg per head)	Spring calving 110 kg cow, 75 kg calf; Autumn 130 kg cow, 120 kg calf		Spring £46.00, **230** kg; Autumn £76.00 **380** kg	

System	Unit	ABC (2017)	Nix (2017) - low	Nix (2017) - average	Nix (2017) - high
	Silage (t fresh weight per head)				
Upland LFA sheep	Head (ewe + lambs)	*1.1 LPE, 0.25 replace to winter keep*	4.0 ewes (1.19 LPE)		
	Concentrates (kg per head)	**30 kg**	£15.00, 75 kg (59 kg per ewe, 10 kg per lamb)		
	Silage (t fresh weight per head)				
Upland LFA beef cattle	Head	Spring calving 1.0 cows; Autumn 1.1 cows		Spring 1.6; Autumn 1.25	
	Concentrates (kg per head)	Spring calving **150** kg cow, **75** kg calf; Autumn **200** kg cow, **100** kg calf		Spring £38.00, **190** kg; autumn £63.00, **315** kg	
	Silage (t fresh weight per head)				

Note: Low, moderate and high denotes performance; LPE lambs per ewe; Upland LFA sheep lowland winter keep 25 weeks (ABC, 2013); feed £200 per t (Nix, 2013 and 2017)

The CS options have been categorised by Natural England into the following classes: (A) No CS option; (B) CS option sufficiently similar to ES, no recalculation required; (C) CS option significantly different to ES option, recalculation required; and (D) New option in CS. Management scenarios for options in classes C and D will be defined using the same approach used for the baseline scenarios (see Appendices). The impact on Greenhouse gas emissions for class C and D options will be calculated using the emission parameters derived in Task 1.2. Where changes to the baseline scenarios of BD2302 and BD5007 are considered appropriate, the Greenhouse gas emissions for class B will be adjusted accordingly.

3.0. Review of literature and data

3.1. Introduction

A review of the literature was undertaken to gather the latest evidence relating to agricultural Greenhouse gas emissions and carbon sequestration associated with CS options and associated land use management practices. The boundaries of the review included: publications applicable to Europe; English language only; and from 2011-2017. The review included the following parameters:

- **CO_2 from fossil fuels:** including product manufacture (pesticides and fertilisers), packaging and transport (to farm); application by spraying or spreading or fuel consumed by tillage operations and drilling; indirect energy (fuel consumed during machinery manufacture and calculated based on depreciation per operation).
- **Nitrous oxide (N_2O):** GWP 298 (Brown et al., 2017) from supplementary nitrogen (N) application accounting for type of material or product, soil type, timing and quantity with reference to the IPCC (2006) and Pachauri *et al.* (2014) methodology supplemented with data provided by e.g. the N balance model SUNDIAL (Smith *et al.*, 1996), MANNER (Chambers *et al.*, 1999) or comparable tools identified during the review, for example Renate (2014). This was in line with management practices and any required modifications identified during the workshop.
- **Methane (CH_4):** GWP 25 (Brown et al., 2017) from livestock systems, from the enteric fermentation of ruminant animals and from the handling of manures, have been calculated per livestock unit for BD2302 and BD5007 (Warner *et al.*, 2008; 2011b) to account for dietary composition, and method of and mean temperature during manure storage (IPCC, 2006; 2014; Thomas, 2004; Williams *et al.*, 2009). The method has been adapted as necessary to changes in management practice identified during the workshop. Methane emission from soils, wetland and peat soils in particular, have been modified where more robust data has been identified.
- **Carbon sequestration:** The existing soil carbon baselines used in BD2302 and BD5007 (Warner *et al.*, 2008; 2011b) for different land management categories have been revised where more robust data exists.

This section also includes reference to the original data used in BD2302 and BD5007.

3.2. Fossil fuels and product manufacture

This section reports on the CO_2e associated with product manufacture (Scope 3 emissions) of pesticides and fertilisers, their packaging, storage and transport (to farm). The most recent report to publish energy and CO_2e data for the manufacture of crop protection products is Audsley *et al.* (2009). The document lists energy consumption (MJ per kg of active ingredient), and a conversion factor of 0.069 kg CO_2e per MJ. The revised active ingredients listed in Table 2.1 will be assigned to the appropriate pesticide class and the CO_2e modified using the data provided by Audsley *et al.* (2009), summarised in Table 3.1. Where an appropriate pesticide class was not available, the active ingredient has been assigned an energy value for the average of insecticide, herbicide or fungicide as applicable.

Table 3.1: Energy (MJ) per kg of active ingredient

Type	Active ingredient	Group	MJ kg ai^{-1}
I&N	1,3-dichloropropene	Organochlorine	226
H	2-4 Dichlorophenoxyacetic acid	Alkylchlorophenoxy	107
I&N	Alpha-cypermethrin	Pyrethroid	518
H	Atrazine	Triazine	208

Type	Active ingredient	Group	MJ kg ai^{-1}
F	Azoxystrobin	Strobilurin	615
F	Boscalid	Carboxamide	713
H	Bromoxynil	Hydroxybenzonitrile	302
F	Carbendazim	Benzimidazole	410
H	Carbetamide	Carbamate	302
H&D	Chloridazon	Pyridazinone	291
GR	Chlormequat (+/-chloride)	Quarternary ammonium compound	270
F	Chlorothalonil	Chloronitrile	313
H&D	Chlorotoluron	Urea	367
I&N, I	Chlorpyrifos	Organophosphate	324
H	Clopyralid	Pyridine compound	432
H&D	Cyanazine	Triazine	221
F	Cymoxanil	Cyanoacetamide oxime	442
I&N, I	Cypermethrin	Pyrethroid	600
F	Cyproconazole	Triazole	551
F	Cyprodinil	Anilinopyrimidine	637
H&D, H	Diflufenican	Carboxamide	540
H&D	Diquat	Bipyridylium	420
F	Epoxiconazole	Triazole	626
GR	Ethephon	Ethephon	194
H&D, H	Ethofumesate	Ethylene generator	367
I&N	Ethoprophos	Organophosphate	334
F	Fenpropimorph	Morpholine	475
H&D	Florasulam	Triazolopyrimidine	691
F	Fluazinam	Phenylpyridinamine	594
H&D	Flufenacet	Oxyacetamide	648
F FST	Fluoxastrobin	Strobilurin	637
H&D, H	Fluroxypyr	Pyridine compound	518
F	Flusilazole	Triazole	529
H&D, H	Glyphosate	Phosphonoglycine	474
GR	Imazaquin	Imidazolinone (racemic mixture)	518
H&D	Iodosulfuron-methylsodium	Sulfonylurea	691
H&D, H	Isoproturon	Urea	378
F	Kresoxim-methyl	Strobilurin	518
I&N	Lambda-cyhalothrin	Pyrethroid	529
H&D	Linuron	Urea	310
GR	Maleic hydrazide	Pyridazine	151
F	Mancozeb	Carbamate	280
H&D,	H MCPA	Aryloxyalkanoic acid	148
H&D	Mecoprop-P	Aryloxyalkanoic acid	194
H&D	Mesosulfuron-methyl	Sulfonylurea	659
H	Mesotrione	Triketone	691
F	Metalaxyl-M	Phenylamide	659
I&N, M&R	Metaldehyde	Cyclo-octane	148
H&D	Metamitron	Triazinone	432
H&D	Metazachlor	Chloroacetamide	388
F	Metconazole	Triazole	615
F	Metrafenone	Benzophenone	713
H&D	Metsulfuron-methyl	Sulfonylurea	518
H	Nicosulfuron	Sulfonylurea	594
I&A&N	Oxamyl	Carbamate	345
H&D	Pendimethalin	Dinitroaniline	421
H&D	Phenmedipham	Carbamate	345

Type	**Active ingredient**	**Group**	**MJ kg ai^{-1}**
F FST	Prochloraz	Imidazole	453
F	Propamocarb hydrochloride	Carbamate	464
H&D	Propaquizafop	Aryloxyphenoxypropionate	561
H&D	Propyzamide	Benzamide	410
H	Prosulfuron	Sulfonylurea	626
F FST, FST	Prothioconazole	Triazolinthione	475
F	Pyraclostrobin	Strobilurin	702
H&D	Simazine	Triazine	226
F	Spiroxamine	Morpholine	669
S, F	Sulphur		3.70
I&N	Tau-fluvalinate	Pyrethroid - synthetic (isomer mix)	486
F FST, FST	Tebuconazole	Triazole	551
H&D, H	Thifensulfuronmethyl	Sulfonylurea	540
H	Tri-allate	Thiocarbamate	270
H&D	Tribenuron-methyl	Sulfonylurea	540
H	Triclopyr	Pyridine compound	432
H	Trifloxystrobin	Strobilurin	680
H&D, H	Trifluralin	Dinitroaniline	171
GR	Trinexapac-ethyl	Cyclohexanecarboxylate derivative	583
I&N	Zeta-cypermethrin	Pyrethroid	615

Note: from Audsley *et al.*, 2009 Table 8; F= fungicide, FST = Fungicide seed treatment, GR = Growth regulator, H&D = herbicide and desiccant, I&N = Insecticide and nematicide.

A review of emissions associated with fertiliser manufacture (Table 3.2) by Brentrup and Pallière (2008) continues to provide a robust source of fertiliser manufacture data. Values published in Hillier *et al.* (2011) who cite the Ecoinvent database (2007) and Williams *et al.* (2009) are further potential sources. The overall CO_2e varies in response to whether optimal manufacturing processes i.e. 'best available technology' (BAT) or the European average overall is quoted. The European average values are used in the calculations.

Table 3.2: The chemical composition of fertiliser products (average Europe) and the greenhouse gas emissions allocated to their manufacture

Product	Composition	GWP (t CO_2e)
ammonium nitrate	34.5% N	0.00217 kg product^{-1}[a]
ammonium sulphate	21% N; 60% SO_3	0.00034 kg product^{-1}
urea	46.4% N	0.00073 kg product^{-1}
triple superphosphate	45.5% P_2O_5 (P_2O_5: 43.6% P)	0.00035 kg product^{-1}
rock phosphate	28.5% P_2O_5	0.00097 kg P^{-1} [22]
muriate of potash	60% K_2O (K_2O: 83% K)	0.00030 kg product^{-1} [25]
sylvinite (rock K)	24% K_2O	0.00086 kg K^{-1} [22]
lime (limestone)		0.0005 kg product^{-1} [22]

Note: [a] Inclusive of N_2O released during manufacturing process.

The application of agrochemicals and amendments by spraying or spreading, tillage operations, sowing, crop harvest, machinery manufacture and depreciation per operation (Warner *et al.* 2008; 2011b) are derived from publications including Williams *et al.* (2009) and correspond closely with values given in Hillier *et al.* (2011). The CO_2e emissions from fuel consumption (gas oil or red diesel) have been adjusted to 2.95 kg CO_2e per litre (42.57 GJ t^{-1} net CV, 1175 L t^{-1}) (DBEIS, 2017ab).

3.2. Nitrous oxide (N_2O)

3.2.1. N_2O from soil

Simulations with the Global Nitrous Oxide Calculator tool (GNOC) developed by Renate (2014) for the Joint Research Council (JRC) has been used to calculate N_2O emissions for winter wheat, spring barley and oilseed rape (Table 3.3). The tool uses the IPCC (2006) methodology with modifications to account for variation in soil texture (coarse, medium, fine). Nitrous oxide emissions have been further adjusted to account for the mean N application rates to the crop management scenarios as defined by the BSFP (2017) and summarised previously in Table 2.2.

Table 3.3: Mean nitrous oxide emissions from soils under various land uses

Land use	**N_2O-N kg ha^{-1} yr^{-1}**	**t CO_2e ha^{-1} yr^{-1}**	**Reference**
Winter wheat 192 kg N ha^{-1} yr^{-1}	3.66 (3.19 – 4.37)	1.71	Renate (2014)
Winter wheat on histosols 25 kg N ha^{-1} yr^{-1}	9.47	4.43	Renate (2014)
Winter wheat no fertiliser N	0.56	0.26	Renate (2014)
Spring barley 106 kg N ha^{-1} yr^{-1}	2.01 (1.79 – 2.33)	0.94	Renate (2014)
Winter oilseed rape 184 kg N ha^{-1} yr^{-1}	3.26 (2.81 – 3.93)	1.53	Renate (2014)
Winter wheat + zero tillage		+0.55	Krauss *et al.* (2017)
Cultivated land (SNS 1) at risk to soil erosion		+0.15 – 0.28	based on van der Knijff *et al.* (2000)
Organic winter wheat + 17 t ha^{-1} FYM	2.21	1.03	Renate (2014)
Semi-improved grassland 30 kg N ha^{-1} yr^{-1}	0.65	0.30	Warner *et al.* (2011b)
Woodland	0.1	0.05	IPCC (2006)
Coniferous woodland		0.06 – 0.17	Luo *et al.* (2013)
Broadleaved woodland		0.11 – 0.41	Luo *et al.* (2013)
Hedgerow	0.05	0.02	estimate based on IPCC (2006)
Heathland burning (10% area)		0.017	IPCC (2006)
Cropland (drained peat)		8.97	Evans et al. (2017)
Drained fen or bog to cultivated land		0.247	IPCC (2014)
Drained fen or bog to temporary grassland		0.190	IPCC (2014)
Intensive grassland (drained peat)		2.80	Evans et al. (2017)
Drained fen or bog to permanent grassland		0.112	IPCC (2014)
Extensive grassland (drained peat)		1.50	Evans et al. (2017)
Bog (grass dominated and modified – drained or undrained)		0.05	Evans et al. (2017)
Bog (rewetted)		0.04	Evans et al. (2017)
Bog (almost natural)		0.03	Evans et al. (2017)
Bog (eroded and modified – drained or undrained)		0.06	Evans et al. (2017)
Bog (heather dominated and modified – drained or undrained)		0.05	Evans et al. (2017)
Drained bog (extraction)		0.087	IPCC (2014)

A meta-analysis of measured soil derived greenhouse gas emissions in agricultural systems by Linquist *et al.* (2012) reports N_2O emission of 1.808 t CO_2e ha^{-1} yr^{-1} measured in wheat crops in receipt of over 200 kg N ha^{-1} yr^{-1}. In the UK variation of 0.328 – 0.843 t CO_2e ha^{-1} yr^{-1} is observed. The same study finds comparable emissions in Denmark (0.295 - 0.641 t CO_2e ha^{-1} yr^{-1}) with greater emissions noted in Germany (0.515 – 1.639 t CO_2e ha^{-1} yr^{-1}). Nitrous oxide emissions from agricultural soils are highly variable spatially and influenced by multiple factors. The IPCC (2006) default for direct N_2O emissions from the application of supplementary N i.e. the proportion of N applied that forms N_2O-N is 1.25%. Country specific factors are reported for England by Cardenas *et al.* (2013) as 1.30% from inorganic fertiliser, 0.53% from organic fertiliser (as farmyard manure and slurry) and 0.13% from grazing deposition. Nitrogen may be further lost to the environment from leaching and surface run-off ($FRAC_{LEACH}$), termed an indirect source of N_2O (IPCC, 2006). The IPCC (2006) default $FRAC_{LEACH}$ factor, and that used by Brown *et al.* (2017) for supplementary N applied as organic and inorganic fertilisers, is 0.3. Of this, 2.5% forms N_2O-N, the total of fractions allocated to groundwater, rivers and estuaries. Cardenas *et al.* (2013) using the NITCAT model devise mean $FRAC_{LEACH}$ factors of 0.28 and 0.09 for cultivated land and grassland respectively in the UK. The mean value for cultivated land is comparable to the IPCC (2006) default, but notably lower for grassland. In addition to land use, the $FRAC_{LEACH}$ varies in response to soil type and annual rainfall. Simulations with the N balance model SUNDIAL (Smith et al., 1996) by Warner *et al.* (2008, 2011b) derived $FRAC_{LEACH}$ values for winter wheat receiving 220 kg N ha^{-1} as ammonium nitrate to account for the impact of soil type and annual rainfall (low, moderate and high). Mean $FRAC_{LEACH}$ values of 0.19 and 0.38 were calculated on clay and sandy soils respectively.

A potential mitigation strategy to reduce leaching is the use of cover crops. To account for N removed by winter cover crops before spring cereals Warner *et al.* (2016, 2017) adjust the $FRAC_{LEACH}$ by accounting for N removed from the soil by plant growth and the available N in the cover crop residues post removal. In areas of high leaching risk the presence of a cover crop reduces net emissions (Table 3.4). Where leaching risk is small the additional field operations associated with the cover crop and its removal, by cultivation in the example below, potentially result in an emissions increase. Tzilivakis *et al.* (2015) also apply a European factored soil loss equation to calculate surface run-off for a given gradient, soil texture and climate zone. This method allows the proportion of N that is lost via leaching and surface run-off ($FRAC_{LEACH}$) to be accounted for in baseline scenarios where soil erosion is potentially a risk.

Table 3.4: Nitrate leaching risk with and without a cover crop as a function of soil type and annual rainfall

Soil texture	Annual rainfall	kg NO_3-N leached with cover crop	Net t CO_2e + cultivation
Coarse	>765 mm	30.0	-0.026
Medium	>765 mm	28.2	-0.026
Fine	>765 mm	13.7	-0.026
Coarse	647 – 765 mm	16.3	-0.026
Medium	647 – 765 mm	13.5	-0.026
Fine	647 – 765 mm	3.0	-0.026
Coarse	534 – 646 mm	16.3	-0.026
Medium	534 – 646 mm	3.0	-0.026
Fine	534 – 646 mm	0.0	0.001
Coarse	451 – 533 mm	8.0	-0.026
Medium	451 – 533 mm	0.0	0.025
Fine	451 – 533 mm	0.0	0.046
Coarse	<451 mm	0.0	0.036
Medium	<451 mm	0.0	0.038
Fine	<451 mm	0.0	0.058

The workshop verified that manures are most likely to be applied to temporary grassland in the non-organic baseline scenarios, as previously assumed. It did however identify the need to modify the organic scenario and assume application of manure to the arable rotation in the organic scenarios. The IPCC (2006) method used in previous assessments (Warner *et al.*, 2008; 2011b) calculates N_2O emissions from livestock manures as a fixed proportion of the N applied to the crop within the manure. As highlighted in Warner *et al.* (2008; 2011b) the proportion of N available to the crop depends on the time of year and method of application (AHDB, 2017). The greater the availability of N to the crop, the less manufactured inorganic fertiliser N that is required, coupled with a decrease in the risk of NO_3^- leaching and NH_3 volatilisation (AHDB, 2017). Other potential sources of N_2O from soils includes the mineralisation of soil organic matter where N_2O is released coupled with a loss of SOC due to the emission of CO_2 (IPCC, 2006, 2014). Where a modification to management results in a loss of SOC, for example due to an increase in tillage frequency, the IPCC (2006, 2014) methodology is applied directly to the quantity of SOC that is predicted to be depleted within the soil. This is noted by the draining of fen or bog habitats and conversion to other land uses (Table 3.3). The N_2O

emitted from soils within coniferous forests was observed by Luo et al. (2013) to vary, depending on soil type, between 0.06 and 0.17 t CO_2e ha^{-1} yr^{-1}. For broadleaved woodland the range was 0.11 – 0.41 t CO_2e ha^{-1} yr^{-1}. The IPCC (2006) default value of 0.05 t CO_2e ha^{-1} yr^{-1} has been used in the calculations.

3.2.2. N_2O from livestock

The benefit of plant nutrients within manures and the associated N_2O emissions are assigned to the crop that they are applied to. This section considers direct deposition by livestock onto grassland and N_2O emissions from the storage of manures necessary when the animal is housed. The total N produced by livestock per ha in the baseline scenarios complies with Nitrate Vulnerable Zone rules (Defra, 2013), a maximum of 170 kg N ha^{-1} farm limit and 250 kg N ha^{-1} field limit. Stocking rates for baseline and option scenarios are based on the NVZ Guidelines Leaflet 3 (Defra, 2013), the CS mid and higher tier manuals (Natural England 2017ab), internal Natural England advisor documentation (R. Gregg *pers comm*) and feedback from the workshop. Following the method of Warner *et al.* (2011b) manure N is allocated as either direct deposition onto grass or, where livestock is housed, 100% solid FYM. A review by Chadwick *et al.* (2011) identifies measured emission factors attributed to different methods of manure storage (Table 3.5).

Table 3.5: Measured N_2O-N emission (kg) per kg N deposited

Animal and type	Method	Treatment / period	months	N_2O (% of total N content)
Cattle manure	active aeration	winter	3	0.45
	static	winter	3	0.88
	active aeration	summer	3	0.36
	static	summer	3	0.57
	static	conventional	3 - 4	0.1 – 4.3
	static	compacted + cover	3 - 4	0.6 – 2.1
	passive aeration	windrow	3	0.62
	active aeration	windrow turned	3	1.07
	static	organic	4	0.28
	static	organic with straw	4	0.26
	static	conventional	4	0.70
	static	conventional with straw	4	0.48

Note: from Chadwick *et al.* (2011)

Due to the incorporation of data from studies conducted outside of Europe (Table 3.5), the IPCC (2006) emission factors for northern Europe have continued to be used, incorporating date from Nix (2017), ABC (2017) and Brown *et al.* (2017). The total N excreted per head per annum is assigned proportionally to each category based on the proportion of the year the animal is grazed or housed. This has been adjusted in response to specifications in, for example, option GS9 (Management of wet grassland for breeding waders) that requires the removal of stock to alternative grazing areas. The IPCC (2006) mean annual default emission factor for deposition onto grassland in northern Europe accounts for leaching due to increased rainfall. The method assumes that 30% of excreted N is leached ($Frac_{LEACH}$). Where livestock are housed during the winter the majority of excreted N, if appropriately stored, will not be vulnerable to leaching. Simulations with MANNER (Chambers, 1999) by Warner *et al.* (2011b) refined the calculations to quantify the $Frac_{LEACH}$ monthly allowing the annual $Frac_{LEACH}$ to be adjusted where stock are housed throughout the winter, depending on the period and month (Table 3.6).

Table 3.6: N_2O-N emission (kg) per kg N deposited revised in response to CS option management prescriptions

Animal type	Period of grazing (months)	Mineral soil	Organic soil

Cattle (non-dairy)	12	0.024	0.044
	11 (housed December)	0.022	0.040
	7 (housed December – April)	0.014	0.025
	Default	0.020	
Sheep	12	0.014	0.024
	11 (housed December)	0.013	0.022
	7 (housed December – April)	0.008	0.014
	Default	0.010	

Note: from Warner *et al.* (2011b)

A further limitation of the IPCC (2006) methods are that they use default annual denitrification N_2O values for deposition that do not account for variation in soil type or condition, specifically the presence of organic soils and waterlogging. In addition to housing during the winter, stock may remain outside but are moved from areas dominated by wet or organic soils (e.g. moorland or marsh) to a semi-improved grassland winter keep dominated by well drained mineral soils. The IPCC (2006) methodology has been adapted for periodically wet organic soils with the emission factors of DeVries *et al.* (2003) and Hiraishi *et al.* (2013). For options where stock may be removed but not necessarily housed e.g. GS9 (Management of wet grassland for breeding waders) the alternative grazing areas for up to 10 months of the year are classed as mineral soils.

3.3. Methane (CH_4)

3.3.1. CH_4 from soil

Methane is emitted from wet soils, non-aquatic habitats tend to be credited with a net CH_4 uptake (Williams *et al.*, 2009) albeit relatively small (Table 3.7) unless the soil is compacted and anaerobic conditions are present. Krauss *et al.* (2017) report an emission of soil CH_4 of 0.002 t CO_2e ha^{-1} yr^{-1} where zero tillage is implemented. An analysis of a temperate spruce forest ecosystem by Luo *et al.* (2013) identifies a mean CH_4 uptake by the soil of 3.45 kg CH_4-C ha^{-1} yr^{-1} (4.60 kg CH_4 ha^{-1} yr^{-1}). In the UK CH_4 is a potentially key emission source from bog and fen habitats (Couwenberg and Fritz., 2012; Levy *et al.*, 2012; Lindsay et al, 2010; Turetsky *et al.* 2014; Worrall *et al.*, 2011). The magnitude of these emissions depends on the type of management, water level and the vegetation present (Table 3.7).

Table 3.7: Methane emission from soils

Land use	**kg CH_4 ha^{-1} yr^{-1}**	**t CO_2e ha^{-1} yr^{-1}**	**Reference**
Winter wheat	-0.650	-0.016	Williams *et al.* (2009)
Winter wheat + zero tillage		0.002	Krauss *et al.* (2017)
Winter wheat no fertiliser N	-0.731	-0.018	Williams *et al.* (2009)
Organic rotation	-0.731	-0.018	Williams *et al.* (2009)
Cropland (drained peat)		0.02	Evans et al. (2017)
Cropland on peat - land	-1.5	-0.04	Evans et al. (2016)
Cropland on peat - ditch	22.7	0.567	Evans et al. (2016)
Intensive grassland beef cattle	-0.650	-0.016	Williams *et al.* (2009)
Semi-improved grassland	-0.650	-0.016	Williams *et al.* (2009)
Unfertilised grassland	-0.731	-0.018	Williams *et al.* (2009)
Intensive grassland (drained peat)		0.37	Evans et al. (2017)
Grassland (managed) on peat - land	-1.3	-0.03	Evans et al. (2016)
Grassland (managed) on peat - ditch	72.0	1.80	Evans et al. (2016)
Extensive grassland (drained peat)		1.82	Evans et al. (2017)
Woodland	-1.625	-0.039	Falloon *et al.* (2004)
Temperate spruce forest	-3.45	-0.115	Luo *et al.* (2013)
Hedgerow	-	-0.020	Estimate based on Falloon *et al.* (2004)

Wetland - cold, moist temperate zone		0.53	Brown *et al*. (2017)
Wet grassland		0.32	Ostle *et al*. (2009)
Temperate peatland - dry	0.20	0.005	Couwenberg and Fritz (2012)
Raised bog (extraction) - land	0.9	0.02	Evans et al. (2016)
Temperate peatland - wet	50.0	1.25	Couwenberg and Fritz (2012)
Bog (vascular plant dominated hummock)		0.83	Lindsay et al (2010)
Bog (vascular plant dominated hollow)		3.25	Lindsay et al (2010)
Bog (*Sphagnum* dominated hollow)		0.44	Lindsay et al (2010)
Bog (non-vegetated hollow)		0.88	Lindsay et al (2010)
Bog (eroded and modified – drained or undrained)		1.19	Evans et al. (2017)
Bog (heather dominated and modified – drained or undrained)		1.36	Evans et al. (2017)
Bog (grass dominated and modified – drained or undrained)		1.36	Evans et al. (2017)
Bog (rewetted)		2.02	Evans et al. (2017)
Bog (almost natural)		2.83	Evans et al. (2017)
Fen (conserved) - land	172.0	4.30	Evans et al. (2016)
Fen (conserved) - ditch	122.7	3.07	Evans et al. (2016)
Fen		4.75	Lindsay et al (2010)
Temperate peatland - wet + shunt	170.0	4.25	Couwenberg and Fritz (2012)
Peatland - per 1 cm increase water table	4.0	0.10	Levy *et al*. (2012)
Peatland - <20 cm surface + aerenchymatous vegetation per 1 cm increase water table	17.0	0.425	Couwenberg *et al*. (2011)
Reedbed		4.75	Estimate based on Lindsay et al (2010)
Heathland burning (10% area)		0.055	IPCC (2006)

A synthesis of CH_4 emissions from wetland ecosystems by Turetsky *et al.* (2014) also concludes that CH_4 emission varies in response to water depth, whether the habitat is pristine or disturbed, and the potential for vascular transport (the 'methane shunt') due to the presence of aerenchymatous plant species and vegetation structure. The detailed assessment of UK wetlands by Lindsay et al (2010) and Evans et al. (2016, 2017) are the most concise evaluation of the topic for the UK. In summary Lindsay et al (2010) identifies the following phases in CH_4 emission from bog habitats, adapted based on the proportion of vegetation types present (Warner *et al.*, 2011b):

- Year 1: formation of non-vegetated aquatic hollows (0.88 t CO_2e ha^{-1} yr^{-1}) with cotton-grass abundant on terrestrial hummocks (0.83 t CO_2e ha^{-1} $year^{-1}$).
- Years 2 and 3: cotton-grass abundant in aquatic hollows (3.25 t CO_2e ha^{-1} yr^{-1}).
- Years 4 to 5: increased colonisation in aquatic hollows by *Sphagnum* species (0.83 t CO_2e ha^{-1} yr^{-1}) with a decline in vascular plants.

A number of studies published since 2011 support the observations of Lindsay et al (2010), and report that CH_4 flux from peat soils is a function of water depth and the presence of vascular plants, namely aerenchymatous vegetation, plants with channels that allow the direct exchange of gases between the roots and leaves (Couwenberg *et al.*, 2011; Couwenberg and Fritz., 2012; Evans et al., 2016; Turetsky *et al.* 2014; Worrall *et al.*, 2011). According to Lindsay et al (2010) *Sphagnum* mats present in hollows prevent the movement of CH_4 from below the water table to the atmosphere. The prolonged presence of CH_4 in an aerobic environment within the mat causes oxidation to CO_2, resulting in negligible CH_4 emission (Table 3.7).

3.3.2. CH_4 from livestock

The previous assessment by Warner *et al.* (2011b) calculated enteric CH_4 in response to the proportion of forage versus concentrates within the diet. This allowed modifications to be made to the diet in response to modifications to the period of housing. This method has been continued with further adaptations where new CS options (Natural England, 2017ab) necessitate modification to the housing period or period on which grazing may be undertaken on potentially waterlogged soils, for example options GS9 (Management of wet grassland for breeding waders) and GS10 (Management of wet grassland for wintering waders and wildfowl). The dietary composition (total metabolisable energy requirement, quantity of concentrates, grass silage and grazing) have been derived from ABC (2017), AHDB (2017), Nix (2017) and Williams *et al.* (2009) as described in section 1.1.

The method to calculate CH_4 from manures produced during housing accounts for the dietary composition (ABC, 2017; AHDB, 2017; Nix, 2017; Williams *et al*, 2009), and the associated volatile solids per kg of feed dry matter (Thomas, 2004) in addition to storage method, storage temperature (IPCC, 2006) and period for a given baseline or CS option (Natural England 2017ab). As in the previous assessment (Warner *et al.*, 2011b) manures produced within the baseline scenarios consist of FYM stored in unconfined piles or stacks at a mean temperature of less than 10°C, or composted in vessel with forced aeration and continuous mixing.

3.4. Carbon sequestration and soil CO_2 emission

3.4.1. Soil organic carbon baselines

A global analysis of soil carbon stocks is undertaken by Scharleman *et al.* (2014) who reference total carbon stocks by IPCC (2006) climate region, there is however no disaggregation of the data to a per unit area basis. Lugato *et al.* (2014a) model SOC content across Europe but do not publish unit area SOC data for individual Member States. Values for selected countries cited by Panagos *et al.* (2013ab) and Toth *et al.* (2013) note mean values ranging between 28.0 (Bulgaria) and 100.1 t C ha^{-1} (Netherlands) or 102.7 - 367.0 t CO_2e ha^{-1}. The latter is comparable to the higher value cited for the UK by Bradley (2005) in Table 3.8, although lower than the mean values disaggregated by land use and soil type in England (Dyson *et al.*, 2009). Cantarello *et al.* (2011) disaggregate soil carbon data for 11 Corine Land Cover 2000 (CLC2000) land use categories present in the south-west of England (Table 3.8) which are broadly in agreement with Bradley (2005) and Dyson *et al.* (2009).

Table 3.8: Mean SOC (t CO_2e) to a depth of 30 cm (and to 1 m in parentheses) in England (and UK where stated).

Land use	t CO_2e ha^{-1}	Reference
Non-irrigated arable land	234.3	Cantarello et al. (2011)
Bioenergy crops	273.5	
Complex cultivation patterns, fruit trees and berry plantations, land principally occupied by agriculture, with significant areas of natural vegetation and transitional woodland-shrub	324.1	
Green urban areas – sport and leisure facilities	334.8	
Moors–heathland	377.7	
Coniferous forest	392.3	
Natural grasslands–pastures	443.7	
Mixed forest	454.7	
Inland and salt marshes	524.3	
Broadleaved forest	594.0	
Peat bogs	2112.0	
Cultivated land – average UK	256.7 (440.0)	Bradley et al. (2005)

Land use	t CO_2e ha^{-1}	Reference
Grassland – average UK	293.3 (477.0)	
Forest / woodland – average UK	366.7 (623.0)	
Cultivated - mineral soil	282.3 (440.0)	Dyson et al. (2009)
Cultivated - organo-mineral soil	429.0 (865.3)	
Cultivated - organic soil	623.3 (2977.3)	
Grassland - mineral soil	352.0 (535.3)	
Grassland - organo-mineral soil	634.3 (693.0)	
Grassland - organic soil	729.7 (2647.3)	
Forest - mineral soil	392.3 (550.0)	
Forest - organo-mineral soil	447.3 (740.7)	
Forest - organic soil	839.7 (4158.0)	

Note: from Bradley *et al.* (2005), Cantarello *et al.* (2011), Dyson *et al.* (2009), West (2011).

The soil organic carbon baselines in Brown et al. (2017) to 1 m are based on earlier data published in Bradley *et al.* (2005) and Milne and Brown (1997). Changes in SOC (section 3.4.2) are typically reported within the top 30 cm of the soil profile. Nocita *et al.* (2014) using diffuse reflectance spectroscopy predict a similar sequence, with cultivated arable soils containing the lowest SOC (3.6 - 3.9 g C kg^{-1}) then grassland (7.2 - 7.9 g C kg^{-1}) with woodland the highest (11.9 - 13.8 g C kg^{-1}). Using a comparable method Stevens *et al.* (2013) draw similar conclusions, stating SOC contents of 4.0 - 4.9 g C kg^{-1} for cultivated arable soils, 6.4 - 9.3 g C kg^{-1} in grassland and 10.3 - 15.0 g C kg^{-1} in samples taken from woodland. Organic soils associated with bog or fen habitats were by far the highest with 50.6 g C kg^{-1}. Bell (2011) measures site specific SOC in the north-east of England at a depth of 20 cm concluding that SOC is far higher in areas where bog habitats were or had been present.

3.4.2. Soil organic carbon gain

Brown et al. (2017) report mean soil organic carbon change to a depth of 100 cm in England as: cultivated land to grassland +23.0 t C ha^{-1} (84.3 t CO_2e ha^{-1}), cultivated land to forest +32.0 t C ha^{-1} (117.3 t CO_2e ha^{-1}), forest to grassland -21.0 t C ha^{-1} (-77.0 t CO_2e ha^{-1}), forest to cultivated land -31.0 t C ha^{-1} (-113.7 t CO_2e ha^{-1}) and grassland to cultivated land -23.0 t C ha^{-1} (-84.3 t CO_2e ha^{-1}). A European scale analysis of SOC change due to land use change undertaken by Poeplau and Don (2013) supports the hierarchy of the SOC values given in Table 3.8, citing the mean change in soil organic carbon overall: cultivated land to grassland +17.0 t C ha^{-1} (63.3 t CO_2e ha^{-1}), cultivated land to forest +18.0 t C ha^{-1} (66.0 t CO_2e ha^{-1}), and grassland to cultivated land -24.0 t C ha^{-1} (-88.0 t CO_2e ha^{-1}). A discrepancy is observed for grassland to forest where a mean decline of 3.0 t C ha^{-1} (-11.0 t CO_2e ha^{-1}) is calculated. Disaggregation of the data reveals variable response to a change in land use from grassland to forest, with both positive, negligible and negative responses evident. The establishment of forest areas on soils with a high organic fraction, where further drying of the land may potentially decrease SOC, is a site and soil type specific response.

Modification to tillage regime and the implementation of non-inversion techniques has been promoted as a means to enhance SOC in cropland without a change in land use, for example by Lal (2011). The precise benefit of reduced and zero tillage on soil C sequestration remains a contentious issue. Reviews by Powlson *et al.* (2011; 2014) cast doubt on the value of minimum and zero tillage as methods to enhance carbon in agricultural soils significantly. The authors dispute the value of both methods, concluding that the SOC is typically redistributed within the soil profile i.e. decreasing in the deeper and increasing in the shallower layers, rather than there being any significant net gain. Krauss *et al.* (2017) interpret this process as being due to non-incorporation of surface present organic material into the deeper soil layers and the potential increase in soil compaction inhibiting root penetration. Louwagie *et al.* (2008) note that topsoil compaction may reduce biomass accumulation and organic matter return to the soil by up to 13%. Soil compaction as influenced by tillage regime is however, as highlighted by Ogle *et al.* (2011), a highly site specific impact. In summary Powlson *et al.* (2015) state that '*no-till is beneficial for soil quality and adaptation of agriculture to* *climate change, but its role in mitigation is widely overstated*'. Similar conclusions are drawn by Sheehy *et al.* (2015) in Europe, Syswerda *et al.* (2011) in the United States and Huang *et al.* (2015) in China. A meta-analysis of zero tillage by Ogle *et al.* (2011) found the response to be highly variable. Factors included climatic variability, variation in seeding method and a potential decrease in crop productivity. The latter resulted in a decline in return of organic matter via the return of plant material. A review of UK relevant literature by Moxley et al. (2014) also concludes that zero tillage has a limited impact on soil carbon (Table 3.9). Although Powlson *et al.* (2015) estimate, subject to caveats, that a value of 0.3 t C ha^{-1} yr^{-1} (1.1 t CO_2e ha^{-1} yr^{-1}) is realistic for zero tillage (Table 3.9) comparable to figures stated by Ostle *et al.* (2009), the value determined by Moxley et al. (2014) have been used in the current analysis. Krauss *et al.* (2017) cite an increase of 2.3 t CO_2e ha^{-1} yr^{-1} in soil organic carbon but critically observe the potential increase in N_2O (0.55 t CO_2e ha^{-1} yr^{-1}) and CH_4 (0.002 t CO_2e ha^{-1} yr^{-1}) to give a net mitigation of 1.76 t CO_2e ha^{-1} yr^{-1}. Removing the accumulation of SOC results in a net increase in soil based emissions.

Regina *et al.* (2015) in response to a 30 year field trial conclude that reduced tillage had a negligible impact on SOC, a similar conclusion was drawn after a seven year trial by Hansen *et al.* (2015). Garcia-Franco *et al.* (2015) found a negligible impact where reduced tillage was used in the absence supplementary plant residues, but increased where a green manure consisting of *Vicia sativa* L. and *Avena sativa* L was present. A data-mining approach comparing conventional with minimum and zero tillage by Francaviglia *et al.* (2017) noted a positive impact for zero tillage, although under Mediterranean climatic conditions. Hillier et al. (2011) assign a factor of 1.09 to carbon sequestration in minimum tilled systems but this is based on the Tier 1 approach in the IPCC (2006).

A meta-analysis of cover crops concludes that annual accumulation for the first 50 years is 0.32 t C ha^{-1} yr^{-1} (1.17 t CO_2e ha^{-1} yr^{-1}), with saturation (equilibrium) reached after 155 years (Poeplau and Don, 2015). A meta-analysis of conventional and organic farming rotations (Gattinger *et al.*, 2012) assigns a sequestration rate of 0.3 t C ha^{-1} yr^{-1} (1.10 t CO_2e ha^{-1} yr^{-1}). Cover crops have the potential to reduce CO_2 emissions due to soil erosion (section 1.2.4.3). Other strategies to enhance SOC in cultivated land include crop residue and farmyard manure incorporation (Blanchet *et al.*, 2016) and the addition of biochar, although a recent evaluation of the strategy by Smith (2016) continues to highlight the uncertainty associated with its precise mitigation potential. Biochar is not included within CS and has not been scrutinised further.

Soil carbon sequestration values attributed specifically to temporary grassland are relatively sparse in the literature. Rutledge *et al.* (2015) in a study in New Zealand observe declines of 100 – 200 g C m^{-2} (3.67 – 7.33 t CO_2e ha^{-1}) within the first three months post cultivation of grassland, before CO_2 emission ceases and sequestration begins. It supports previous statements by authors such as Smith *et al.* (2008) that SOC is lost rapidly, and the previous estimation by Warner *et al.* (2011b) that the temporary grassland baseline is lower than that of permanent grassland, although Warner *et al.* (2011b) use a mean SOC baseline value and do not account for the period of time since cultivation. The baseline SOC for temporary grassland in Warner *et al.* (2011b) decreases the permanent grassland SOC cited by Dyson *et al.* (2009) by a factor of 1.01. This factor is estimated with data derived for permanent grassland on mineral soils (Dyson *et al.*, 2009) and from the difference in SOC between neutral grassland and improved grassland in England from the Countryside Survey of 2007 (Carey *et al.* 2008). Rutledge *et al.* (2015) measure sequestration rates of 165 g C m^{-2} yr^{-1} (6.05 t CO_2e ha^{-1} yr^{-1}) once SOC stocks in temporary grassland begin to recover but do not specify the exact time period over which this rate of accumulation occurs. The high rate accumulation rate would suggest that it is over a relatively short period. Wang *et al.* (2011) are one of the few studies to publish data related to temporary or cultivated and reseeded grassland. The data is shown as percent change in SOC and is derived under climatic conditions attributed to China rather than Europe. Further, there is insufficient detail within the publication regarding the total SOC present and soil bulk density to allow the calculation of the change in SOC as t CO_2e ha^{-1} yr^{-1}. A mean annual percent change in soil carbon stocks of 6.4% where cultivated arable land is converted to temporary grassland, is included in Table 3.9 for reference purposes.

Lugato *et al.* (2014b) cite 1.44 t C ha^{-1} yr^{-1} (5.28 t CO$_2$e ha^{-1} yr^{-1}) by Vleeshouwers and Verhagen (2002) when arable land is converted to grassland, although they do not state the management protocol of the grassland. Values of 0.15 and 0.25 t C ha^{-1} yr^{-1} (0.55 and 0.92 t CO$_2$e ha^{-1} yr^{-1}) are also cited for straw incorporation and minimum tillage respectively, but these values are cited from a 2002 study and do not represent an improvement on the figures of Ostle *et al.* (2009). Smith (2014a) highlights the importance of appropriate management of grasslands in order to maximise and maintain their value as a C sink. Grassland management practices cited in the published literature to potentially improve SOC accumulation rates include liming and appropriate supplementary nutrition (Fornara *et al.*, 2011; 2013) and avoidance of damage to the soil structure by livestock (Stockman *et al.*, 2013). Stockmann *et al.* (2013) assign 0.02 – 0.4 t C ha^{-1} yr^{-1} (0.07 – 1.14 t CO$_2$e ha^{-1} yr^{-1}) to ‘improved grazing’, grazing that does not cause land degradation through excessive stocking rates. This is attributed to the capacity to induce greater proliferation of fine root production and an increase in overall root biomass compared to where grazing is absent (Acharya *et al.*, 2012). Moderate grazing levels are proposed by Klumpp *et al.* (2011) as a means to maintain a balance between multiple microbial respiration pathways i.e. heterotrophic and autotrophic during periods of environmental stress such as drought, maintaining microbial diversity also highlighted as important by Lange *et al.* (2015). A reduction in soil disturbance frequency decreases the number of gram+ bacteria within the soil (McSherry *et al.*, 2013). This group of bacteria are responsible for the accelerated decomposition of organic carbon greater than 0.5 of a year old, resulting in increased emission of CO$_2$ and a decline in SOC.

A change in land use may result in overall gains or losses depending on the nature of the land use change. The rate at which SOC changes and establishes a new equilibrium also depends on the nature of the land use change. Brown *et al.* (2017) denote SOC loss as being ‘fast’ (50 – 150 years in England) and gain as ‘slow’ (100 – 300 years in England). A mean period of 100 and 200 years are used for loss and gains in SOC respectively. Increasing plant species diversity within a grassland, which promotes soil microbial activity within the system, potentially increases SOC accumulation (Lange *et al.*, 2015) by up to 317 g C m^{-2} (11.28 t CO$_2$e ha^{-1} yr^{-1}) according to De Dyn *et al.* (2011). The latter authors acknowledge that this value is high, citing the site specific factors of the trial site as a likely cause. This value was excluded for use in the calculations.

Table 3.9: Soil Organic Carbon accumulation (to 30 cm, post 2010 references).

Original land use	New land use / management practice	t CO$_2$e ha^{-1} yr^{-1}	Reference
Cultivated arable	minimum tillage	0	Moxley *et al.* (2014)
	zero tillage	0	Moxley *et al.* (2014)
	increased crop rotation complexity	^{a}*0.73*	Stockmann *et al.* (2013)
	bare soil only	^{a}*-0.92*	Stockmann *et al.* (2013)
	organic rotation	1.10	Gattinger *et al.* (2012)
	permanent grassland (to 1 m)	0.28 – 0.84	Brown *et al.* (2017)
	permanent grassland	1.05	Cantarello *et al.* (2011)
	forest (to 1 m)	0.39 – 1.17	Brown *et al.* (2017)
	minimum intervention woodland	^{b}0.37 - ^{c}0.55	West (2011); Forestry Commission (2018)
Fertilised permanent grassland	balanced nutrient management	0.26 – 0.55	Fornara *et al.* (2011)
	improved grazing	^{a}*0.73*	Stockmann *et al.* (2013)
	woodland - ground preparation by hand turfing year 1	^{d}0	West (2011); Forestry Commission (2018)
	forest (to 1 m)	0.31 – 0.92	Brown *et al.* (2017)
Unfertilised grassland	marshy grassland (drainage)	-0.07	Buys *et al.* (2014)
Peat	rewetted terrestrial area	0.84	IPCC (2014)

Note: ^{a}data derived from Canada; ^{b}>50 years; ^{c}year 0 – 50; ^{d}for 2700 trees ha^{-1} on mineral soil.

Lindsay et al (2010), Ostle *et al*. (2009) and Dawson and Smith (2007) cite a C net gain in restored UK peatlands of 0.7, 0.73 and 1.83 t CO_2e ha^{-1} yr^{-1} respectively, the former two values being broadly in agreement with the 0.84 t CO_2e ha^{-1} yr^{-1} cited by the IPCC (2014). The description of restored peatlands corresponds closely with that of the 'peat soil post grip blocking' of Worrall *et al*. (2011), which has a somewhat lower value of 0.2 t CO_2e ha^{-1} yr^{-1} due to accounting for the additional GWP from CH_4 emission.

3.4.3. Soil CO_2 emission

Carbon within soil may be lost through wind or water erosion (Lugato *et al*., 2016). Dawson and Smith (2007) and Ostle *et al*. (2009) cite a mean loss 0.22 t soil ha^{-1} yr^{-1}. Warner *et al*. (2013) and Tzilivakis *et al*. (2015) estimate SOC loss (and surface run-off of nitrate) for different land uses by calculating soil erosion using land cover (C) factors (Table 3.10) applied to a European specific soil loss equation (van der Knijff et al., 2000). The equation also accounts for annual rainfall and the energy with which it impacts the soil surface (erosivity), the gradient of the land coupled with the characteristics of the ground cover as indicated by the C-factor. What is of interest with the C-factor is that it is the one element of the erosion calculation that can be manipulated by anthropogenic intervention through modification to land management and vegetation cover. The lower the C-factor of a given land use, the lower the risk of soil erosion and loss of soil carbon. The most recent C-Factors for Europe are provided by Panagos *et al*. (2015) and are summarised (highest to lowest) in Table 3.10.

Table 3.10: Soil erosion C-Factor values

Land cover	C-Factor
Burnt areas	0.1–0.55
Fallow land	0.50
Sparsely vegetated areas	0.1–0.45
Grain maize – corn	0.38
Annual crops associated with permanent crops	0.07–0.35
Oilseeds	0.28
Common wheat and spelt	0.20
Complex cultivation patterns	0.07–0.2
Land principally used for agriculture, with significant areas of natural vegetation	0.05–0.2
Pastures	0.05–0.15
Agro-forestry areas	0.03–0.13
Moors and heathland	0.01–0.1
Natural grasslands	0.01–0.08
Transitional woodland-shrub	0.003–0.05
Broad-leaved forest	0.0001–0.003
Coniferous forest	0.0001–0.003
Mixed forest	0.0001–0.003

Note: from Panagos *et al.* (2015)

Erosion may be mitigated by ensuring continuous vegetation cover (Guerra *et al*., 2016; Guerra and Pinto-Correia, 2016). The type of vegetation cover is a key determinant of the extent of that mitigation, as shown in Table 3.11. Burnt areas feature prominently, as is illustrated for increasing the risk of erosion in heathland habitats by Cawson *et al*. (2012). Greenhouse gas emissions from the burning of heathland may be calculated using the IPCC (2006) method although Lindsay et al (2010) and Santana *et al*. (2015) note that precise losses vary in response to the NVC community and duration since the previous burn. Carbon loss through soil erosion is estimated between <0.05 t C ha^{-1} yr^{-1} (0.18 t CO_2e ha^{-1} yr^{-1}) where slopes are negligible to 0.1 – 0.3 t C ha^{-1} yr^{-1} (0.37 – 1.10 t CO_2e ha^{-1} yr^{-1}) on more steeply sloping land (Borelli *et al*., 2016). The median value for Italy is estimated as 0.11 t C ha^{-1} yr^{-1} (0.40 t CO_2e ha^{-1} yr^{-1}). For the UK, where the baseline is assumed to carry a risk of soil erosion due to its presence on, for example, steeply sloping land, a value of 0.7 t CO_2e ha^{-1} yr^{-1} has been allocated using the method of van der Knijff et al. (2000) applied to winter wheat on cultivated land with a C-factor of 0.2. Where a change in vegetation cover results due to the implementation of CS, the C-factor for winter wheat is substituted with the relevant C-factor derived from Table 3.10. An evaluation of the effectiveness of GAEC measures as means to mitigate soil erosion by Borrelli *et al*. (2016) derives values of less than 0.004 t C ha^{-1} yr^{-1} (0.015 t CO_2e ha^{-1} yr^{-1}) on flat land to between 0.009 and 0.030 t C ha^{-1} yr^{-1} (0.033 – 0.11 t CO_2e ha^{-1} yr^{-1}) on gradients.

The overall t CO_2e, inclusive of N_2O and CH_4 in addition to CO_2, for a variety of management practices and habitat condition for bog and fen is summarised in Table 3.11. The negative value attributed to pristine bog and peat soil post grip blocking denotes the accumulation of organic carbon with the soil. The protection of organic high C peat soils found in bog habitats is a cited by numerous authors as a priority strategy in northern Europe to mitigate CO_2 emission from soils (Schils *et al.*, 2008; Smith *et al*., 2008). Generic estimates of CO_2 emissions where habitat degradation occurs used for national inventory purposes include 18.3 t CO_2e ha^{-1} yr^{-1} from organic soils managed as cropland, (29.0 t CO_2e ha^{-1} yr^{-1} is reported by the IPCC, 2014 although this value is not presently used by Brown et al., 2017). Management specific evaluations which are of greater value to the assessment of CS options are provided by Evans et al. (2016), Berglund and Berglund (2011), Couwenberg (2011), Lindsay et al (2010) and Worrall *et al*. (2011), summarised in Table 3.11. The data provided by Evans et al. (2016), Lindsay et al (2010) and Worrall *et al*. (2011) includes UK specific values.

Table 3.11: Net greenhouse gas emissions (t CO_2e ha^{-1} yr^{-1}) associated with peat soils

Habitat	Condition	t CO_2e ha^{-1} yr^{-1}
Bog	pristine	-4.11
	drained peat soil + afforestation	2.49
	as forestry on poor soils	2.49
	as forestry on rich soils	2.49
	cultivated	36.67
	drained peat soil + cultivation or temporary grassland	22.42
	drained peat soil + permanent improved grassland	8.68
	grassland	9.17
	drained peat soil + extraction	10.27
	drained peat soil + rotational burning	2.56
	peat soil post grip blocking	-0.2
	peat soil + overgrazing	0.1
Fen	pristine	4.2
	drained peat soil + afforestation	2.49
	drained peat soil + cultivation	28.97
	drained peat soil + temporary grassland	22.37
	drained peat soil + permanent improved grassland	13.20
	drained peat soil + removal	1.57
	dissolved organic carbon (DOC)	1.14

Note: from Couwenberg (2011), Evans et al. (2016), IPCC Wetlands (2014) and Worrall et al. (2011); a positive value indicates a net flux to the atmosphere.

Both Couwenberg *et al*. (2011), Couwenberg and Fritz (2012), Evans et al. (2016) and Worrall *et al*. (2011) note significant emissions from degraded peat habitats. Fens are noted to emit greenhouse gases while in pristine condition, mainly due to the presence of aerenchymatous vegetation however this is greatly amplified upon drainage due to the mineralisation of SOC.

3.4.4. Biomass carbon

Cantarello *et al.* (2011) devise carbon stocks for 11 Corine Land Cover 2000 (CLC2000) land use classifications within the south-west UK (Table 3.12). A review of the mean C sequestration in woodland tree biomass within the UK (Ostle *et al.*, 2009) cites 140.0 t C ha^{-1} (513.3 t CO_2e ha^{-1}), higher than values for broadleaved forest by Cantarello *et al.* (2011).

Table 3.12: Total biomass (t CO_2e) for 11 Corine Land Cover 2000 (CLC2000) land use classifications

Land use	t CO_2e ha^{-1}
Broadleaved forest	407.0
Complex cultivation patterns, fruit trees and berry plantations, land principally occupied by agriculture, with significant areas of natural vegetation and transitional woodland-shrub	53.9
Coniferous forest	216.7
Green urban areas – sport and leisure facilities	30.5
Inland and salt marshes	30.9
Mixed forest	286.0
Moors–heathland	26.1
Natural grasslands–pastures	11.4
Non-irrigated arable land	8.7
Bioenergy crops	10.6
Peat bogs	26.2

Note: from Cantarello *et al.* (2011)

The Forestry Commission (2018) publish data for selected trees found in the UK (Table 3.13) and include variables for growth class and spacing. Where conifers are removed from within a woodland and left to decay without intervention, coarse woody biomass does not release CO_2 until post year three (Morison et al., 2012). During years one and two there is no decay, during year three the biomass is transferred to the non-woody debris pool linearly at a rate of 5% per year over the subsequent 20 year period (Morison et al., 2012). Once in the non-woody debris pool, CO_2 is released at a rate of 50% per year i.e. full decomposition within two years (Morison et al., 2012). If hypothetically a 10% area is cleared of 50 year old European Larch, equivalent to 52.8 t CO_2 e ha^{-1}, and the biomass left to decay, an estimated 2.6 t CO_2e ha^{-1} yr^{-1} is released during years 5 – 24 (50% of this value is released in year four). Replanting of the equivalent percent area with a broadleaved species at 3.0 m spacing results in net CO_2 emissions during the initial five or 10 year period depending on species, before biomass accumulation exceeds the decay rate.

Table 3.13: Total carbon in biomass (t CO_2 e ha^{-1}) and mean annual carbon sequestration rate (t CO_2e yr^{-1}) at 5 year increments to year 50 for selected tree species present in the UK.

Species / age	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50	150
Beech	2.0	80	31.0	109.0	290.0	455.0	538.0	596.0	655.0	713.0	1432.0
gain t CO_2e yr^{1}	0.3	1.3	4.5	15.7	36.1	33.0	16.7	11.5	11.9	11.6	
Oak	4.0	23.0	94.0	270.0	448.0	529.0	585.0	641.0	693.0	745.0	1320.0
gain t CO_2e yr^{1}	0.8	3.8	14.3	35.2	35.6	16.2	11.2	11.2	10.3	10.4	
Sycamore, ash and birch	8.0	44.0	158.0	313.0	420.0	528.0	629.0	690.0	735.0	770.0	982.0
gain t CO_2e yr^{1}	1.6	7.3	22.7	31.1	21.3	21.8	20.1	12.1	9.1	7.1	
Mean broadleaves	5.5	27.4	98.0	233.7	387.2	504.1	584.1	642.1	694.3	742.8	1245.0
gain t CO_2e yr^{1}	1.1	4.4	14.1	27.1	30.7	23.4	16.0	11.6	10.4	9.7	
Douglas fir	7.0	19.0	41.0	90.0	218.0	353.0	391.0	456.0	514.0	561.0	878.0
gain t CO_2e yr^{1}	1.5	2.4	4.3	10.0	25.6	27.0	7.6	12.9	11.7	9.4	
European larch	8.0	27.0	73.0	187.0	293.0	349.0	409.0	455.0	495.0	528.0	704.0

gain t CO_2e yr^{1}	1.7	3.7	9.1	22.8	21.4	11.0	12.0	9.3	8.0	6.6	
Hybrid larch	12.0	40.0	115.0	230.0	292.0	351.0	391.0	423.0	449.0	472.0	691.0
gain t CO_2e yr^{1}	2.4	5.6	14.9	23.0	12.4	12.0	7.8	6.4	5.3	4.6	
Japanese larch	12.0	41.0	118.0	237.0	302.0	365.0	407.0	441.0	469.0	494.0	727.0
gain t CO_2e yr^{1}	2.5	5.8	15.3	23.9	13.0	12.6	8.3	6.8	5.6	4.9	
Sitka spruce	2.0	6.0	16.0	43.0	124.0	240.0	298.0	360.0	422.0	476.0	762.0
gain t CO_2e yr^{1}	0.4	0.8	2.0	5.5	16.3	23.1	11.6	12.4	12.4	10.8	
Mean conifers	8.5	26.7	72.3	157.4	246.0	331.6	379.0	426.8	469.7	506.1	752.0
gain t CO_2e yr^{1}	1.7	3.6	9.1	17.0	17.7	17.1	9.5	9.6	8.6	7.3	

Note: from Forestry Commission (2018); assumes broadleaves growth class 8, spacing 3.0m; conifers growth class 8, spacing 1.7m

3.4.5. Burning

The management for lowland heathland (LH1) permits burning on a proportion of the area. Greenhouse gas emissions from the burning of plant residues, L_{fire}, are summarised in Equation 1 (IPCC, 2006). The IPCC (2006) methodology considers CH_4 and N_2O only, CO_2 is included if there is either a change in land use or growth rates dictate that the carbon within the combusted material is not replaced completely by the accumulation of biomass in regrowth the following year. The biomass in dwarf shrub vegetation is assumed replaced within a five year period.

Equation 1

$$L_{fire} = A \times M_B \times C_f \times G_{ef} \times 10^{-3}$$

where:

A: *area burnt, ha^{-1}*

M_B: *mass of fuel available for combustion (default value for Calluna = 11.5 t DM ha^{-1})*

C_f: *combustion factor (default value for Calluna = 0.71)*

G_{ef}: *emission factor as g kg^{-1} dry matter burnt (default values $CH_4 = 2.7$, $N_2O = 0.07$)*

4.0 Method

The method adopts a Life-cycle Assessment (LCA) approach adopted by previous assessments (Warner *et al.*, 2008, 2011b) for Defra (projects BD2302 and BD5007) and for the European Commission (Lewis *et al.*, 2010, 2012). The following section cites the method described in Warner et al. (2014). It is described in more detail in the ISO 14040 Guidelines (ISO, 2006ab). The net change in greenhouse emissions, either positive or negative, is quantified for each CS option relative to the baseline land use. Life Cycle Assessment is an internationally standardised method for the evaluation of all the environmental impacts (both positive and negative) of a product (or a service) throughout its complete life cycle (ISO 14040) (ISO, 2006ab) and has to date been successfully applied to agriculture and horticulture (Defra, 2003; Tzilivakis *et al.*, 2005ab; Warner *et al.*, 2008, 2010, 2011b). For the purpose of this assessment the focus of the LCA is greenhouse gas emissions only, however the principles of the analysis will be applied. The alterations in land management associated with each CS option will have firstly, a direct impact on the processes that affect greenhouse gas emissions from within the immediate environment i.e. where the CS option is implemented (such as increased emissions of N_2O from the soil). Secondly, they will also have indirect impacts through, for example, the reduction or prohibition of the use of certain agro-chemical products. Each product has greenhouse gas emissions (namely CO_2 from the combustion of fossil fuels) associated with their manufacture, packaging and transport and these must also be taken into account. An LCA considers the impacts of the entire system and potential impacts throughout a product's life, where in this case the product is each CS option.

A typical LCA consists of the following steps:

1. Goal and Scope Definition: describes the application covered, the reasons for carrying out the study, and the target audience. The scope is the detailed technical description of the "product system" under study, in this case the baseline scenario and each CS option (years one to five) to the farm gate.

2. Life Cycle Inventory Analysis: consists of the compilation and quantification of the environmental inputs and outputs for the product system throughout its life cycle. It will include greenhouse gas emissions from the manufacture of any products applied, the manufacture of machinery used and the fuel consumed for field operations, changes in N_2O or CH_4 emissions and carbon sequestration associated with changes in land use and/or management through the implementation of CS options. This stage may use meta-modelling to derive impacts in addition to standard methodologies. For example soil erosion and surface run-off of nitrate. The risk of surface flow of NO_3^- into water courses was calculated by Lewis et al. (2012) using a combination of soil erosion risk (Kirkby *et al.*, 2004) and residual soil nitrogen, the existing mineral NO_3^--N and NH_4^+-N, and the potential nitrogen available from mineralisation of organic matter within a soil following a winter wheat crop (Soil Nitrogen Supply = 1) (AHDB, 2017) using Equation 2.

Equation 2

$$N_2O_{(erosion)} = S_{er} * N_{soil\ 1,\ 2 \ldots n} * 0.0075 * 44/28$$

Where:
S_{er} = mean weight of soil eroded (t ha^{-1})
N_{soil} = residual soil N per t of soil for soil texture 1, 2...n
0.0075 = Nitrogen leaching/runoff factor (kg N_2O-N kg N^{-1} leaching/runoff)
44/28 = conversion N_2O-N to N_2O

3. Life Cycle Impact Assessment: to interpret and evaluate the magnitude and significance of the potential environmental impacts of the product system. For each option the overall greenhouse gas balance is calculated and compared with that of the baseline scenario.

4. Interpretation: the conclusions and recommendations are derived from the findings of the life cycle inventory analysis and impact assessment in line with the defined goal and scope. The overall impact of CS options on greenhouse gas emissions within England based on national uptake per hectare (ha).

5.0 Results

The key management and the associated impact on greenhouse gas emissions and carbon sequestration are summarised for each option. They have been grouped into the following broad categories:

1. options that retain the original land use but modify the management
2. options that change the land use on a proportion of the area
3. options that create or manage semi-natural habitats
4. options on organic land

The greenhouse gas emissions associated with the baseline scenarios (see Appendices for descriptions) are summarised in Figure 5.1. Key emission sources on cultivated land, orchards in production and temporary grassland include supplementary nitrogen, the emission of N_2O from soils and direct and maintenance emissions from machinery use. The livestock scenarios are low input, resulting in emissions mainly from the livestock themselves. Habitats of note include degraded fen and bogs where CO_2 emissions from the oxidation of soil organic carbon are equivalent to 18.3 t CO_2e ha^{-1} yr^{-1}. The management of fen and bog habitat assumes and average of maintenance and restoration. Other habitats emit N_2O from soils albeit from the mineralisation of plant residues not supplementary nitrogen application, or CH_4 where the land is subject to intermittent inundation.

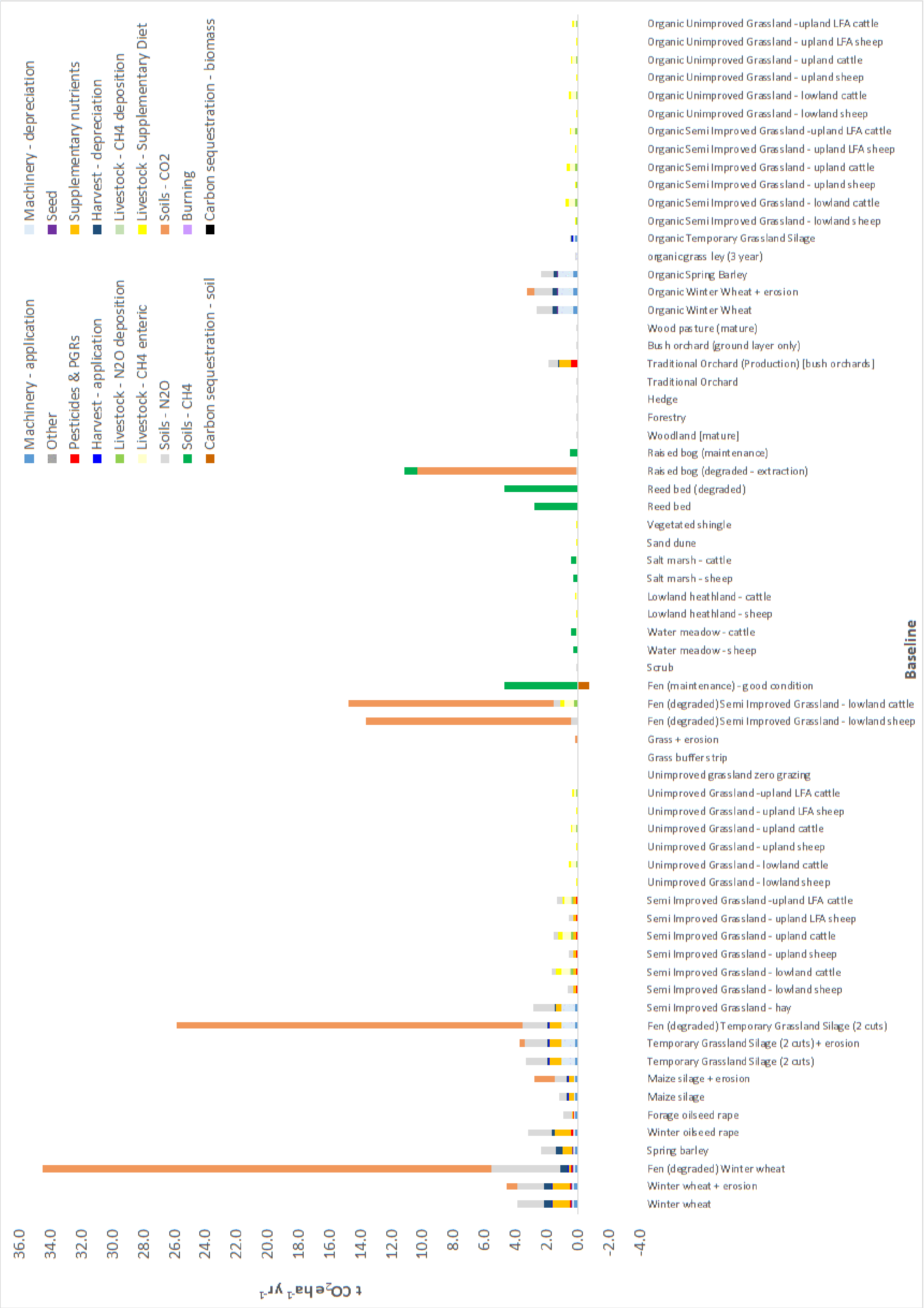


Figure 5.1. Greenhouse gas emissions (t CO_2e ha^{-1} yr^{-1}) per individual baseline scenario.

5.1. Options that retain the original land use

Two options stipulate reduced tillage, HS3 and HS9. On cultivated land an annual decrease in the CO_2e from fuel consumption associated with deeper cultivations is observed (Figure 5.2). An intermediate sandy clay loam is used in this example, emissions associated with ploughing may vary between 0.16 and 0.39 t CO_2e ha^{-1} on sandy and clay soils respectively. On clay soils, soil compaction may risk an increase in N_2O from denitrification, being potentially more prolific where rainfall is greater and soil temperatures warmer, although this is reported mainly for zero tillage systems rather than reduced tillage. The inclusion of a sown cover one year in five in option HS9 aims to reduce compaction and soil erosion risk. No supplementary nutrients are applied to the sown cover, eliminating emissions from product manufacture and fertiliser derived soil N_2O during that year in the rotation. The spatial variability in both soil type and climate within the UK mean the precise balance will vary regionally. A 10% yield penalty decreases the crop biomass at equilibrium.

A reduction to crop inputs, especially nitrogen fertiliser is well documented to be a key determinant of agricultural greenhouse gas emissions both from the manufacturing perspective and potential impact on soil N_2O (for example Williams *et al.*, 2009). Option AB14 (harvested low input cereal) reduces nitrogen fertiliser from the mean 192 kg N ha^{-1} typically down to 25 kg N ha^{-1}, reflected in the emissions associated with product manufacture and soil N_2O (0.27 t CO_2e ha^{-1}) in Figure 5.2. The lower yield will in all probability decrease the carbon sequestered in crop biomass, this will be compensated for in part by the presence of arable flora due to the cessation of herbicide use. The decline in herbicide use while evident in the emissions from manufacture and application (Figure 5.2) does not contribute as greatly (-0.02 t CO_2e ha^{-1}). A comparable process is evident in option AB13 (brassica fodder crop) where nitrogen rates decline to 30 kg N ha^{-1}. Pest and disease applications are restricted owing to grazing of the crop by livestock during the winter months. Deposition by livestock is comparable to a baseline lowland grassland option i.e. onto mineral soils. Transfer of livestock onto cultivated mineral soils has not been calculated as modifying the rate of soil N_2O or CH_4.

Option AB15 (Two year sown legume fallow) retains the land use in cultivation but decreases the frequency of tillage from an annual to a biennial regime. It is purposely sown with a grass species (66% perennial ryegrass) and a mixture of legumes including 15% red clover, 10% common vetch and 7% birdsfoot trefoil. The duration of the agreement permits the accumulation of soil organic matter and potentially soil organic carbon, while the minimal management requirements eliminate most inputs with the exception of seed, drilling and intermittent cutting (Figure 5.2). As noted previously, the removal of nitrogen fertiliser application coupled with partial removal of deeper tillage are key drivers of the overall emissions reduction of agricultural systems on cultivated land. The impact of removing pest and disease control while decreasing emissions is compared to the removal of nitrogen fertiliser lower, -0.08 t CO_2e ha^{-1}. A similar pattern is observed for Option BE4 Management of traditional orchards that maintains an element of production but with reduced yield and inputs, namely approximately 50% of the original nitrogen fertiliser application and 50% of fungicide applications.

Option AB11 Cultivated areas arable plants retains the land in cultivation although no crop is sown or managed. Emissions are derived mainly from tillage operations. A '*fine surface*' across the area necessitates the use of shallow tines post ploughing. No pesticides are permitted except for the application of Natural England approved herbicides (the scenario applies amidosulfuron at 0.03 kg ai ha^{-1}) using a weed-wiper or by spot-treatment. This, in tandem with topping to prevent seeding stops the spread of injurious weeds, non-native species, nettles or bracken. Soil erosion is a risk on recently cultivated soil although where natural generation proceeds this is mitigated in following years (García-Ruiz., 2010). The annual cultivation regime prevents this to a certain extent. It also maintains the soil organic carbon equilibrium equivalent to that of the baseline. Biomass from natural regeneration will in all probability be lower than that for a sown crop and the annual cultivation regime will not permit this to increase in subsequent years.

Figure 5.2. Net change (t CO_2e ha^{-1} yr^{-1}) in greenhouse gas emissions (mean 5 year period) for category C and D options with no change in overall land use.

A minimal impact on management interventions results from the supplementary winter feeding of farmland birds (option AB12). This option does not modify the management of the area, rather supplementary feed in the form of 500 kg of seed (25kg spread a minimum of once per week between 1st December until 30th April) is imported and distributed within a target area. The increase in greenhouse gas emissions (0.07 t CO_2e ha^{-1}) arise mainly with the production phase of the seed and fuel to dive a small vehicle (for example an all-terrain vehicle or ATV) to the required destination 22 times per year.

Options implemented on grassland offer two main mechanisms to reduce greenhouse gas emissions: a reduction in inputs, particularly nitrogen fertiliser; and a reduction in nitrogen deposition by livestock onto high risk organic or wet soils. Options that decrease the application rate of nitrogen fertiliser include GS3 (Ryegrass seed-set winter food birds) that does not apply the later nitrogen applications of the temporary grassland baseline, applying 50 kg N ha^{-1} instead of 138 kg N ha^{-1}, with a decrease of 0.5 t CO_2e ha^{-1} associated with fertiliser manufacture. Other grassland options reduce nitrogen applications albeit not on the same scale, for example from 30 kg N ha^{-1} to 9 kg N ha^{-1} (GS2 Permanent grassland very low inputs (outside SDAs) and GS5 Permanent grassland very low inputs (SDAs)). Option GS4 Legume and herb-rich swards eliminates the need for nitrogen application through the inclusion nitrogen fixing legumes within the sward. GS13 Management of grassland for target features shifts the management to a low input system comparable to that of unimproved grassland, although there is no net reduction in stocking rate. The emissions from supplementary nutrient manufacture decline by 0.13 – 1.14 t CO_2e ha^{-1}.

Modification to the end-point of nitrogen deposition through changes to outdoor grazing periods and locations include SW10 Seasonal livestock removal on grassland in SDAs next to streams, rivers and lakes. This option complements the establishment of riparian buffer strips from a greenhouse gas mitigation perspective, preventing the deposition of nitrogen onto wet anaerobic or organic soils. Other inputs remain the same. The Lenient grazing supplement option GS17 implemented with option GS2 or GS5 moves stock to alternative grazing areas, otherwise management remains the same. This will have an impact where there is a change in soil type, for example organic to mineral, or from areas at risk to waterlogging to well drained mineral soils, equivalent to 0.001 – 0.007 t CO_2e LU^{-1} per month.

The final option within this category is GS16 Rush infestation control supplement. The introduction of an additional mowing operation to approximately 10% of the area results in a slight increase in emissions, equivalent to 0.002 t CO_2e ha^{-1}. There is also a potential removal of biomass where rushes are cut although on relatively low input or unimproved grassland with a more diverse sward composition the impact is likely to be small, an estimated 0.11 t CO_2e ha^{-1} yr^{-1}.

5.2. Options that modify a proportion of the area of the original land use

The options implemented along field peripheries change a proportion of the land use. Those evaluated reduce inputs of supplementary nutrients, pest and disease control and reduce the frequency of tillage operations. This permits the accumulation of soil organic carbon for the duration of the agreement. Inputs are restricted mainly to seed and machinery use for drilling and cultivation during the initial phases of establishment. Post year one these inputs are not required. Minimal interventions are in the form of controlling injurious weeds by targeted application of a Natural England approved herbicide (amidosulfuron at 0.03 kg ai ha^{-1}). Amidosulfuron manufacture is estimated to decrease emissions by 0.005 t CO_2e ha^{-1} yr^{-1} relative to, for example, 2 l ha^{-1} fluroxypyr (200 g l^{-1}) applied previously to the baseline. Unfertilised grass strips are implemented through SW1 4-6m buffer strip on cultivated land / SW2 4-6m buffer strip on intensive grassland / SW11 Riparian management strip on semi-improved grassland. The impact on greenhouse gas emissions include subtle differences observed in response to spatial location. The riparian buffer strip may potentially intercept surface run-off into water courses which depends on the topography of the adjacent farmland. The baseline assumes semi-improved grassland in receipt of 30 kg N ha^{-1}, for which both the N application rate and surface run-off risk (Panagos *et al.*, 2015) is lower than for cultivated land. Boundary options that consist of species mixtures include AB8 Flower-rich margins and plots and AB16 Autumn sown bumblebird mix. The establishment of both options assumes cultivation by ploughing to reduce weed pressure prior to establishment and to facilitate the non-use of herbicides. AB12 may be spring or autumn sown which has an associated minor difference in the number of cuts in years one and two.

Other options in this category change the management of a proportion of the land use, but are not specifically implemented along crop edges. Option GS1 Take field corners out of management and SW7 Arable reversion to grassland with low fertiliser input remove potentially larger components of the cultivated area, but are strategically placed. This may be to prevent for example soil erosion or the management of areas where access may be difficult or waterlogging through impeded drainage is present. Again, both options may modify the management of cultivated land to reduce supplementary nutrient input and pest and disease control. Tillage is limited to year one when the grass area is established. SW12 Making space for water is another specifically targeted area aimed to accommodate rises in river levels. As such, inputs are reduced to those of unimproved grassland. Carbon sequestration in soils proceeds at a rate equivalent to that for cultivated land converted to grassland.

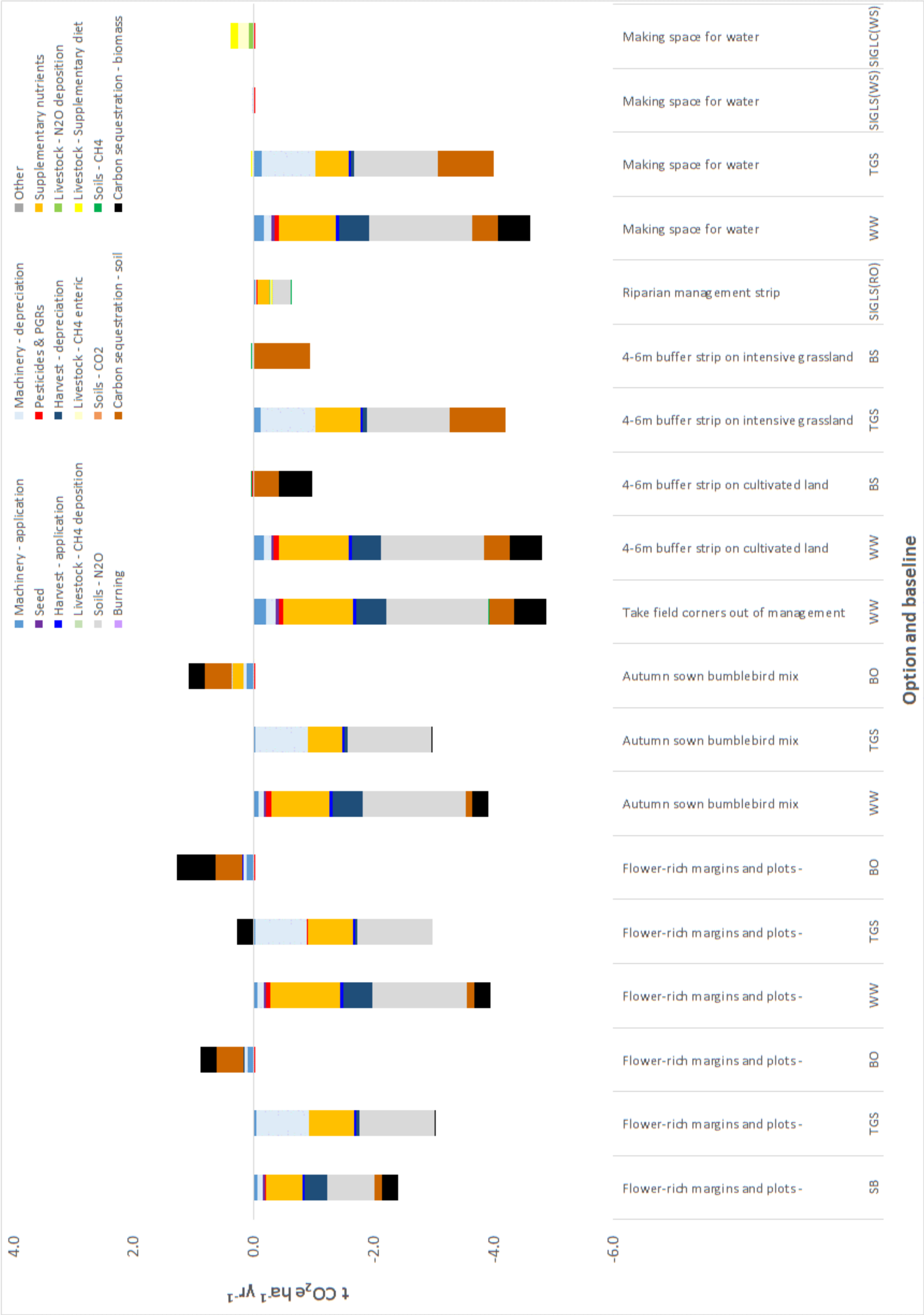


Figure 5.3. Net change (t CO_2e ha^{-1} yr^{-1}) in greenhouse gas emissions (mean 5 year period) for category C and D options with a change in a proportion of the land use.

5.3. Options that create or manage semi-natural habitats

Options where an increase in plant biomass is the main change are the woodland and wood pasture options. WD1 Woodland creation Maintenance / WD2 Woodland Improvement aims to '*reduce the proportion of coniferous species present*' and specifies the replanting of the equivalent of 1100 broadleaved trees per ha. The net biomass carbon balance is dependent on the proportion of conifers present originally, a value of 10% is assumed based on the definition of broadleaved woodland by the JNCC Phase 1 Habitat Survey methodology (JNCC, 1990). The removal of 10% conifers and replanting with the equivalent of 1100 saplings ha^{-1} on 10% of the area results in an initial loss of biomass carbon depending on the species replaced, the age of the tree and the species of broadleaved tree that is planted (Figure 5.4).

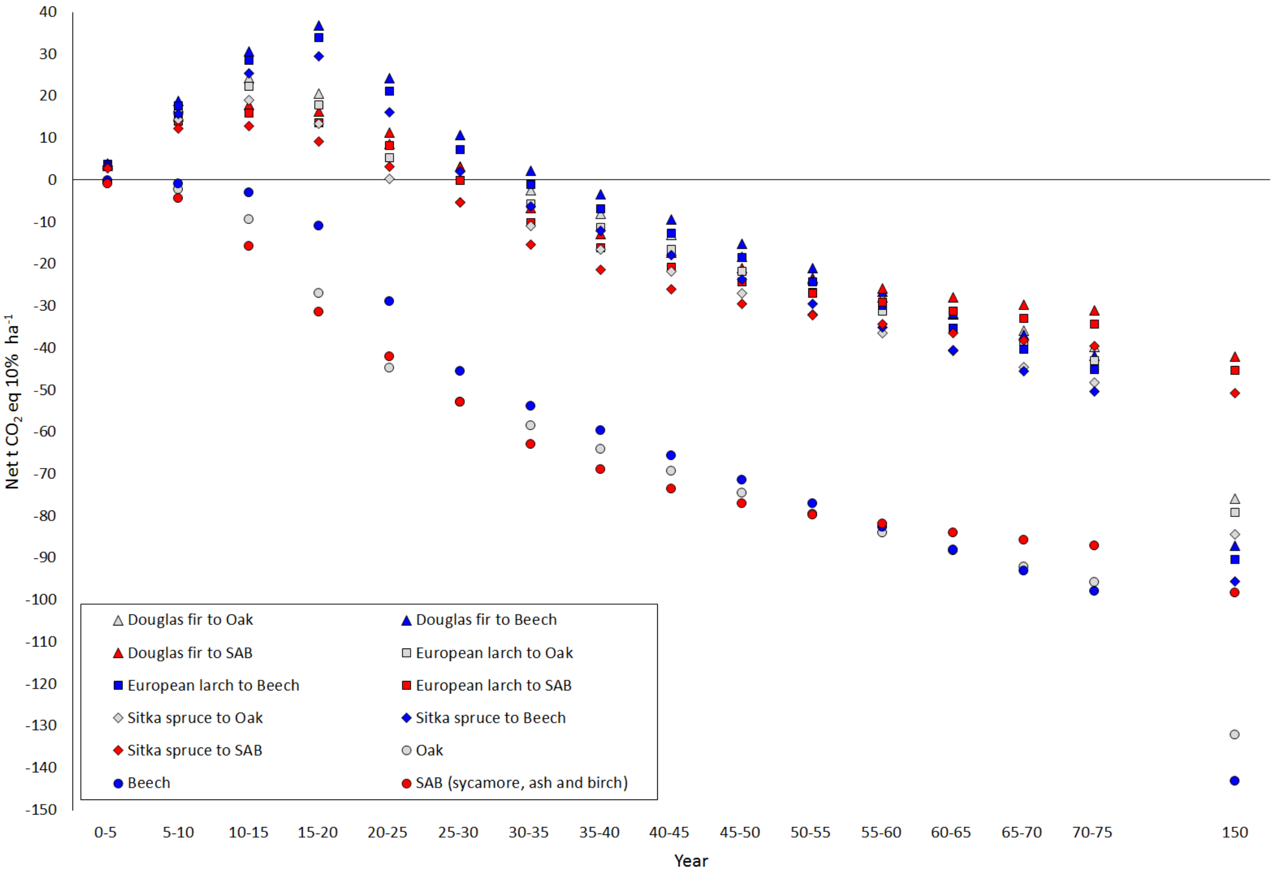


Figure 5.4. Net change (t CO_2e ha^{-1} yr^{-1}) in greenhouse gas emissions from biomass for the removal and natural decay of selected conifer species (50 years old, growth class 8, 1.7m spacing) and replacement with broadleaves (growth class 8, 3.0m spacing) on 10% of a woodland using option WD2. Carbon sequestration is displayed for beech, oak and SAB individually. Emissions data is cumulative displayed at five year increments to year 75, and long term (year 150).

The release of CO_2 from natural decay between years four and 24 (Morison *et al.*, 2012) combined with broadleaved sequestration rates lower than those of emissions from decay (Forestry Commission, 2018) results in net cumulative CO_2 emissions during the initial growth phases. For the tree species, growth class and planting densities under consideration, net sequestration occurs post years 25 - 35. It is also worthy of note that a sycamore (*Acer pseudoplatanus*), ash (*Fraxinus excelsior*) and silver birch (*Betula pendula*) mixture (red fill) accumulates biomass C more rapidly during early growth phases (Forestry Commission, 2018), especially compared to species such as beech (*Fagus sylvatica*) (blue fill). Sequestration in the long term is however greater overall for beech and oak (Figure 5.4). The requirement to '*remove competing, non-native or invasive species by mechanical or chemical control*' utilises spot herbicide application and direct application to tree stumps. Machinery is not utilised, the quantity of herbicide active ingredient applied is nominal. WD5 Restoration of wood pasture '*restores existing lowland wood pasture and parkland considered to be in poor condition*'. As a consequence tree biomass is already present although this is supplemented further with the addition of 50 tree saplings per ha planted in year one. As part of the management specification the area is grazed or cut so that an area of closely grazed turf is maintained. The requirement for taller tussocks to be present in combination with a short sward means that cattle are preferred as livestock to produce a range of vegetation heights. Option WD6 Creation of wood pasture is also grazed preferably by cattle. This is implemented on existing semi-natural grassland, on which 200 tree saplings are planted during year one, equivalent to 0.17 t CO_2e ha^{-1} yr^{-1} (mean all broadleaves assuming 1100 individual trees per ha – Morison *et al.*, 2012) as biomass carbon. The management specifies the selection of regional tree species resilient to climate change for the given area. Growth rates are calculated to follow average rates that have not been suppressed by unsuitable climatic conditions. Stocking rates or the allocation of grazing location do not change during the year. On a related note, albeit not adding biomass per se, the greatest benefit of BE6 Veteran tree surgery is most likely to be the health of the tree and increased lifespan. As a veteran tree the biomass and carbon accumulation rate will be in decline (Adger *et al.*, 1993; Morison *et al.*, 2012) and therefore contribution to carbon sequestration will not be evident. An increase in lifespan maintains the carbon in biomass form.

Livestock managed within applicable options GS9 Management wet grassland breeding waders / GS10 Management wet grassland wintering waders / HS7 Management historic water meadows are grazed on alternative land or housed during the winter removing the deposition of nitrogen onto wet anaerobic soils. As there is no overall change in land use, soil carbon sequestration does not change. The emission of CH_4 from soils is low or negative for most options. Couwenberg and Fritz (2012) list *Eriophorum* (cotton grass) present in bog habitats and *Phragmites australis*, characteristic of reed beds and fen, as plant species capable of increasing emissions through the 'methane shunt'. This process is of relevance to options WT6 Management of reedbed / WT7 Creation of reedbed / WT8 Management of fen / WT8 Maintenance of fen / WT8 Restoration of fen / WT10 Management lowland raised bog / WT10 Maintenance lowland raised bog / WT10 Restoration lowland raised bog. Differences are observed due to variation in abundance of methane shunt species between habitats, and the phase of the restoration or creation process where applicable. The restoration / maintenance of fen and reedbed habitat emits 4.75 t CO_2e ha^{-1} yr^{-1} as CH_4 (Couwenberg and Fritz, 2012; Lindsay et al, 2010), an increase relative to a degraded baseline (0.88 t CO_2e ha^{-1} yr^{-1}). The management of reedbed '*manage scrub and vegetation to maintain a predominantly open reedbed*' results in the removal of *P. australis* and a decrease in the methane-shunt potential of the habitat. The emitted CH4 is estimated to decline from 4.75 to 2.81 t CO_2e ha^{-1} yr^{-1} (based on figures derived from Lindsay et al, 2010). Fen habitat compensates for this increase through a reduction in soil CO_2, equivalent to up to 18.3 t CO_2e ha^{-1} yr^{-1} (Brown *et al.*, 2017). Option WT8 specifies '*priority fen habitat in good condition*' as a baseline but permits the '*re-wetting areas with drained peat next to them'* where a restoration process is possible. The calculated emissions change corresponds to an assumed average 10% of the baseline as being degraded fen habitat, the remainder classed as in good condition. The 10% that is restored reduces CO_2 emissions from restoration of the degraded organic soil (average 1.83 t CO_2e ha^{-1} yr^{-1}), coupled with an increase in CH_4 (mean 0.475 t CO_2e ha^{-1} yr^{-1}) due to rewetting and regrowth of methane-shunt vegetation. WT10 '*priority lowland raised bog habitat which can be kept wet enough for peat to form*' and to '*maintain structures that help to control water levels*' rather than install them. The baseline assumes a bog habitat in good condition. The increase in CH_4 from bog habitat restoration is according to Lindsay et al (2010) lower than fen, but is dependent on the proliferation of *Sphagnum* dominated plant communities established relative to *Eriophorum* as part of the restoration process.

The following options require the removal of scrub and plant biomass. HS4 Scrub control on historic features / WD7 Management successional areas and scrub require that livestock are removed between the

1st October and 30th April and the mowing of 20% of the area annually. Livestock are grazed on alternative land, this land is assumed to be of comparable condition i.e. the baseline is not prone to flooding during the winter or an organic soil type. The N_2O from deposition during the period of livestock removal and relocation does not change. HS6 Maintenance engineered water bodies on areas of existing scrub is mown once with a brushwood cutter and follow up glyphosate application to the stumps applied to 10% of the area. There is an initial decrease in biomass carbon where the 10% of the area is cut, the woody vegetation removed is assumed less than 10 years old, equivalent to 1.05 t CO_2e ha^{-1}. The options associated with coastal habitats CT1 Management coastal sand dunes and vegetated shingle are implemented on existing coastal sand dune or vegetated shingle priority habitat. There is no change in land use, the main impacts are due to removal of scrub and the creation of habitat mosaic including areas of bare ground. The management operations are not fuel intensive resulting in nominal increases in greenhouse gas emissions (<0.001 t CO_2e ha^{-1} yr^{-1}). There is a decrease in biomass carbon where scrub is removed. The CT6 Coastal vegetation management supplement allows agreement holders to '*carry out specific cutting or grazing management tailored to their site*'. This may introduce grazing to previously ungrazed areas however this is implemented through a relocation of livestock for a given period rather than a net increase in stocking rates associated specifically with the option. Biomass removal will focus primarily on scrub, accounted for in option CT1.

The following group of options permit burning. Burning emits carbon within biomass to the atmosphere as CO_2. The quantity is dependent on the weight of biomass burnt (IPCC, 2006; Renate, 2014) and this has been estimated using the biomass equilibriums in Table 3.12 and the IPCC (2006). Option LH1 Management of lowland heathland stipulates implementation of the option either on existing heathland, or partially degraded heathland where '*a shift towards acid grassland plant communities are becoming evident*'. The creation of bare areas through introduction of shallow tine on 5% of the area carries an associated nominal increase in fuel consumption and machinery use (0.001 t CO_2e ha^{-1}). The baseline assumes existing heathland. The management consists of ongoing prevention of succession to woodland it does not assume succession has occurred and that the removal of trees is a requirement. No decrease in biomass carbon due to tree removal is calculated. Upland options UP1 Enclosed rough grazing and UP3 Management of moorland permits burning on a proportion of the area. Natural England (2007) stipulate the burning of 10% of the area although Allen *et al.* (2016) observe a figure of 0.9% in reality. Burning converts plant biomass to N_2O, CH_4 and CO_2 (IPCC, 2006). Calluna heathland consists of 11.5 t ha^{-1} of potentially combustible dry matter (IPCC, 2006). Given that there is no change in land use and the vegetation will regenerate, CO_2 emission has not been included. The emission of N_2O and CH_4 equates to 0.072 t CO_2e ha^{-1} where 10% of the area is burnt, or 0.006 t CO_2e ha^{-1} where this area is reduced to 0.9%. There is, as highlighted in Table 3.11, a potential increase in the risk of soil erosion due to the higher associated C-factor of burnt areas (Panagos *et al.*, 2015) although the higher end of the stated range would more likely be associated with areas that have sustained damage to the soil structure from an excessive burn temperature. Compliance with Natural England (2007) reduces the risk to an assumed C-factor of 0.1 during the first year post burning. Option UP2 Management rough grazing for birds does not use burning but implements an additional mowing on the equivalent of 20% of the area, increasing the CO_2e from diesel consumption by 0.003 t CO_2e ha^{-1} yr^{-1}.

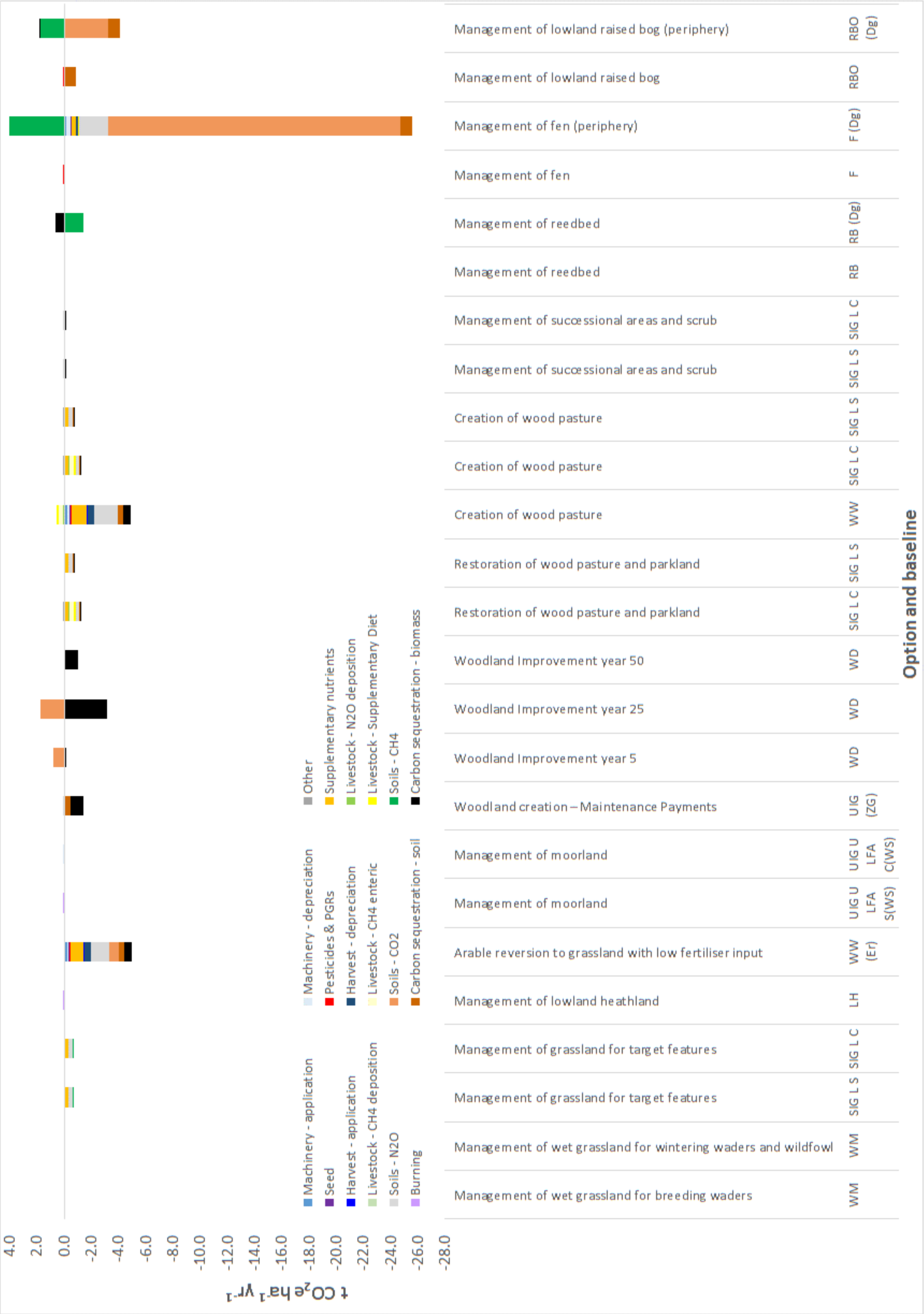


Figure 5.5. Net change (t CO_2e ha^{-1} yr^{-1}) in greenhouse gas emissions (mean 5 year period) for category C and D options on semi-natural habitats.

5.4. Options on organic land

The organic farming baseline arable scenarios incorporate FYM, they therefore do not assume a proportional use of reduced tillage (Chesterton, 2009). Option OP1 Overwintered stubble on organic land is a rotational option that modifies the management of an average 30% of the crop (option specifies on at least 10%, but not more than 50%, of the option area). In this 30% of the crop an additional 6 kg of suitable overwinter cover crop species (e.g. mustard or fodder radish) are drilled and established using shallow cultivation and non-inversion methods. Where a cover crop is established the area is not ploughed and does not receive 17 t ha^{-1} of farmyard manure. The emissions associated with the loading (0.03 t CO_2e ha^{-1}) and application (0.02 t CO_2e ha^{-1}) of farmyard manure, and the soil N_2O from the 102 kg N ha^{-1} applied (6 kg N t^{-1} – AHDB, 2017) are removed. Cover crops may reduce nitrate leaching during the winter, the magnitude depending on the species, soil type and local climate. Where the additional machinery operation is a shallow cultivation on a sandy soil as opposed to a deep inversion technique, the reduction in CO_2e from reduced nitrate leaching and N_2O emission is greater than the additional CO_2e from the fuel consumed by the tractor (Warner *et al.*, 2017). This option is highlighted in the Handbook (Natural England, 2017a) as a potential mechanism to reduce soil erosion. No specific cover crop species is stipulated however based on the cover factor values in Table 3.11 a mixture containing a grass species will offer the greatest potential for soil erosion mitigation.

The baseline organic rotation includes a grass ley. The establishment of a Multi Species Ley in year 1 of option OP4 would most likely run simultaneously with this period of the rotation. The impact of implementing the option would be to increase the species diversity of the ley (species composition needs to be at least 5 grasses, 3 legumes and 3 herbs with the grass component no greater than 75% of the seed mix by weight). The main implications of this are on soil carbon sequestration due to resource partitioning between species, although at present the precise impact can only be estimated. The baseline assumes grazing by livestock during the rotation, the option requires that this period of grazing or cutting be restricted to specific dates and to establish two different regimes each on 50% of the area (1st April and 15th May or 15th May and 30th June). This modification to the timing is not anticipated to impact on greenhouse gas emissions. Grazing is assumed within the baseline, a stockless system would require an additional mowing operation equivalent to 0.015 t CO_2e ha^{-1}.

Option OP5 Undersown cereal is required to '*establish an autumn or spring sown cereal crop (not maize) undersown by 30 April with a grass/flower-rich legume ley*'. The ley is retained for 2 years post-harvest. Since the baseline organic scenario rotation includes a grass / clover ley, this phase of the rotation is assumed substituted with option OP5. The main difference attributed to this option is therefore the species mixture within the ley itself. All other inputs remain the same. Any potential difference will be associated with soil carbon sequestration rates due to resource partitioning within the ley, a relatively uncertain quantity at present. The C-factors of the soil erosion risk methodology does not differentiate between species mixtures within leys, just the presence of a ley within the rotation. At present the methodology does not identify any increase or decrease in emissions as the only modification is the sown mixture itself, not the management.

As described previously for option AB12 option OP3 Supplementary feeding farmland birds has minimal impact on management of the land. Organic seed (500 kg in total applied 22 times per year) is used in this option as supplementary feed which, in a similar way to option AB12, increases greenhouse gas emissions from the manufacture of seed and fuel to power an ATV. Option OR2 (Organic conversion – unimproved permanent grassland) is implemented on '*unimproved permanent grassland and rough grazing that is below the moorland line*'. The stocking rates on unimproved grassland are similar in both organic and non-organic systems. Otherwise management remains the same i.e. the pre-conversion unimproved grassland scenario does not apply supplementary nutrients or crop protection products.

5.5. Option uptake and impact on emissions

Uptake data supplied by Natural England (provisional figures) notes the area (ha) of CS options within England. Supplementary feed is documented as tonnes. An area basis estimate has been made by converting the total tonnes to ha with an assumed 500 kg per ha. Total emissions for category C and D options are summarised in Table 4.1.

Table 5.1. Net change in greenhouse gas emissions (t CO_2e ha^{-1} yr^{-1}) for England based on uptake for all CS options (as of March 2018).

Region	**t CO_2e yr^{-1}**
England total	-1,025,700
East Midlands	-128,400
East of England	-225,500
London	-3,700
North East	-72,300
North West	-46,600
South East	-157,300
South West	-188,400
West Midlands	-111,000
Yorkshire and Humber	-92,900
[a]*(Scotland)*	*0*
[a]*(Wales)*	*-1,000*
unknown	-3,600

Note: [a]denotes agreements whose boundaries overlap the England/Scotland or England/Welsh border

Options with the greatest uptake area include AB8 Flower-rich margins and SW1 4-6m buffer strip on cultivated land, both of which reduce emissions and potentially sequester carbon in soils. Greatest emissions reductions are observed where degraded bog or fen habitat are restored, these options continue to be funded as part of CS.

6.0. Option uptake and the Natural England Countryside Stewardship Climate Change Mitigation Database (CS-ClimMitD)

This section reports on Task 4, scaling up the emissions using uptake statistics, specifically detailing the processes employed to combine data on GHG emissions with CS uptake data and how this might be updated the future (Section 6.5).

6.1. The scaling up process

The algorithm for scaling up the data is simple. The net GHG emission value for each CS option (expressed as tCO_2e^{-ha}) is multiplied by the uptake of that CS option (Equation 1) and summed up for each region or nationally (Equation 2).

$$SUO_n^{GHG} = O_n^{GHG} * (UV * CF) \qquad \text{Equation 1}$$

$$SUR_{GHG} = \sum_{i=1}^{n}(SUO_n^{GHG})_i \qquad \text{Equation 2}$$

Where: SUO_n^{GHG} = Scaled up net GHG emissions for CS option *n* (tCO_2e)
SUR_{GHG} = Scaled up net GHG emissions for a region for CS options 1 to *n* (tCO_2e)
O_n^{GHG} = Option net GHG emissions per hectare for CS option *n* (tCO_2e^{-ha})
UV = Uptake value (generally in hectares, but with a few variants)
CF = Conversion Factor, to convert options where uptake is not report in hectares (see Table 2.3)

However, the two datasets are quite substantial, which in combination with the need to provide regional breakdowns, means the technical process of combining the data is not so straightforward. To aid the process a bespoke software application, the Natural England Soil Carbon Database (NESCarD) Builder, has been developed which performs the following functions:

1. Import and structuring of net GHG emissions data for each option (Section 6.3).
2. Import and structuring of uptake data (Section 6.4).
3. Export and combining of net GHG emissions data and uptake data into a new spreadsheet (Section 6.5).

6.2. Net emissions data

Project tasks 1-3 have resulted in a detailed dataset for each CS option profiling the GHG emissions and carbon sequestration that is likely to occur compared to a given baseline. In summary, a detailed scenario of activities is defined for each CS option and each baseline. These activities are then subject to a life cycle assessment (LCA) to derive the GHG emissions and carbon sequestration inventory data, which is then converted to tCO_2e using GWP_{100} impact characterisation factors. The resulting data cover the following life cycle elements for each CS option:

- Machinery (application)
- Machinery (depreciation)
- Other
- Seed
- Pesticides & PGRs
- Livestock (CH_4 deposition)
- Livestock (CH_4enteric)
- Livestock (supplementary diet)
- Soils (N_2O)
- Soils (CO_2)

- Supplementary nutrients
- Harvest (application)
- Harvest (depreciation)
- Livestock (N_2O deposition)
- Soils (CH_4)
- Burning
- Carbon sequestration (soil)
- Carbon sequestration (biomass)

Each option has also been assessed for its displacement risk, i.e. the risk that any reductions in GHG emissions are displaced/exported to other locations, locally, regionally, nationally or globally. This is based on previous work undertaken for Natural England (Warner *et al.*, 2013). The risk has been categorised as Low (L), Moderate (M) and High (H).

The scenarios, emissions inventory and impact data for each option have been calculated in detailed and complex spreadsheets, thus are not conducive to be easily combined with uptake data. Additionally, it is not necessary to use this detailed data for the scaling up process, just the net values are required. Therefore, to streamline the process, the NESCarD Builder software has routines to import the GHG emissions and carbon sequestration data required for the scaling up process from the complex spreadsheets used for the LCA into a core database.

Each CS option has a range of net GHG emission values calculated based on the following variables:

- Option variant: e.g. spring or autumn sown for AB8 - Flower rich margins and plots.
- ES equivalent: where a number of ES options relate to the new CS option.
- Baseline: where a number of different baselines have been calculated for an option, e.g. AB12 - Supplementary winter feeding for farmland birds, with baselines of arable land, temporary grass, and bush orchards.
- Year: practices for an option may vary from year to during the agreement period, so net emissions are calculated for 5 years (10 years are used for a few options where necessary) to account for these differences.

This data is imported, so that the variability in the data can be presented in the final output. However, as outlined in Section 6.3, the uptake data does not have this level of detail, so an average figure across all the variations listed above is used when scaling up the data.

As well as an overall net emission for each CS option, the emissions and sequestration data for each life cycle element are also imported so that this detail can be provided in the final output.

6.3. Uptake data

The data on uptake of CS options has been provided by Natural England as an output from their central IT systems, thus the format is beyond the control of this project. The data pertinent to this study consists of the fields described out in Table 6.1 (other data fields are included in the raw data but are not used in this study).

Table 6.1: Description of pertinent uptake data fields

Field	Description
Countryside Stewardship Agreement Type	This field is used to determine in the option has been implemented under Mid or Higher Tier of CS. For example, the data might be "NELMS - (MT) COUNTRYSIDE STEWARDSHIP" or "COUNTRYSIDE STEWARDSHIP (HT)"
Options Code	This is the unique identifier for each CS option, e.g. "AB1".
Area of parcel under option	The metric used to define the size of the option implemented.

Unit Of Measurement	The units for the above metric. For the majority of options the metric is hectares (ha), but some it is different, e.g. metres for hedgerows. In the case of the latter a conversion factor is needed to convert a length of hedgerow to an area, as the net emissions data are all per ha.
Nuts 1	The NUTS1 region where the option has been implemented.
NUTS 2	The NUTS2 region where the option has been implemented.
CS agreement start date	The start date for the agreement, used to determine the year in which the agreement started, thus allowing uptake and emissions to be assessed on an annual basis.
NUTS 3	The NUTS3 region where the option has been implemented.

The amount of uptake data is substantial. For example, in the current raw uptake dataset there is 145245 rows of data. The NESCarD Builder software has a routine to automatically process this data and import it into the same core database as the emissions data (this can take ~30 mins for 145245 rows of data). In the process it sums up the uptake values for each option for each of the NUTS1-3 regions and England as a whole, and classifies it according to whether it is mid or higher tier, and the year the agreement started. Thus, for example, it is possible to determine the uptake of AB1, in 2016, under mid-tier for the East Midlands region.

6.4. Scaling up the data

The processes above result in a database that contains all the net GHG emissions data for each CS option (broken down by life cycle element and option variants) and all the uptake data for each option (broken down by region, mid/higher tier and start year). The next step is to combine them to provide the net GHG emissions for each option scaled up using the uptake data. This output also needs to be provided in a format that can be easily used to look up the data for any CS option.

Routines have been developed within the NESCarD Builder software to export the data to an MS Excel® workbook (see Appendix A), the Natural England Countryside Stewardship Climate Change Mitigation Database (CS-ClimMitD), that contains the data in a variety for formats on different worksheets including scaling up the data for each option regionally and nationally by combining the net emissions data (Section 6.3) with the uptake data (Section 6.4). Table 6.2 lists the worksheets that are created, the data they contain and the functions they perform.

Table 6.2: Structure of data export workbook

Worksheet	Description
Contents	Provides a contents page for all the other worksheets in the workbook.
Instructions	Provides description and instructions for the workbook.
Compare (uptake)	This provides a worksheet to compare the data for 2 more options. For each option, the data displayed includes: the Net $tCO_2e\ ha^{-1}$; the range in values (in the complete dataset); the displacement risk; the national uptake data (and unit); and the uptake Net tCO2e (i.e. uptake data multiplied by the Net $tCO_2e\ ha^{-1}$). Users select options from the drop down list in column A. The drop list can be 'searched' by entering a term in the search box in column B – this will limit the drop down list too all options that contain that text. The data displayed on this sheet is drawn from 'CS Data (averaged)' worksheet.
Compare (LCA)	This sheet is similar to the 'Compare (uptake)' worksheet, except the data are drawn from the 'CS Data (all)' worksheet. The options that can be selected in the drop down list include all variants for each CS option (including option variants, ES equivalents,

	baselines and years. The data displayed is the net GHG emission value for each life cycle element of the option, plus the displacement risk for each option.
CS Data (scaled)	This provides the net GHG emission value for each NUTS1, 2 and 3 region, and nationally, based on the uptake figures in each region. Column A lists the region and Column B lists the net GHG emission value. The data for this worksheet are drawn from the 'CS Data (averaged)' worksheet.
CS Data (all)	This worksheet contains all the 'raw' data for each CS option, including a breakdown of the net GHG emissions by life cycle element. This data supports the Compare (LCA)' worksheet. The data on this sheet can be filtered by clicking on the drop down arrows at the top of each column.
CS Data (averaged)	This worksheet contains average net GHG emission values for each CS option, plus the uptake data for each option nationally and for each NUTS1, 2 and 3 region. The net GHG emission value nationally and for each region is also provided on the sheet, using a formulae that multiplies the net GHG emission value per ha by the uptake value. For some options (for which uptake is not reported in hectares) a conversion factor is used to convert the uptake data (see Table 2.3). The uptake values on this worksheet could be updated in the future and this would then update all the other worksheets automatically including the 'Compare (uptake)' and 'CS Data (scaled)' worksheets.
CS Data (uptake breakdown)	This worksheet provides a breakdown of the uptake data and the net GHG emissions nationally and for each NUTS1, 2 and 3 region, including the year in which the agreement started and whether it is under mid-tier (MT) or higher-tier (HT). The data on this sheet can be filtered by clicking on the drop down arrows at the top of each column. The uptake values on this sheet are a duplicate of those on the 'CS Data (averaged)' worksheet, so updating the uptake values on the 'CS Data (averaged)' worksheet will not alter these values.

The uptake conversion values used for options that do not use per ha units, for example hedgerows, are summarised in Table 6.3.

Table 6.3: Uptake conversion values

Option	Unit	Conversion factor	Description
AB4	Unit	0.0036	Assumes that each plot (unit) is 36m^2
BE3	Metres	0.0002	Assumes that the width of the hedge is 2m
BE6	Plant	0.002	Assumes that each plant is 20m^2
BE7	Trees	0.0125	Assumes that each tree is 125m^2
WT3	Metres	0.0001	Assumes that the width of the ditch is 1m

The routines to create the Excel workbook, export the data and format the worksheets are automated and take ~25 mins to run.

The uptake data that is imported to the database (Section 6.3) is included in the exported workbook (Table 6.2). The workbook has been designed so that the uptake figures could be updated within the workbook, and automatically update the related spreadsheets. However, it is acknowledged that this would be a fairly laborious and time consuming process, so a range of options for updating the data have been outlined in Appendix 3.

6.6. Excel workbook

An overview of datasheets displayed in the Excel workbook produced for Task 4 are summarised in Figures 6.1 to 6.7.

Impact of Countryside Stewardship
on soil carbon and climate change mitigation

NATURAL ENGLAND

Version: 02/07/2018
Work package number: ECM50416
Evidence Programme Reference number: RP04176

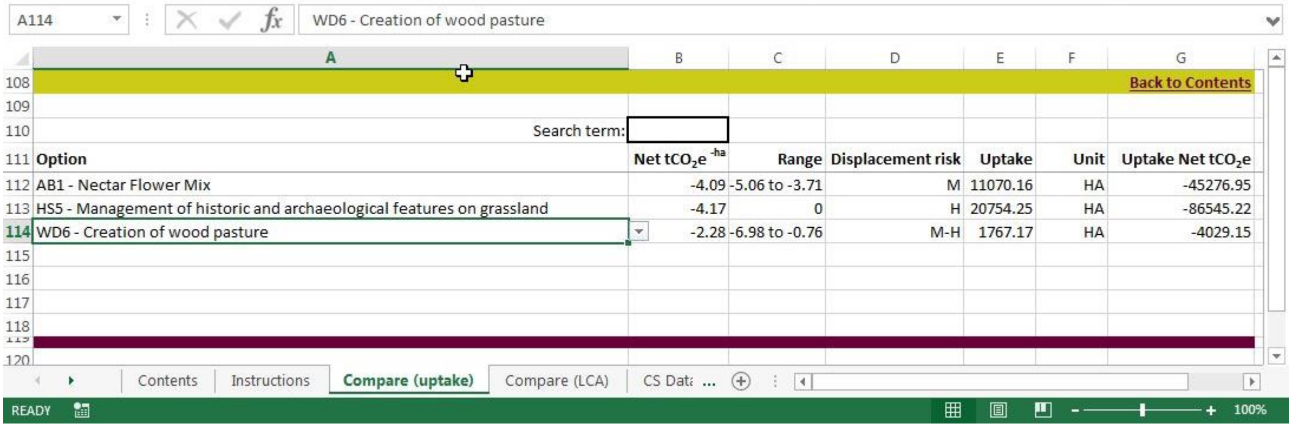
Contents

- Instructions
- Compare (uptake)
- Compare (LCA)
- CS Data (scaled)
- CS Data (all)
- CS Data (averaged)
- CS Data (uptake breakdown)
- ES Data (all)
- ES Data (averaged)

Created by the Agriculture and Environment Research Unit (AERU), University of Hertfordshire.

www.herts.ac.uk/aeru/

Figure 6.1: Contents worksheet of the Natural England Countryside Stewardship Climate Change Mitigation Database (CS-ClimMitD) Excel® workbook



A114 — WD6 - Creation of wood pasture

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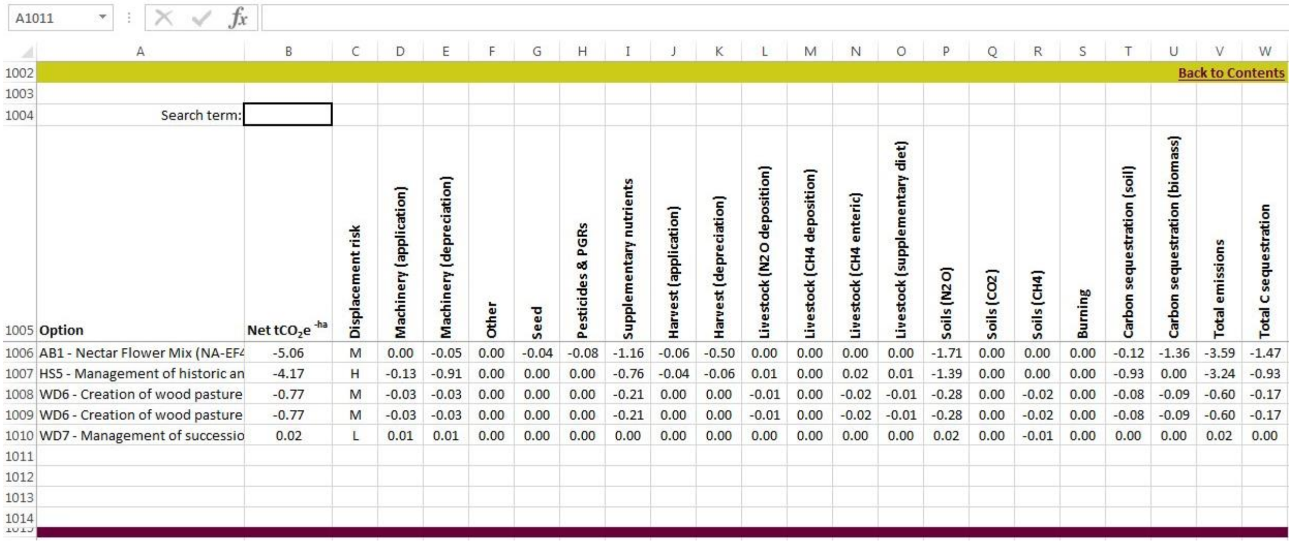
Search term:

Option	Net tCO_2e^{-ha}	Range	Displacement risk	Uptake	Unit	Uptake Net tCO_2e
AB1 - Nectar Flower Mix	-4.09	-5.06 to -3.71	M	11070.16	HA	-45276.95
HS5 - Management of historic and archaeological features on grassland	-4.17	0	H	20754.25	HA	-86545.22
WD6 - Creation of wood pasture	-2.28	-6.98 to -0.76	M-H	1767.17	HA	-4029.15

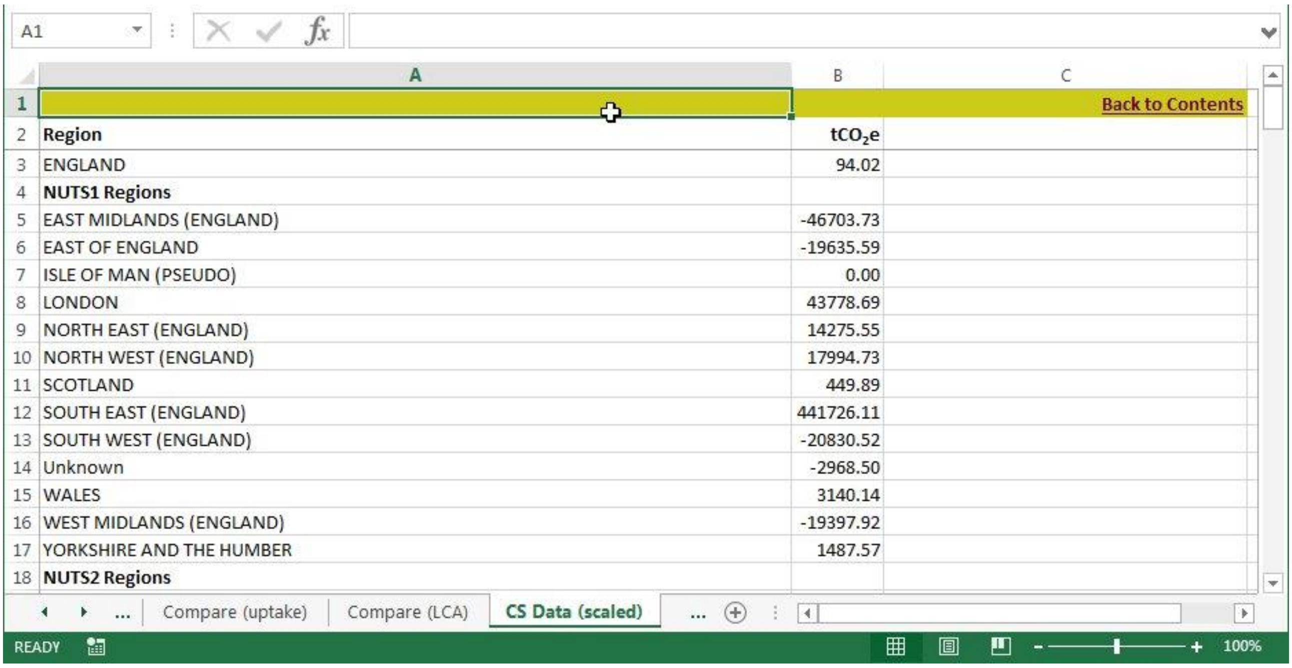
Figure 6.2: Compare (uptake) worksheet



Search term:

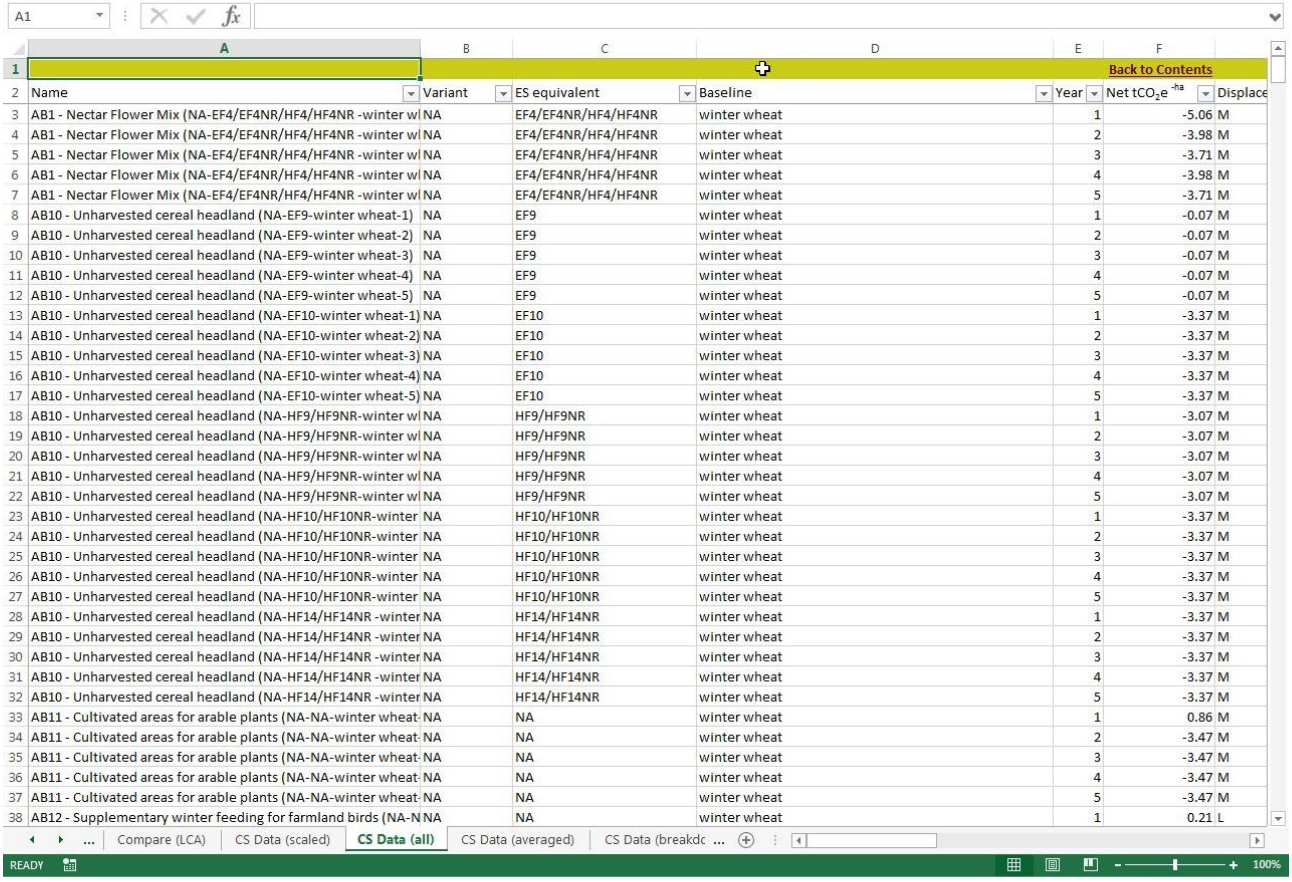
Option	Net tCO_2e^{-ha}	Displacement risk	Machinery (application)	Machinery (depreciation)	Other	Seed	Pesticides & PGRs	Supplementary nutrients	Harvest (application)	Harvest (depreciation)	Livestock (N2O deposition)	Livestock (CH4 deposition)	Livestock (CH4 enteric)	Livestock (supplementary diet)	Soils (N2O)	Soils (CO2)	Soils (CH4)	Burning	Carbon sequestration (soil)	Carbon sequestration (biomass)	Total emissions	Total C sequestration
AB1 - Nectar Flower Mix (NA-EF4	-5.06	M	0.00	-0.05	0.00	-0.04	-0.08	-1.16	-0.06	-0.50	0.00	0.00	0.00	0.00	-1.71	0.00	0.00	0.00	-0.12	-1.36	-3.59	-1.47
HS5 - Management of historic an	-4.17	H	-0.13	-0.91	0.00	0.00	0.00	-0.76	-0.04	-0.06	0.01	0.00	0.02	0.01	-1.39	0.00	0.00	0.00	-0.93	0.00	-3.24	-0.93
WD6 - Creation of wood pasture	-0.77	M	-0.03	-0.03	0.00	0.00	0.00	-0.21	0.00	0.00	-0.01	0.00	-0.02	-0.01	-0.28	0.00	-0.02	0.00	-0.08	-0.09	-0.60	-0.17
WD6 - Creation of wood pasture	-0.77	M	-0.03	-0.03	0.00	0.00	0.00	-0.21	0.00	0.00	-0.01	0.00	-0.02	-0.01	-0.28	0.00	-0.02	0.00	-0.08	-0.09	-0.60	-0.17
WD7 - Management of successio	0.02	L	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	-0.01	0.00	0.00	0.00	0.02	0.00

Figure 6.3: Compare (LCA) worksheet



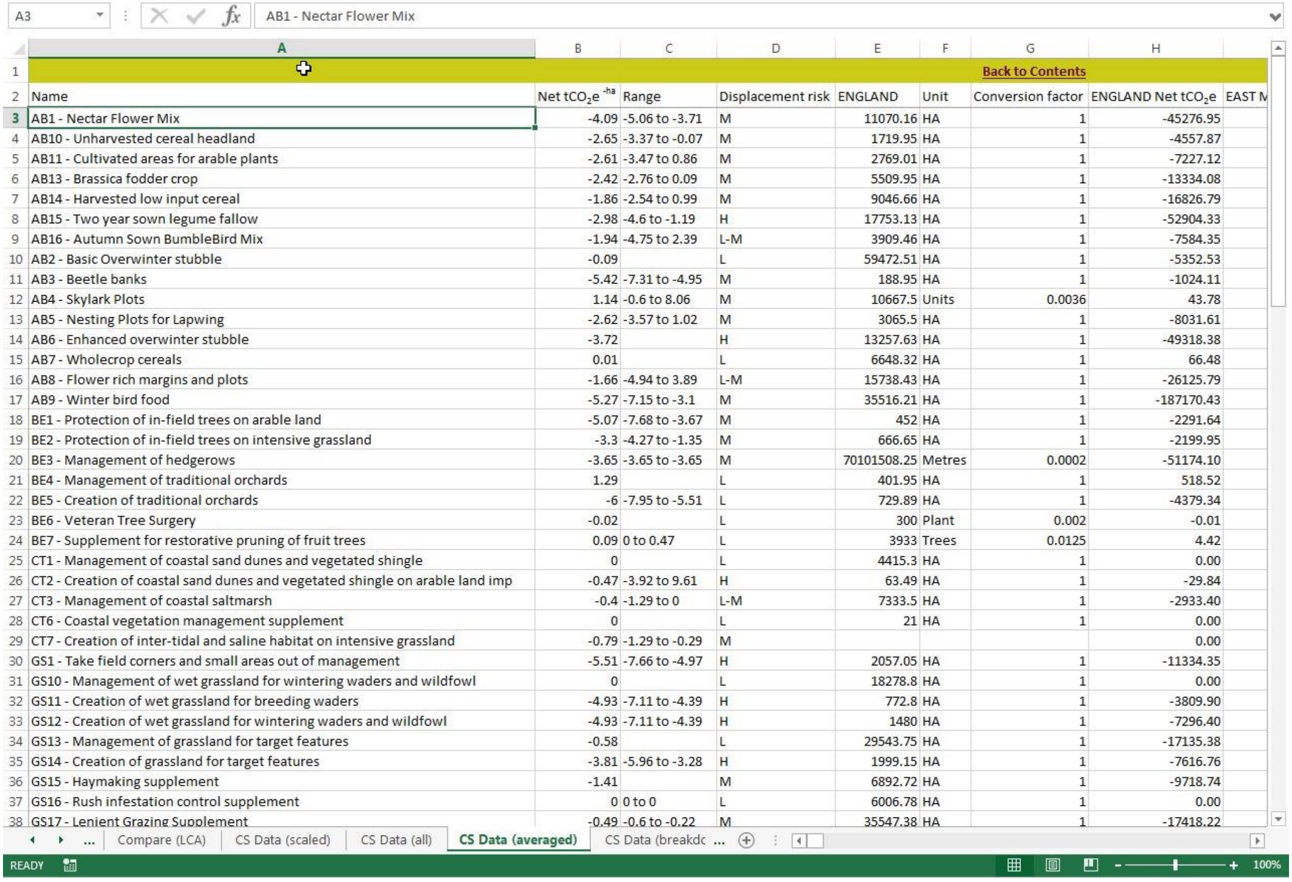
Region	tCO_2e
ENGLAND	94.02
NUTS1 Regions	
EAST MIDLANDS (ENGLAND)	-46703.73
EAST OF ENGLAND	-19635.59
ISLE OF MAN (PSEUDO)	0.00
LONDON	43778.69
NORTH EAST (ENGLAND)	14275.55
NORTH WEST (ENGLAND)	17994.73
SCOTLAND	449.89
SOUTH EAST (ENGLAND)	441726.11
SOUTH WEST (ENGLAND)	-20830.52
Unknown	-2968.50
WALES	3140.14
WEST MIDLANDS (ENGLAND)	-19397.92
YORKSHIRE AND THE HUMBER	1487.57
NUTS2 Regions	

Figure 6.4: CS Data (scaled) worksheet



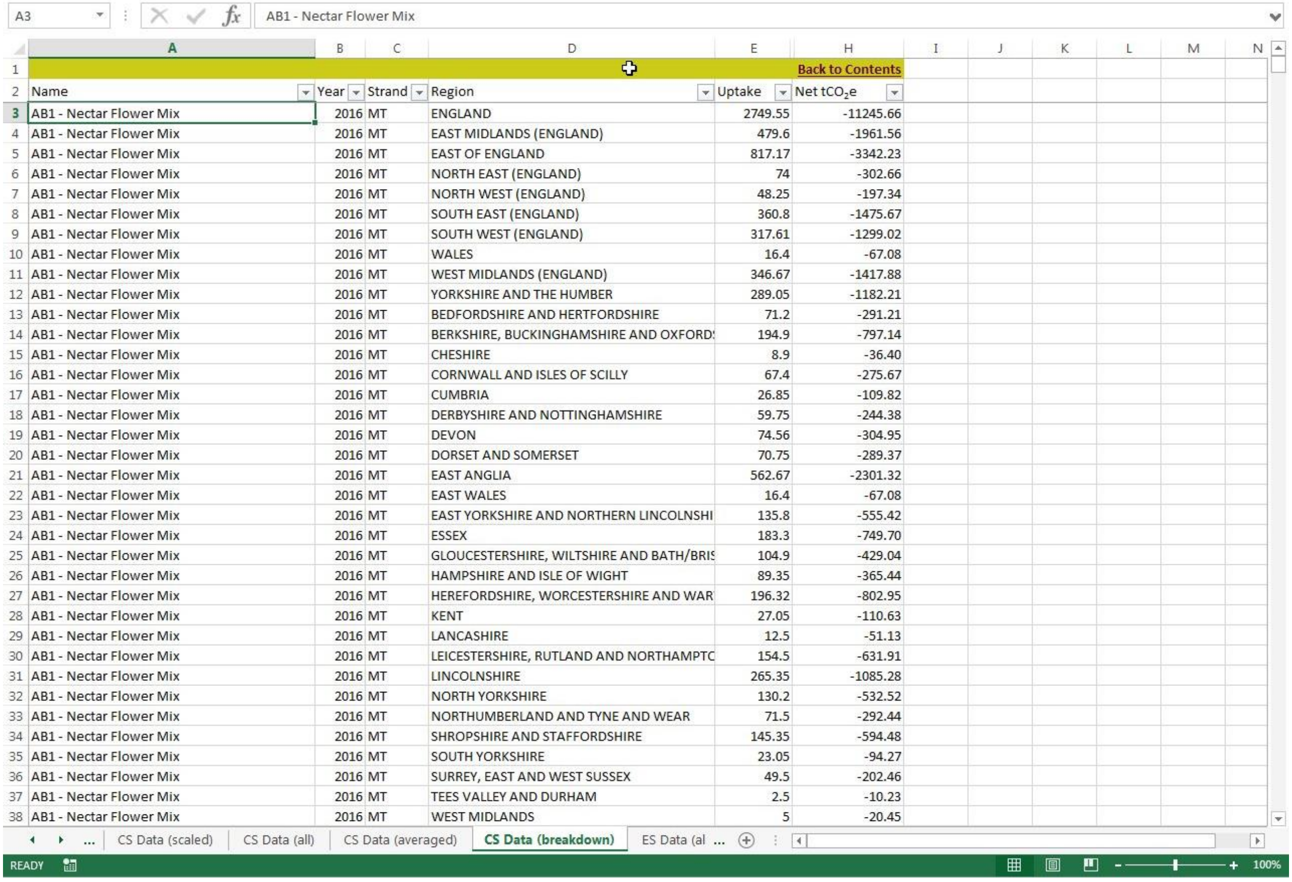
	A	B	C	D	E	F	
1						Back to Contents	
2	Name	Variant	ES equivalent	Baseline	Year	Net tCO_2e^{-ha}	Displace
3	AB1 - Nectar Flower Mix (NA-EF4/EF4NR/HF4/HF4NR -winter w	NA	EF4/EF4NR/HF4/HF4NR	winter wheat	1	-5.06	M
4	AB1 - Nectar Flower Mix (NA-EF4/EF4NR/HF4/HF4NR -winter w	NA	EF4/EF4NR/HF4/HF4NR	winter wheat	2	-3.98	M
5	AB1 - Nectar Flower Mix (NA-EF4/EF4NR/HF4/HF4NR -winter w	NA	EF4/EF4NR/HF4/HF4NR	winter wheat	3	-3.71	M
6	AB1 - Nectar Flower Mix (NA-EF4/EF4NR/HF4/HF4NR -winter w	NA	EF4/EF4NR/HF4/HF4NR	winter wheat	4	-3.98	M
7	AB1 - Nectar Flower Mix (NA-EF4/EF4NR/HF4/HF4NR -winter w	NA	EF4/EF4NR/HF4/HF4NR	winter wheat	5	-3.71	M
8	AB10 - Unharvested cereal headland (NA-EF9-winter wheat-1)	NA	EF9	winter wheat	1	-0.07	M
9	AB10 - Unharvested cereal headland (NA-EF9-winter wheat-2)	NA	EF9	winter wheat	2	-0.07	M
10	AB10 - Unharvested cereal headland (NA-EF9-winter wheat-3)	NA	EF9	winter wheat	3	-0.07	M
11	AB10 - Unharvested cereal headland (NA-EF9-winter wheat-4)	NA	EF9	winter wheat	4	-0.07	M
12	AB10 - Unharvested cereal headland (NA-EF9-winter wheat-5)	NA	EF9	winter wheat	5	-0.07	M
13	AB10 - Unharvested cereal headland (NA-EF10-winter wheat-1)	NA	EF10	winter wheat	1	-3.37	M
14	AB10 - Unharvested cereal headland (NA-EF10-winter wheat-2)	NA	EF10	winter wheat	2	-3.37	M
15	AB10 - Unharvested cereal headland (NA-EF10-winter wheat-3)	NA	EF10	winter wheat	3	-3.37	M
16	AB10 - Unharvested cereal headland (NA-EF10-winter wheat-4)	NA	EF10	winter wheat	4	-3.37	M
17	AB10 - Unharvested cereal headland (NA-EF10-winter wheat-5)	NA	EF10	winter wheat	5	-3.37	M
18	AB10 - Unharvested cereal headland (NA-HF9/HF9NR-winter w	NA	HF9/HF9NR	winter wheat	1	-3.07	M
19	AB10 - Unharvested cereal headland (NA-HF9/HF9NR-winter w	NA	HF9/HF9NR	winter wheat	2	-3.07	M
20	AB10 - Unharvested cereal headland (NA-HF9/HF9NR-winter w	NA	HF9/HF9NR	winter wheat	3	-3.07	M
21	AB10 - Unharvested cereal headland (NA-HF9/HF9NR-winter w	NA	HF9/HF9NR	winter wheat	4	-3.07	M
22	AB10 - Unharvested cereal headland (NA-HF9/HF9NR-winter w	NA	HF9/HF9NR	winter wheat	5	-3.07	M
23	AB10 - Unharvested cereal headland (NA-HF10/HF10NR-winter	NA	HF10/HF10NR	winter wheat	1	-3.37	M
24	AB10 - Unharvested cereal headland (NA-HF10/HF10NR-winter	NA	HF10/HF10NR	winter wheat	2	-3.37	M
25	AB10 - Unharvested cereal headland (NA-HF10/HF10NR-winter	NA	HF10/HF10NR	winter wheat	3	-3.37	M
26	AB10 - Unharvested cereal headland (NA-HF10/HF10NR-winter	NA	HF10/HF10NR	winter wheat	4	-3.37	M
27	AB10 - Unharvested cereal headland (NA-HF10/HF10NR-winter	NA	HF10/HF10NR	winter wheat	5	-3.37	M
28	AB10 - Unharvested cereal headland (NA-HF14/HF14NR -winter	NA	HF14/HF14NR	winter wheat	1	-3.37	M
29	AB10 - Unharvested cereal headland (NA-HF14/HF14NR -winter	NA	HF14/HF14NR	winter wheat	2	-3.37	M
30	AB10 - Unharvested cereal headland (NA-HF14/HF14NR -winter	NA	HF14/HF14NR	winter wheat	3	-3.37	M
31	AB10 - Unharvested cereal headland (NA-HF14/HF14NR -winter	NA	HF14/HF14NR	winter wheat	4	-3.37	M
32	AB10 - Unharvested cereal headland (NA-HF14/HF14NR -winter	NA	HF14/HF14NR	winter wheat	5	-3.37	M
33	AB11 - Cultivated areas for arable plants (NA-NA-winter wheat-	NA	NA	winter wheat	1	0.86	M
34	AB11 - Cultivated areas for arable plants (NA-NA-winter wheat-	NA	NA	winter wheat	2	-3.47	M
35	AB11 - Cultivated areas for arable plants (NA-NA-winter wheat-	NA	NA	winter wheat	3	-3.47	M
36	AB11 - Cultivated areas for arable plants (NA-NA-winter wheat-	NA	NA	winter wheat	4	-3.47	M
37	AB11 - Cultivated areas for arable plants (NA-NA-winter wheat-	NA	NA	winter wheat	5	-3.47	M
38	AB12 - Supplementary winter feeding for farmland birds (NA-N	NA	NA	winter wheat	1	0.21	L

Figure 6.5: CS Data (all) worksheet



Name	Net tCO$_2$e^{-ha}	Range	Displacement risk	ENGLAND	Unit	Conversion factor	ENGLAND Net tCO$_2$e	EAST M
AB1 - Nectar Flower Mix	-4.09	-5.06 to -3.71	M	11070.16	HA	1	-45276.95	
AB10 - Unharvested cereal headland	-2.65	-3.37 to -0.07	M	1719.95	HA	1	-4557.87	
AB11 - Cultivated areas for arable plants	-2.61	-3.47 to 0.86	M	2769.01	HA	1	-7227.12	
AB13 - Brassica fodder crop	-2.42	-2.76 to 0.09	M	5509.95	HA	1	-13334.08	
AB14 - Harvested low input cereal	-1.86	-2.54 to 0.99	M	9046.66	HA	1	-16826.79	
AB15 - Two year sown legume fallow	-2.98	-4.6 to -1.19	H	17753.13	HA	1	-52904.33	
AB16 - Autumn Sown BumbleBird Mix	-1.94	-4.75 to 2.39	L-M	3909.46	HA	1	-7584.35	
AB2 - Basic Overwinter stubble	-0.09		L	59472.51	HA	1	-5352.53	
AB3 - Beetle banks	-5.42	-7.31 to -4.95	M	188.95	HA	1	-1024.11	
AB4 - Skylark Plots	1.14	-0.6 to 8.06	M	10667.5	Units	0.0036	43.78	
AB5 - Nesting Plots for Lapwing	-2.62	-3.57 to 1.02	M	3065.5	HA	1	-8031.61	
AB6 - Enhanced overwinter stubble	-3.72		H	13257.63	HA	1	-49318.38	
AB7 - Wholecrop cereals	0.01		L	6648.32	HA	1	66.48	
AB8 - Flower rich margins and plots	-1.66	-4.94 to 3.89	L-M	15738.43	HA	1	-26125.79	
AB9 - Winter bird food	-5.27	-7.15 to -3.1	M	35516.21	HA	1	-187170.43	
BE1 - Protection of in-field trees on arable land	-5.07	-7.68 to -3.67	M	452	HA	1	-2291.64	
BE2 - Protection of in-field trees on intensive grassland	-3.3	-4.27 to -1.35	M	666.65	HA	1	-2199.95	
BE3 - Management of hedgerows	-3.65	-3.65 to -3.65	M	70101508.25	Metres	0.0002	-51174.10	
BE4 - Management of traditional orchards	1.29		L	401.95	HA	1	518.52	
BE5 - Creation of traditional orchards	-6	-7.95 to -5.51	L	729.89	HA	1	-4379.34	
BE6 - Veteran Tree Surgery	-0.02		L	300	Plant	0.002	-0.01	
BE7 - Supplement for restorative pruning of fruit trees	0.09	0 to 0.47	L	3933	Trees	0.0125	4.42	
CT1 - Management of coastal sand dunes and vegetated shingle	0		L	4415.3	HA	1	0.00	
CT2 - Creation of coastal sand dunes and vegetated shingle on arable land imp	-0.47	-3.92 to 9.61	H	63.49	HA	1	-29.84	
CT3 - Management of coastal saltmarsh	-0.4	-1.29 to 0	L-M	7333.5	HA	1	-2933.40	
CT6 - Coastal vegetation management supplement	0		L	21	HA	1	0.00	
CT7 - Creation of inter-tidal and saline habitat on intensive grassland	-0.79	-1.29 to -0.29	M				0.00	
GS1 - Take field corners and small areas out of management	-5.51	-7.66 to -4.97	H	2057.05	HA	1	-11334.35	
GS10 - Management of wet grassland for wintering waders and wildfowl	0		L	18278.8	HA	1	0.00	
GS11 - Creation of wet grassland for breeding waders	-4.93	-7.11 to -4.39	H	772.8	HA	1	-3809.90	
GS12 - Creation of wet grassland for wintering waders and wildfowl	-4.93	-7.11 to -4.39	H	1480	HA	1	-7296.40	
GS13 - Management of grassland for target features	-0.58		L	29543.75	HA	1	-17135.38	
GS14 - Creation of grassland for target features	-3.81	-5.96 to -3.28	H	1999.15	HA	1	-7616.76	
GS15 - Haymaking supplement	-1.41		M	6892.72	HA	1	-9718.74	
GS16 - Rush infestation control supplement	0	0 to 0	L	6006.78	HA	1	0.00	
GS17 - Lenient Grazing Supplement	-0.49	-0.6 to -0.22	M	35547.38	HA	1	-17418.22	

Figure 6.6: CS Data (averaged) worksheet



Name	Year	Strand	Region	Uptake	Net tCO$_2$e
AB1 - Nectar Flower Mix	2016	MT	ENGLAND	2749.55	-11245.66
AB1 - Nectar Flower Mix	2016	MT	EAST MIDLANDS (ENGLAND)	479.6	-1961.56
AB1 - Nectar Flower Mix	2016	MT	EAST OF ENGLAND	817.17	-3342.23
AB1 - Nectar Flower Mix	2016	MT	NORTH EAST (ENGLAND)	74	-302.66
AB1 - Nectar Flower Mix	2016	MT	NORTH WEST (ENGLAND)	48.25	-197.34
AB1 - Nectar Flower Mix	2016	MT	SOUTH EAST (ENGLAND)	360.8	-1475.67
AB1 - Nectar Flower Mix	2016	MT	SOUTH WEST (ENGLAND)	317.61	-1299.02
AB1 - Nectar Flower Mix	2016	MT	WALES	16.4	-67.08
AB1 - Nectar Flower Mix	2016	MT	WEST MIDLANDS (ENGLAND)	346.67	-1417.88
AB1 - Nectar Flower Mix	2016	MT	YORKSHIRE AND THE HUMBER	289.05	-1182.21
AB1 - Nectar Flower Mix	2016	MT	BEDFORDSHIRE AND HERTFORDSHIRE	71.2	-291.21
AB1 - Nectar Flower Mix	2016	MT	BERKSHIRE, BUCKINGHAMSHIRE AND OXFORD	194.9	-797.14
AB1 - Nectar Flower Mix	2016	MT	CHESHIRE	8.9	-36.40
AB1 - Nectar Flower Mix	2016	MT	CORNWALL AND ISLES OF SCILLY	67.4	-275.67
AB1 - Nectar Flower Mix	2016	MT	CUMBRIA	26.85	-109.82
AB1 - Nectar Flower Mix	2016	MT	DERBYSHIRE AND NOTTINGHAMSHIRE	59.75	-244.38
AB1 - Nectar Flower Mix	2016	MT	DEVON	74.56	-304.95
AB1 - Nectar Flower Mix	2016	MT	DORSET AND SOMERSET	70.75	-289.37
AB1 - Nectar Flower Mix	2016	MT	EAST ANGLIA	562.67	-2301.32
AB1 - Nectar Flower Mix	2016	MT	EAST WALES	16.4	-67.08
AB1 - Nectar Flower Mix	2016	MT	EAST YORKSHIRE AND NORTHERN LINCOLNSHI	135.8	-555.42
AB1 - Nectar Flower Mix	2016	MT	ESSEX	183.3	-749.70
AB1 - Nectar Flower Mix	2016	MT	GLOUCESTERSHIRE, WILTSHIRE AND BATH/BRIS	104.9	-429.04
AB1 - Nectar Flower Mix	2016	MT	HAMPSHIRE AND ISLE OF WIGHT	89.35	-365.44
AB1 - Nectar Flower Mix	2016	MT	HEREFORDSHIRE, WORCESTERSHIRE AND WAR	196.32	-802.95
AB1 - Nectar Flower Mix	2016	MT	KENT	27.05	-110.63
AB1 - Nectar Flower Mix	2016	MT	LANCASHIRE	12.5	-51.13
AB1 - Nectar Flower Mix	2016	MT	LEICESTERSHIRE, RUTLAND AND NORTHAMPTC	154.5	-631.91
AB1 - Nectar Flower Mix	2016	MT	LINCOLNSHIRE	265.35	-1085.28
AB1 - Nectar Flower Mix	2016	MT	NORTH YORKSHIRE	130.2	-532.52
AB1 - Nectar Flower Mix	2016	MT	NORTHUMBERLAND AND TYNE AND WEAR	71.5	-292.44
AB1 - Nectar Flower Mix	2016	MT	SHROPSHIRE AND STAFFORDSHIRE	145.35	-594.48
AB1 - Nectar Flower Mix	2016	MT	SOUTH YORKSHIRE	23.05	-94.27
AB1 - Nectar Flower Mix	2016	MT	SURREY, EAST AND WEST SUSSEX	49.5	-202.46
AB1 - Nectar Flower Mix	2016	MT	TEES VALLEY AND DURHAM	2.5	-10.23
AB1 - Nectar Flower Mix	2016	MT	WEST MIDLANDS	5	-20.45

Figure 6.7: CS Data (breakdown) worksheet

7.0 Discussion

7.1. Options that retain the original land use but modify the management

Option AB15 Two year sown legume fallow has the potential to impact upon soil nitrogen and consequently losses of nitrogen. There are several interconnected aspects to consider:

- Legumes functioning as a catch crop, i.e. reducing excess nitrogen.
- Nitrogen fixation by legumes, and consequently release of nitrogen.
- Ground cover, cultivation and consequent impacts on soil erosion.

The autumn establishment of a legume offers potential for it to function as a catch crop during the first winter where a spring sown crop is substituted in the rotation. The stipulation to establish AB15 before the 7th September is conducive with this requirement although where the baseline uses a winter sown crop its ability to function in a cover crop capacity is likely to be diminished. Legumes present in a cover crop can both take up nitrogen from the soil and fix nitrogen from the atmosphere. They contribute to soil nitrogen both during growth if temperatures are sufficient and as mineralisation when the plant is destroyed, in this case when the ley is removed at the end of year 2. The impact of clover (*Trifolium* spp.) on nitrate loss while actively growing is reported in studies both on grassland and leys on cultivated land. Kaspar *et al*. (2008) assessed the use of legumes as cover crops and, although they accumulate less N during the winter, they will assimilate surplus N if present. When N is present, clover does not fix N, rather it assimilates residual N within the soil, plus legumes such as clover do not fix N when soil temperatures are low. Cuttle *et al*. (1992) report losses of 2-24 kg N ha^{-1} from ryegrass fertilised with 150 - 200 kg N ha^{-1} and 6-33 kg N ha^{-1} from an unfertilised ryegrass / white clover pasture respectively after 3 years. Stopes *et al* (2002) found leaching of nitrate to be similar between the grass/clover ley of an organic rotation (45 kg N ha^{-1}), long-term grassland in receipt of <200 kg N ha^{-1} (44 kg N ha^{-1}) and a grass ley under conventional management (50 kg N ha^{-1}). Although nitrate leaching may occur from leguminous crops while the crop is growing the quantity varies depending on the crop, its ability to establish ground cover and morphological features such as the rooting system. Crops approved under Environmental Focus Areas (EFAs) in Europe include Alfalfa (*Medicago*). If this species is allowed to grow for more than one year it may produce potentially deep rooting systems (Mathers *et al*., 1975) that permits removal of residual soil nitrate to a depth of 1.8 m after one years growth, increased to 3.6 m after 2 years. The inclusion of alfalfa within a rotation of continuous corn reduced nitrate leaching during crop growth from 55-81 kg N ha^{-1} during the previous corn crop, to 9 kg N ha^{-1} (Toth & Fox, 1998). Conversely, the loss of nitrate during the growth of lupin crops (*Lupinus* spp.) was found to be higher, although not significantly, than from ryegrass and mustard in a study in New Zealand (McLenaghen *et al*., 1996).

In addition to the species of legume, the timing of the removal of a grass/clover ley and the type of crops that follow are a key factor in determining nitrogen loss according to Djurhuus and Olsen (1997). Nitrate leaching from a grass/clover ley followed by a winter wheat crop, then either spring barley or winter rye was variable, between 3 - 84 kg N ha^{-1} yr^{-1} in response to 150 - 250 kg N ha^{-1} of supplementary N. Leaching was reduced, especially on coarse sand soils when the ley was removed in spring compared to late autumn, and when the second crop after removal of the N-fixing crop was winter rye compared to spring barley. Kavdir *et al*. (2005) measured 75 kg N ha^{-1} leachate from the mineralisation of root and shoot material followed its destruction by glyphosate. The timing of the removal of the N-fixing crop and the type of crop that follows is critical in minimising nitrate loss at this stage. Finally, with regard to ground cover and soil erosion, Wilson (2012) found that a clover crop sown in September, compliant with the 7th September cut-off date for AB12, doubles infiltration compared to conventional tillage, reducing the risk of surface run-off and soil erosion. Cover crops that are managed to increase the soil organic matter content will potentially contribute to limit soil erosion by improving its cohesiveness (Bruno and Fox, 2003).

Option SW10 Seasonal livestock removal on grassland has the potential to affect soil nitrogen, soil compaction, housing of livestock and manure handling and storage, which can all impact of losses of nitrogen (nitrate leaching, ammonia and nitrous oxide emissions) and methane emissions. There are several interconnected aspects to consider:

- Nitrogen deposition in the field.
- Soil compaction.
- Manure handling and storage from housed livestock

Countryside Stewardship options that permit winter stock removal are most likely to be applicable to sheep, since cattle tend to be housed during the winter as standard procedure. The removal of livestock from grassland can help reduce greenhouse gas emissions in the field, by reducing excess nitrogen in the soil and reducing the incidence of soil compaction. This does require an increase in the time that livestock are housed, and consequently can increase the quantity of manure produced, which needs to be handled, stored and applied, all of which can result in greenhouse gas emissions. However, the methods and techniques employed for handling, storage and application can greatly affect the magnitude of emissions, thus there is more control (compared to deposition in the field).

Nitrous oxide emission results from the N excreted by livestock, either as deposition onto grassland or when stored as manure or slurry during periods of housing. Nitrogen may be lost during storage as solid manures since they contain both aerobic and anaerobic micro-sites where NH_4^+-N can be nitrified to NO_3^-, providing a source of N_2O emission by denitrification (Monteny *et al.*, 2006; Chadwick et al., 2011). A combination of anaerobic conditions and high organic content coupled with the absence of oxygen results in CH_4 production during manure and slurry storage (IPCC, 2006; Monteny, 2006). The rate of CH_4 production increases with ambient storage temperature (IPCC, 2006). The CH_4 produced during manure storage is a product of total manure volatile solid content (for example highly fibrous material such as straw has a high volatile solid content), the method of storage (Chadwick, 2005; IPCC, 2006; Williams *et al.*, 2009) and temperature (IPCC, 2006). Nitrogen is excreted by the animal in faeces and urine due to a proportion of the crude protein (CP) not being digested. The greater the intake of CP in excess of the animal requirements, the greater the N excreted (Schils *et al.*, 2007). Feeds contain different quantities of CP per unit of metabolisable energy ME (Thomas, 2004) and satisfaction of the ME requirement may yield variable N excretion rates in response to dietary composition. The N excreted may be increased by excessive intake of N by the animal which is not utilised for growth. The supplementary feed provided to stock in the baseline scenarios derived from ABC (2017) and Nix (2017) utilise average supplementary feed rates for England. Nitrogen deposition per animal is derived from Brown *et al.* (2017). Where sheep are removed from potentially vulnerable soils, either organic soils or those prone to waterlogging it is assumed that they are grazed on mineral soils in e.g. a winter keep. The proportion of supplementary feed or grazing in the diet does not change, and hence the quantity of nitrogen excreted does not change. It is the destination of the nitrogen excreted during the winter that changes.

The removal of livestock from habitats dominated by organic soils e.g. moorland may be beneficial if they are grazed where firstly, waterlogging is not such a risk and secondly, dominated by mineral soils as opposed to organic soils. Deposition of N onto waterlogged soils (e.g. water meadow or salt marsh applicable to options HS7 Management of historic water meadows through traditional irrigation or GS9 Management of wet grassland for breeding waders when implemented on coastal or floodplain grazing marsh identified as priority habitat) during the winter increases the risk of denitrifcation (Machefert *et al.*, 2002) although rates are unlikely to increase until soil temperatures rise during the spring. Relocation of stock during the winter onto fields less susceptible to flooding reduces the N deposited and present where anaerobic soil conditions will persist for longer after soil temperatures increase. Deposition of N onto organic soils increases the proportion of N that is denitrified (DeVries *et al.*, 2003). While denitrification will be an inevitable consequence on all soils, it may be reduced where grazing during the winter on habitats dominated by organic soils prone to waterlogging is substituted with grazing on land dominated by mineral soils. As HS7 is a maintenance option the stock are assumed to have already been moved from land during the winter so no net change in emissions is observed.

The grazing of livestock on wet soils during the winter also risks soil compaction. This in turn inhibits grass growth and biomass formation by up to 13% and 35% for topsoil and subsoil compaction respectively (Louwagie *et al.*, 2008). Excessive grazing by livestock on wet soils may cause topsoil compaction. A decrease in grass growth equates to a reduction in potential SOC accumulation and the SOC at equilibrium of the specified area of grassland. The housing of livestock during the winter has been cited as a potential greenhouse gas mitigation strategy (Moorby et al., 2007). It does not necessarily require a reduction in stocking rates or a change of dominant land use. The removal of stock from grassland during the winter when there is negligible active grass growth prevents the deposition of N onto grass that will not utilise it immediately. Removal of N deposition during periods of greater daily rainfall in the winter reduce the risk of leaching and surface run-off of that N (Moorby *et al.*, 2007, Schils *et al.*, 2008).

The options that utilise a reduction in tillage depth (HS3 Reduced-depth cultivation historic features / HS9 Restricted depth crop establishment archaeology) potentially reduce energy use (and associated greenhouse gas emissions) but also influence the nitrous oxide emissions from the soil. Firstly, a decrease in cultivation depth (or a switch to minimum tillage) reduces emissions from diesel consumption (Williams *et al.*, 2009). Shallower cultivations require less energy, and this will vary with soil type, albeit very shallow cultivations (for example 5 cm) are not impacted greatly by soil type. So switching from deep (20 cm or more) to shallow cultivation can reduce energy use and emissions associated with diesel consumption. Importantly, N_2O emitted from soil is reported to increase (Newell-Price *et al.*, 2011), albeit this increase is mainly reported as being associated with zero tilled systems (King *et al.*, 2004; Krauss et al., 2017) as opposed to using shallow cultivations, when implemented in areas of higher precipitation in combination with soils prone to compaction (King *et al.*, 2004; Schils *et al.*, 2008). Dryer climates in the main, observe negligible change in N_2O emissions in response to zero tillage (Marland *et al.*, 2001; Helgason *et al.*, 2005). Where archaeological features are present in association with soils susceptible to compaction there will be a potential risk that the soil N_2O will exceed the reductions derived from decreased fuel consumption.

Option AB11 Cultivated areas arable plants creates uncropped, cultivated areas for scarce and declining arable plants, and provides areas of less densely vegetated ground for insects and other invertebrates, and summer foraging habitats for declining farmland birds. While necessary for the propagation of rare arable flora, a potential downside of this option and the associated annual cultivation regime relates to its effect on soil erosion. García-Ruiz (2010) report that alternating fallow periods with cultivation increases the risk of soil erosion due to the prevention of natural succession, and that continuity of land within fallow needs to be maintained without soil disturbance to allow vegetation growth and succession to proceed. While natural succession is permitted, it is only for a one year period. Minimum plant biomass is present where land is recently cultivated, so from a greenhouse gas emission perspective this risks loss of residual N in surface run-off (increased risk of indirect N_2O emission) combined with either water soil erosion (Freibauer, 2004; Smith et al., 2008) and wind erosion (Campbell et al., 1990; Janzen, 1987). The impact on erosion risk is in part determined by how rapidly natural generation will proceed. This is in turn a result of the underlying soil type and the species present in the seedbank. On calcareous soils, Romero-Díaz (2003) found that the development of an extensive native plant cover was achieved quickly and erosion rates reduced to ones comparable with those measured on natural or semi-natural habitats. Soils with a high sodium content and limited permeability have unstable aggregates resulting in the formation of a surface crust when left bare, this can inhibit natural plant colonization and increases the risk of erosion (Romero-Díaz, 2003; Lesschen *et al.*, 2007). Ruiz-Flaño *et al.* (1992) consider that the colonisation of bare ground by native plants has a significant mitigation role in runoff and sediment reduction on sloping land once they are established, although no distinction is made between annual and perennial plant species. In the case of the latter, the annual cultivation regime of AB11 will not enable longer term establishment. Additionally, where rainfall and natural plant colonisation is potentially limited, the soils have poor structure and low organic matter content, correlated with low infiltration rates and a higher risk of surface run-off (Pugnaire *et al.*, 2006).

7.2. Options that change the land use on a proportion of the area

Changes in, or part changes in land use can impact on above and below ground carbon, both in terms of permanent emissions and carbon sequestration. When land use is changed, carbon can be sequestered or released until a new equilibrium is reached (when the rate of C accumulation and loss balance out). Consequently, strategic changes in land use can minimise carbon emissions and create opportunities to sequester carbon. Above ground carbon is greater in more permanent vegetation such as woodland, where carbon can be stored in biomass such as timber, which when eventually harvested can be retained (if not destroyed, e.g. by burning). Whereas carbon stored in annual crops, generally results in no net gain, as the crops are either consumed or the biomass returned to the soil. Carbon sequestration in soils is influenced by annual precipitation and temperature (Ganuza and Almendros, 2003; Verheijen, et al., 2005), soil type, land use (e.g. cultivated, permanent grassland, woodland) and management practice (e.g. grass ley, zero tillage) (Dawson and Smith, 2007; Schils et al., 2008). When a land use change does occur, and annual sequestration rate can be calculated (or annual emissions in instances where SOC is lost) the IPCC standard is currently calculated for a period of 20 years, at which point it is assumed a new equilibrium is reached. However it is possible to have variable periods of time before equilibrium is reached. Cultivated land contains less SOC at equilibrium than grassland or woodland for a given soil type (Bradley et al., 2005; Dyson et al., 2009). The frequent cultivation and disturbance of the soil accelerates the oxidation of SOC to CO_2. This is not replaced due to smaller returns of plant residues to the soil (Smith *et al.*, 2000ab).

Options implemented as buffer strips take land out of production and have the potential to perform a number of functions subject to appropriate location including the filtration of nutrients, sediments and other pollutants, and, if the change in land use is permanent, sequestration of carbon. Included within this classification for the category C and D options are SW1 4 - 6 m buffer strip on cultivated land / SW2 4 - 6 m buffer strip on intensive grassland / SW11 Riparian management strip. The function and performance of these options will vary with local circumstances. However, under ideal circumstances they contribute to reduction of loss of nutrients and sediment (and associated greenhouse gas emissions from the surface run-off of nitrate – see above) and increases in sequestration of carbon. The function of SW11 is specifically aimed at mitigating this process, where it '*should be used in targeted areas to reduce diffuse water pollution, in particular where livestock access to the watercourse is causing a significant water quality issue*'. Buffer strips (both grassed and vegetated) can be effective in removing dissolved nutrients, with some studies suggesting that removal rates for nitrogen, phosphorus and potassium, can all be over 90% within 3-4 m of a buffer strip (Barling & Moore, 1994). In general however, it is in terms of nitrogen that most work has been done, applicable to the objectives of option SW11. The effectiveness of buffers strips in dealing with this nutrient has been found to be extremely variable, with both considerable benefits and burdens being reported in the literature (Kay *et al.*, 2009; Leeds-Harrison *et al.*, 1999; Lovell & Sullivan, 2006). The reasons for this would appear to be that performance is highly dependent on site specific properties such as those related to soil, climate, vegetation cover, physical dimensions, sediment properties and local land management practices (Kay *et al.*, 2009; Leeds-Harrison *et al.*, 1999; Blackwell *et al.*, 1999).

In order for buffer strips to be effective at removing nitrogen within surface run-off and reducing the formation of N_2O, the strip must intercept the run-off and uptake of nitrogen by the vegetation present proceed before its removal via other pathways within the nitrogen cycle. Hill (1996) reports a potential benefit where an impermeable layer is present close to the surface, so as to ensure that subsurface flow is within reach of the root system. Balestrini *et al.* (2011) find that within the riparian buffer strip zone, evapotranspiration (when sufficiently high) can be effective in inducing draw up of water from depth. This allows a greater level of flow interception, and therefore nitrogen removal, than might otherwise be possible. These properties are unlikely to occur everywhere, so the merits of each potential buffer strip location must be considered on a site by site basis (Leeds-Harrison *et al.*, 1999), but there is sufficient evidence to suggest that under suitable conditions, such as in flat catchments where the rate of water flow between the field and watercourse is relatively slow (Balestrini *et al.*, 2011), nitrogen removal can be significant, at least on a local scale, although catchment scale effectiveness is much less clear (Kay *et al.*, 2009).

Recommended buffer strip widths for nutrient removal vary considerably, being anything between 3 and 200 m, no doubt at least in part as a result of their impact being highly nutrient and site specific, although most are for something in the range of 5 - 15 m (Kay *et al.*, 2009), comparable to the 4 - 12 m specified for option SW11. Research suggests that the majority of nitrogen capture for example, occurs in the first 5 - 8 m (Kay *et al.*, 2009) so a 6 m wide buffer strip, the potential maximum stipulated for options SW1 and SW2 would offer potential to intercept, according to Kay et al. (2009) a proportion of nitrate in surface run-off. As far as sediment transport is concerned, this is in part reduced as a result of the extensive root systems which may be associated with buffer strips, since these hold soils together and increase infiltration, i.e. they reduce overland flow (Lovell & Sullivan, 2006), thereby reducing erosion. Again, where appropriately located, a buffer strip will potentially reduce CO_2 emissions associated with soil erosion albeit the overall impact being highly site specific. Where erosion or run-off is not a risk the reduction in greenhouse gas emissions is derived solely for substituting the baseline crop management (Warner et al., 2017). The key process is that associated with the trapping of sediments being carried in overland flow, so as to prevent their subsequent entry into a waterbody (Barling & Moore, 1994; Uusi-Kämppä & Jauhiainen, 2010). This occurs most efficiently when flow rates are sufficiently low as to ensure that the vegetation in the buffer strip doesn't become submerged, and where it enters the buffer strip approximately uniformly across its length. Focused flow will often lead to buffers being breached, and effectively ignored. However, buffer strip performance declines significantly as sediment particle size reduces, such that there is an inverse relationship between the length of a grass filter required and particle size. For example, the optimal trapping distances for sands, silts and clays has been determined to be 3 m, 15 m and 122 m respectively (for an overland flow rate of 1.02 litres sec^{-1} m^{-1}) (Barling & Moore, 1994). Another factor that may undermine the effectiveness of buffer strips are underlying features such as field drains (Leeds-Harrison *et al.*, 1999; Blackwell *et al.*, 1999; Kay *et al.*, 2009).

Other options may form strips along crop edges (Options AB8 Flower-rich margins / AB16 Autumn sown bumblebird mix or utilise areas that are e.g. potentially inaccessible to farm machinery (GS1 Take field corners out of management). In terms of mitigation of surface run-off and soil erosion their positioning is less likely to be conducive with this function. The impact on emissions of these options therefore is more likely to be due to substitution of the management associated with crop production and potential carbon sequestration due to reduced tillage frequency.

7.3. Options that create or manage semi-natural habitats

Option LH1 (Management of lowland heathland) is implemented on existing lowland heathland unlike previous analyses (Warner et al., 2011b) that assessed heathland sites where encroachment by trees or utilisation as forestry were the baseline land use. Lowland heathland in favourable condition consists of a minimum 25% cover of dwarf shrub communities (JNCC, 2009). It may be classed as wet or dry, and so the processes for managing and maintaining carbon vary slightly. Wet heathland is present where the soil surface is just above the level of the groundwater and may be periodically flooded (groundwater gley soils) (Catt, 2010). Dry heathland exists on more elevated areas that remain dry throughout the year. Both are present on organo-mineral soils (Catt, 2010) but are distinguished by the depth of the organic soil layer above the mineral layer. Restoration via deforestation replaces tree biomass with dwarf shrub plant communities and has a corresponding loss of biomass carbon. Accounting for this process was not necessary for option LH1.

The main impacts in this case are associated with the creation of the required habitat mosaic, including areas of bare soil created by shallow tillage on between 1% and 10% of the area. Provided this is not situated in areas where soil erosion may be a risk, the impact is restricted to a loss of herb or dwarf shrub biomass in the selected area. Selective burning of a proportion of the area is also permitted. Biomass equivalent to that contained within the dwarf shrub layer is removed immediately (Renate, 2014) although regeneration of the heather plants resumes post burning. Nitrous oxide and CH_4 are also released during burning. A potential risk associated with this from of management is excessive burn temperatures that oxidise carbon within the soil in addition to the plant biomass. This will not be an issue where appropriate burning protocols are observed.

The options WD1 Woodland creation maintenance payments and WD2 Woodland Improvement create new woodland (plant 1100 trees per ha) or improve existing woodland, both of which can have benefits for carbon sequestration in plant biomass (IPCC, 2006). As trees grow, carbon is sequestered in biomass (timber) until an equilibrium is reached, the precise quantity dependent on the tree species and ecological zone (IPCC, 2006; Milne and Brown, 1997; Dawson and Smith, 2007). A linear C accumulation rate is normally assumed in most calculations (IPCC, 2006), although it is known that this is subject to the age of the tree and the tree species (Milne and Brown, 1997). The management of WD1 removes competing vegetation and provides tree protection to aid establishment, facilitating the initial accumulation rates of biomass that tend to be lower in the initial phases of establishment (for example Table 3.13 - Morison *et al.*, 2012). It is conducive with favourable practices within the Forest Management Alternatives (FMAs) as reported by Read *et al* (2009a & b). The requirement to plant region specific or climate resilient species has important implications to permit growth and retain biomass in more well established woodlands, especially in regions such as the south-east of England where prolonged periods without summer rainfall are becoming increasingly more frequent. The biomass accumulation values in Table 3.13 for sweet chestnut (*Castanea sativa*) would be representative of a climate resilient species in the south-east region, for example Kent, although it is not a native species.

In addition to biodiversity benefits, fen (WT8 Management of fen) and bog (WT10 Management lowland raised bog) habitats are potentially large stores of carbon (e.g. fen contains deep layers of highly organic carbon rich soils - Carey *et al.*, 2008), so their maintenance is important with respect to preventing the emission of carbon, and their restoration could result in carbon sequestration. Two key process within the carbon cycle dictate the emissions associated with these two habitats. Drainage of fen and bog habitats creates aerobic soil conditions resulting in the oxidation of soil carbon and the release of CO_2 (Brown *et al.*, 2017; Schils *et al.*, 2008). Therefore, the preservation of peat soils as a means to mitigate Greenhouse gas emissions is identified as a priority by several authors both in the UK and throughout Europe (Brown *et al.*, 2017; Dawson and Smith, 2007; Dyson *et al.*, 2009; Schils *et al.*, 2008; Ostle *et al.*, 2009). In particular, their removal from cultivation, where CO_2 emissions may be significant (Freibauer, 2003; Ostle *et al.*, 2009; Schils *et al.*, 2008) due to drainage and loss of the anaerobic soil conditions conducive with peat formation is targeted. Restoration usually occurs on land where improvements, notably drainage, have been undertaken. Measures that remove drainage and restore these habitats potentially reverse the CO_2 release (Freeman *et al.,* 2001; Moorby *et al.,* 2007), the quantity of which is dependent on depth. The mitigation of CO_2 emissions is potentially greatest on deep and / or cultivated peat soils. Lowland peat bogs and fen habitats may be associated with both sets of parameters. The second important component of the carbon cycle associated with the rewetting of organic rich soils is the potential increase in CH_4 emissions (Worrall *et al.*, 2003, 2011; Lindsay et al, 2010). The magnitude of the increase is dependent on the presence of vegetation capable of performing the 'methane-shunt', also termed 'shunt' vegetation (Brown *et al.*, 2017; Couwenberg and Fritz, 2012). This increase does not tend to persist on peat bogs (Mojeremane *et al.*, 2010) because of the greater proliferation of target vegetation such as *Sphagnum* species in response to the restoration process (Lindsay et al, 2010). Where 'methane shunt' species, such as *Eriophorum* or *Phragmites* persist, CH_4 emissions may continue at elevated rates (4.75 t CO_2e ha^{-1} yr^{-1}) although this will be attributed more to fen and reedbed habitats. A net decrease in emissions is observed in fen habitat overall due to the higher initial CO_2 emission rates.

7.4. Options on organic land

In option OP1 Overwintered stubble a '*suitable cover crop species*' is stipulated, although no specific species mixture is required. Reducing excess nitrogen in the soil during the winter can help reduce losses via the leaching of nitrate and emissions of nitrous oxide (Newell-Price *et al.*, 2011). Areas where precipitation is higher also risk greater environmental loss to leaching and denitrification, in combination with high soil erosion risk. Vegetative cover and root systems will also affect soil erosion and thus potentially loss of soil carbon. Soil erosion removes a layer of topsoil and the soil carbon within, potentially oxidising the soil organic carbon to CO_2. The emissions of CO_2 due to soil erosion are proportional to the weight of soil organic carbon per tonne of soil for a given soil texture (Lewis *et al.*, 2012). These processes and the pathways by which excess nitrogen is lost (including emissions of nitrous oxide) will depend on site specific factors such as soil type, climate and management. Cover crops offer potential to remove surplus nitrogen from within the soil during fallow periods (e.g. preceding a spring sown crop) and decrease nitrate loss via leaching or surface run-off (Silgram & Harrison, 1998; Newell-Price *et al.*, 2011). The latter authors note that cover crops are of greatest potential benefit on light sand soils. The soil type is a key driver that determines the pathway that nutrients may enter watercourse, and the impact of cover crops. Freely draining sandy soils are most vulnerable to loss via leaching (Smith *et al.*, 1996). According to Silgram and Harrison (1998), the inclusion of a winter cover crop on sandy soils in northern Europe preceding a spring sown cereal potentially decreases NO_3^- leaching by 25 - 50 kg N $ha^{-1}yr^{-1}$. Yeo *et al.* (2014) point out that early planting is essential to maximise the benefit of catch crops, and predict that for every 30 days additional time the cover crop spends growing, nitrate loss is decreased by approximately 2 kg ha^{-1}.

Cover crop species differ in their potential to assimilate nitrogen during the winter, establish ground cover and their overall impact on preventing nitrogen leaching. In terms of mixtures to optimise nitrogen removal and reduce nitrate leaching and N_2O emissions Shepherd (1999) evaluate three catch crop species: forage rape (*Brassica napus*), winter rye (*Secal cereale*) and Dutch white turnip (*Brassica rapa*), over an 8 year period in sugar beet and potato crops. They report that nitrogen loss was reduced by a mean 25 kg NO_3-N ha^{-1} per growing season. Dabney *et al.* (2001) report that grass or brassica cover crops when grown as a single species mix are more effective at removing N than legume crops. Interestingly, both species performed more effectively when grown in combination with legumes. This would suggest a potential benefit to be realised where flexibility on the species sown is possible. Many authors report rye as operating more effectively in reducing nitrate leaching. A ryegrass catch crop reduced N leaching from 33 kg N ha^{-1} on bare soil (control) to 2.5 kg N ha^{-1} (McLenaghen *et al.*, 1996) or by 80% compared to bare soil during the winter when sown immediately post-harvest of zero tilled corn (Staver and Brinsfield., 1998). Ryegrass was found to be more effective than winter field beans (*Vicia faba*) and lupins (*Lupinus augus-tifolius*) (McLenaghen *et al.* (1996). The mechanism behind the suitability of rye is reported as its rapid growth during early growth stages (Yeo *et al.*, 2014). The authors report a 67% reduction when sown in September and 54% removal in November. Although an increase in emissions is associated with the establishment of a cover crop, on sandy soils where nitrate leaching is a higher risk, coupled with the ease of establishment on such soils using seed broadcasting and light cultivation (Newell-Price et al., 2011), the net impact is a decrease in CO_2 emissions. It is, as for many potential mitigation options, site specific i.e. a risk needs to be present otherwise the net change in CO2 is solely due to the establishment of the cover crop (Warner et al., 2017).

An increase in grassland species diversity such as that targeted in option OP4 Multi Species Ley and OP5 Undersown cereal (*grass/flower-rich legume ley*') has the potential to enhance 'resource partitioning' within the sward. Different grass or forage species utilise nutrients in variable forms from multiple layers within the soil profile, potentially at different times of the year (Conant *et al.*, 2001; 2005). Due to a theoretical reduced intensity in resource competition between plant species the growth of biomass and return of soil organic matter to the soil may potentially be enhanced. Underlying data with regards to this process however is currently sparse and in need of further research therefore no increase in soil carbon accumulation rates has been allocated.

7.5. Impact on greenhouse gas emissions in England

Globally 35.3 billion tonnes of carbon dioxide equivalents (t CO_2e) were emitted in 2013, with the European Union (EU) accounting for 11% (Olivier *et al.* 2014). Agriculture and land use change accounts for 9% of EU emissions (EC 2009), and this figure increases to approximately 30% globally (Smith *et al.* 2014b). In the UK in 2016, total emissions were 467.9 million t CO_2e, with agriculture accounting for 10%. Agricultural emissions are dominated by methane and nitrous oxide (57% and 32% of agricultural emissions respectively) (DBEIS, 2018a). Agriculture contributes 26.3 Mt CO_2e and 14.6 Mt CO_2e toward UK emissions of methane and nitrous oxide. Between 1990 and 2016, greenhouse gas emissions from agriculture decreased by around 16%, with a general downward trend in emissions since the late 1990s. This was driven by a fall in animal numbers and an increase in production efficiency over the period, together with a decrease in synthetic fertiliser use. Between 2015 and 2016 there was very little change in emissions from the agriculture sector (DBEIS, 2018a). The calculation of the precise contribution of ES and now CS to greenhouse gas emissions reduction in England is complex and subject to the following caveats. The approach taken here applies a full LCA including upstream emissions from the manufacture of agrochemicals and machinery, not included in the UK National Inventory (Brown et al., 2017). The UK National Inventory allocates N_2O emissions from soils spatially, based on regionally modified $FRAC_{LEACH}$ values (Cardenas *et al.*, 2013) as opposed to the mean emission value from three soil textures (Renate, 2014). Further, two CRF sectors are impacted, 3 Agriculture and 4 Land use, land use change and forestry. This requires the consideration of two types of potential emissions mitigation pathways: ‘permanent’, applicable to reducing CO_2, CH_4 and N_2O and ‘temporary’ that includes carbon sequestered in soils and biomass. Carbon sequestration is considered temporary due to the potential for loss of any carbon gained should there be a return to the original land use or management practice. The calculations consider the lifetime of the agreement (5 or 10 years) but do not account for changes in management post end of agreement.

With respect to carbon sequestration, the land use, land use change and forestry (LULUCF) data for the UK (which consists of emissions and removals from forest land, cropland, grassland, settlements and harvested wood products) shows that there was a net sink in 2016 of 14.6 million t CO_2e (consisting of -16 million tonnes of CO_2 and +1.4 million tonnes of N_2O). There has been a net sink in the UK from LULUCF every year since 1990. The value in 1990 was 2.1 million t CO_2e. The increase in sequestration has been driven by land converted to grassland and forest land, with an increasing uptake of carbon dioxide by trees as they reach maturity, in line with the historical planting pattern. There has also been some reduction in emissions since 1990 due to less intensive agricultural practices (DBEIS, 2018a). However the pace of removals is declining due to the ageing profile of trees (CCC, 2017). An inventory of land use change on carbon stocks in the UK by Buys *et al*. (2014) maps changes and losses spatially at the Nomenclature des Unités Territoriales Statistiques (NUTS) 3 level. From cropland, losses are mostly within the 0 to 15 t C km^{-2} (0 to 0.15 t C ha^{-1} or 0 to 0.55 t CO_2e ha^{-1}). Existing grassland is considered a declining net sink, with gains of 0 to 20 t C km^{-2} (0 to 0.20 t C ha^{-1} or 0 to 0.73 t CO_2e ha^{-1}). A further factor to consider is the impact of climate change, although the magnitude of the impact remains uncertain and depends on soil type. Barraclough et al. (2015) report organic soils as being the most vulnerable to decline via this mechanism, and that declines in England and Wales were influenced primarily by a rise in temperature. A factor hypothesised in this decline was a potential successional shift in vegetation structure, *Sphagnum* moss being replaced by terrestrial plant species with an associated reduction in the deposition of plant litter. Although climate change was reported as contributing to the decline of SOC in organo-mineral soils, the change was less prominent, with a stronger link to changes in rainfall being established rather than temperature.

UK emissions were 42% below 1990 levels in 2016, approximately halfway to the 2050 commitment to reduce emissions by at least 80% on 1990 levels. The first carbon budget (2008-12) has been met and the UK is currently on track to outperform the second (2013-17) and third (2018-22) carbon budgets, but is not on track to meet the fourth, which covers the period 2023-27. Since 2012, progress has been dominated by the power sector. Carbon dioxide emissions from transport and buildings rose in 2015 and 2016, while progress in driving emissions reductions in industry and for non-CO_2 greenhouse gases has been minimal (CCC, 2017). With regard to agriculture and land use, it is considered that the sector is not on track to deliver the agreed level of ambition for a reduction of 3 million t CO_2e in England (4.5 million t CO_2e in the UK) by 2022. As mentioned above, future sequestration is at risk due to the ageing profile of trees and the low level of new tree planting (CCC, 2017). Countryside Stewardship options are in the main conducive with reducing greenhouse emissions, subject to the caveat of accounting for production displacement risk. In reference to CS option uptake (as of March 2018) the estimated decrease in emissions, accounting for all LCA components, is just over 1 Mt yr^{-1}.

Defra has just implemented a smart GHG and ammonia emission inventory for UK agriculture (February 2018), using a new model created by experts. Changes have been implemented as part of Defra's improvement programme to ensure that the UK inventory is more accurately representing the UK agricultural sector. Improvements include: the development of a Tier 3 approach for estimating enteric methane emissions for all cattle and sheep; an improved Tier 2 methodology for methane and nitrous oxide emissions from livestock manure management, implementing a mass-consistent nitrogen flow model through the manure management chain; the implementation of UK-specific emission factors for nitrous oxide emissions from soils arising from fertiliser and manure applications and excretal returns from grazing livestock, using UK-specific data. Other improvements include a Tier 3 approach modelling nitrogen flow through livestock manure management in the UK.

Former and other smaller improvements have resulted in a decrease in estimates of emissions of 3.3 million tCO_2e and 4.0 million tCO2e in 1990 and 2015 respectively. There have also been amendments to the techniques for assessing emissions from LULUCF sector, including amendment to the CARBINE model (Matthews et al., 2017), decreasing estimates of emissions by around 7.1 million tCO_2e in 1990 and by around 8.3 million tCO_2e in 2015 (DBEIS. 2018b). Tomlinson et al. (2018) highlight that actual land use change is approximately three times that of net land use change, and that carbon flux calculations have potential to be improved further.

The Committee on Climate Change (CCC, 2017) have outlined that for the Government's plan to meet the fourth and fifth carbon budgets, agricultural emissions need to fall by 17% between 2015 and 2030 and afforestation rates to deliver 15,000 hectares a year. They suggest the following to achieve this:

- A stronger policy framework for agricultural emissions reduction across all nations to 2022, as current progress is not on track.
- The new 'Smart' inventory for agriculture to be introduced in 2018, to enable better monitoring of progress in reducing emissions including assessment of mitigation options.
- New policies and measures required to deliver emissions reductions in agriculture and afforestation to 2030 that moves beyond the current voluntary approach, and with CAP replaced, from 2020, by a policy that links support more closely to the reduction and removal of emissions in agriculture, forestry and other land use sectors.
- Addressing financial and non-financial barriers to increase afforestation rates and on-farm tree planting schemes.

With respect to the third bullet point and linking support more closely to the reduction and removal of emissions in agriculture, most CS options reduce emissions relative to the baseline land management scenario. In terms of emissions removal from agriculture those options that integrate mechanisms that permit either a reduction in emissions per unit of yield or, where the crop is removed, confer benefit that is additional to the emissions associated with the removal of the crop itself. Such options confer 'true' mitigation potential, that is, emissions reduction coupled with a low risk of production displacement. For example, if a crop is removed from an area of high soil erosion risk and replaced with a CS option where erosion is reduced, a net emissions reduction occurs equivalent to the NO_3^- and SOC embedded within the erosion process in addition to the emissions associated with the crop production cycle. Such options require strategic positioning but where located appropriately, will reduce emissions while minimising the risk of production displacement. Warner *et al*. (2016) prioritise former ES options on cultivated land that minimise the risk of production displacement, in addition to reducing greenhouse gases. Taking this perspective and applying it to CS, importance is allocated to options that, while maintaining agricultural production, protect soils at risk to erosion (e.g. SW5 Enhanced management of maize crops) or reduce nitrate leaching (e.g. SW6 Winter cover crops), subject to the options being targeted spatially. The financial compensation associated with the growing of, for example, a cover crop is a useful mitigation strategy that can be met by CS. Priority is also given to land removed from production for this purpose e.g. SW4 12-24 m watercourse buffer strip on cultivated land where the option is in an optimal location. Another example is the removal of livestock from wet soils during the winter (SW10 Seasonal livestock removal on grassland in SDAs next to water). This option does not affect stocking rates, rather it relocates livestock to areas that are not vulnerable to elevated emissions of N_2O due to deposition onto waterlogged soils. Countryside Stewardship also has an important role in the protection and restoration of habitats with high carbon containing soils and mitigation of CO_2 emission through options such as WT10 Management of lowland raised bog and WT8 Management of fen. Due to the potential lag effect associated with the restoration process (Worrall et al., 2011), full benefit may not be realised within the ten year agreement period.

Afforestation is not generally applicable to CS but options exist to enhance on-farm tree planting, namely through options WD5 (Restoration of wood pasture and parkland) or WD6 (Creation of wood pasture). This option has parallels with silvopasture, cited by Mosquera-Losada *et al*. (2018) as a potential greenhouse gas mitigation strategy. Unlike silvopasture the biomass within wood pasture is not typically harvested, it does however permit continued livestock grazing while simultaneously increasing biomass. If implemented in conjunction with the selection of tree species appropriate to the location and future climate change scenarios, it offers a mechanism for climate change adaptation. Improvement to woodland quality and the inclusion of broadleaved tree species with a greater potential to accumulate C in biomass in the longer term (Forestry Commission, 2018) is possible through option WD2 (Woodland Improvement). As iterated earlier on in the report, the release of CO_2 from the natural decay of conifer trees removed (Morison *et al*., 2012) potentially exceeds the rate of C sequestration in the biomass of newly planted broadleaved species (Forestry Commission, 2018). This results in net cumulative CO_2 emissions during the initial growth phases, with net sequestration not occurring until after years 25 - 35. Countryside Stewardship has the potential to contribute to increased C sequestration in both soils and biomass, but agreements will need to be for the long term in order for it to be fully realised.

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Appendix 1. Baseline and option scenario descriptions

A1.0. Grassland baselines

A1.1. Temporary grassland for silage

Table A1.1. Temporary grassland (NVZ) for silage (2 cuts) 130 kg N ha-^{1} total; average growth class, average SNS, limited clover present, soil P and K index of 2.

	Date	Activity	Product / active ingredient
Rotation	every 5 years	lime	ground limestone 0.75 t ha^{-1} yr^{-1}
		plough (20 cm)	
		power harrow	
		drill	25 kg seed ha^{-1}
Annually		rolling	
	Mar	N fertiliser	70 kg N
	Mar	herbicide (weedwipe) docks, annual dicots	2 l fluroxypyr (200 gl^{-1})
	Mar	FYM	17 t
	Apr	1st cut (20 tha^{-1})	
		bale	
		N fertiliser	50 kg N
		P & K fertiliser	2.8 kg P_2O_5
	May	2nd cut (12 tha^{-1})	
		bale	
		transport to on farm storage (2 km) (32 t ha^{-1})	

A1.2. Semi-improved grassland grazed by cattle or sheep / lowland or upland

Table A1.2. Permanent semi-improved grassland baseline scenarios grazed by cattle + sheep, cattle only or sheep only. Cattle refers to average values of spring and autumn calving combined.

	Date	Activity	Product / active ingredient
Rotation	every 5 years	lime	ground limestone 0.75 t ha^{-1} yr^{-1}
Annually		stocking rate (lowland)	1.14 LU: 0.9 cattle (single suckling) @ 0.6 LU / forage ha (average) + 5 ewes with lambs (5 * 0.12 LU) / forage ha (average) or 1.2 LU: 10 ewes + lambs (10 * 0.12 LU) / forage ha (average) or 0.93 LU: 1.5 cattle (single suckling) @ 0.6 LU / forage ha (average)
		stocking rate (upland)	0.84 LU: 0.8 cattle (single suckling) @ 0.6 LU / forage ha (average) + 4.5 ewes + lambs (4.5 * 0.08 LU) / forage ha (average) or 0.72 LU: 9 ewes + lambs (9 * 0.08 LU) / forage ha (average) or 0.86 LU: 1.4 cattle (single suckling) @ 0.6 LU / forage ha (average)
		stocking rate (LFA upland)	0.46 LU: 0.5 cattle (single suckling) @ 0.6 LU / forage ha (average) + 2.0 ewes + lambs (2.0 * 0.08 LU) / forage ha (average) or

			0.32 LU: 4.0 ewes + lambs (4 * 0.08 LU) / forage ha (average) or 0.63 LU: 1.05 cattle (single suckling) @ 0.6 LU / forage ha (average)
	Feb / Mar	N fertiliser	30 kg N
	Mar	P & K fertiliser	15 kg P_2O_5 15 kg K_2O
	Mar	herbicide (weedwipe) docks, annual dicots,	2 l fluroxypyr (200 gl^{-1})
	April	chain harrow	
	winter	concentrates (lowland)	103 kg per ewe (including lambs) or 245 kg per cow (including calf, spring / autumn calving)
		(upland)	50 kg per ewe (including lambs) or 253 kg per cow (including calf, spring / autumn calving)
		(LFA upland)	30 kg per ewe (including lambs) or 375 kg per cow (including calf, spring / autumn calving)
	winter	grass silage (lowland)	104 kg DM per ewe (including lambs) or 651 kg DM per cow
		(upland)	89 kg DM per ewe (including lambs) or 593 kg DM per cow
		(LFA upland)	89 kg DM per ewe (including lambs) or 593 kg DM per cow
	winter	housing (lowland)	sheep 0 days cattle 151 days (0.41 year)
		(upland)	sheep 0 days cattle 151 days (0.41 year)
		(LFA upland)	sheep 0 days cattle 151 days (0.41 year)

A1.3. Unimproved grassland grazed by cattle or sheep / lowland or upland

Table A1.3. Unimproved grassland baseline scenarios grazed by cattle + sheep, cattle only or sheep only. Cattle refers to average values of spring and autumn calving combined.

	Date	Activity	Product / active ingredient
Annually		stocking rate (lowland)	0.42 LU: 0.4 cattle (0.6 LU per head) (average) + 1.5 ewes (0.12 LU per ewe) (average) or 0.36 LU: 3 ewes (0.12 LU per ewe) (average) or 0.48 LU: 0.8 cattle (0.6 LU per head) (average)
		stocking rate (upland)	0.36 LU: 0.34 cattle (0.6 LU per head) (average) + 2 ewes (0.08 LU per ewe) (average) or 0.32 LU: 4 ewes (0.08 LU per ewe) (average) or 0.4 LU: 0.67 cattle (0.6 LU per head) (average)
		stocking rate (LFA upland)	0.2 LU: 0.25 cattle (0.6 LU per head) (average) + 0.65 ewes (0.08 LU per ewe) (average) or 0.1 LU: 1.3 ewes (0.08 LU per ewe) (average) or 0.3 LU: 0.5 cattle (0.6 LU per head) (average)
	winter	concentrates (lowland)	87 kg per ewe (including lambs) or 291 kg per cow (including calf, spring / autumn calving)
		(upland)	47 kg per ewe (including lambs) or 221 kg per cow (including calf, spring / autumn calving)
		(LFA upland)	35 kg per ewe (including lambs) or 221 kg per cow (including calf, spring / autumn calving)
	winter	grass silage (lowland)	104 kg DM per ewe or

				651 kg DM per cow
			(upland)	89 kg DM per ewe or 593 kg DM per cow
			(LFA upland)	89 kg DM per ewe or 593 kg DM per cow
	winter	housing	(lowland)	sheep 0 days cattle 151 days (0.41 year)
			(upland)	sheep 0 days cattle 151 days (0.41 year)
			(LFA upland)	sheep 0 days cattle 151 days (0.41 year)

A1.4. Organic temporary grassland for silage

Table A1.4. Temporary organic grassland for silage.

	Date	Activity	Product / active ingredient
Rotation	every 5 years	lime	ground limestone 0.75 t ha^{-1} yr^{-1}
		plough (20 cm)	
		power harrow	
		drill	25 kg seed ha^{-1}
Annually	Feb	roll	
	Feb / Mar	NPK	17 t ha^{-1} FYM
	Apr	chain harrow	
	Apr	1st cut 20.0 t ha^{-1}	
	Apr	bale	
	June	2nd cut 13.5 t ha^{-1}	
	June	bale	
		transport to on farm storage (2 km) (33.5 t ha^{-1})	

A1.5. Organic semi-improved grassland grazed by cattle or sheep / lowland or upland

Table A1.5. Organic semi-improved grassland baseline scenarios grazed by cattle + sheep, cattle only or sheep only.

	Date	Activity	Product / active ingredient
Rotationally	every 5 years	lime	ground limestone 0.75 t ha^{-1} yr^{-1}
Annually		stocking rate (lowland)	0.84 LU: 0.5 cattle (single suckling) @ 0.6 LU / forage ha (average) + 4.5 ewes and lambs (4.5 * 0.12 LU) / forage ha (average) or 1.08 LU: 9 ewes + lambs (9 * 0.12 LU) / forage ha (average) or 0.6 LU: 1.0 cattle (single suckling) @ 0.6 LU / forage ha (average)
		stocking rate (upland)	0.78 LU: 0.8 cattle (single suckling) @ 0.6 LU / forage ha (average) + 3.75 ewes and lambs (3.75 * 0.08 LU) / forage ha (average) or

				0.6 LU: 7.5 ewes + lambs (7.5 * 0.08 LU) / forage ha (average) or
				0.55 LU: 0.92 cattle (single suckling) @ 0.6 LU / forage ha (average)
		stocking rate (LFA upland)		0.46 LU: 0.5 cattle (single suckling) @ 0.6 LU / forage ha (average) + 2.0 ewes and lambs (2.0 * 0.08 LU) / forage ha (average) or
				0.32 LU: 4.0 ewes + lambs (4 * 0.08 LU) / forage ha (average) or
				0.41 LU: 0.68 cattle (single suckling) @ 0.6 LU / forage ha (average)
	April	chain harrow		
	August	chain harrow		
	winter	concentrates	(lowland)	52.5 kg per ewe or
				240 kg per cow (including calf, spring calving)
			(upland)	40 kg per ewe or
				190 kg per cow (including calf, spring calving)
			(LFA upland)	30 kg per ewe or
				190 kg per cow (including calf, spring calving)
	winter	grass silage	(lowland)	104 kg DM per ewe or
				651 kg DM per cow
			(upland)	89 kg DM per ewe or
				593 kg DM per cow
			(LFA upland)	89 kg DM per ewe or
				593 kg DM per cow
	winter	housing	(lowland)	sheep 0 days
				cattle 151 days (0.41 year)
			(upland)	sheep 0 days
				cattle 151 days (0.41 year)
			(LFA upland)	sheep 0 days
				cattle 151 days (0.41 year)

A1.6. Organic unimproved grassland grazed by cattle or sheep / lowland or upland

Table A1.6. Organic unimproved grassland baseline scenarios grazed by cattle + sheep, cattle only or sheep only.

	Date	**Activity**		**Product / active ingredient**
Annually		stocking rate (lowland)		0.42 LU: 0.4 cattle (0.6 LU per head) (average) + 1.5 ewes (0.12 LU per ewe) (average) or
				0.36 LU: 3 ewes (0.12 LU per ewe) (average) or
				0.48 LU: 0.8 cattle (0.6 LU per head) (average)
		stocking rate (upland)		0.36 LU: 0.34 cattle (0.6 LU per head) (average) + 2.0 ewes (0.08 LU per ewe) (average)
				0.24 LU: 3 ewes (0.08 LU per ewe) (average) or
				0.4 LU: 0.67 cattle (0.6 LU per head) (average)
		stocking rate (LFA upland)		0.2 LU: 0.25 cattle (0.6 LU per head) (average) + 0.65 ewes (0.08 LU per ewe) (average) or
				0.1 LU: 1.3 ewes (0.08 LU per ewe) (average) or
				0.3 LU: 0.5 cattle (0.6 LU per head) (average)
	winter	concentrates	(lowland)	52.5 kg per ewe or
				240 kg per cow (including calf, spring calving)

		(upland)	40 kg per ewe or 190 kg per cow (including calf, spring calving)
		(LFA upland)	30 kg per ewe or 190 kg per cow (including calf, spring calving)
winter	grass silage	(lowland)	104 kg DM per ewe or 651 kg DM per cow
		(upland)	89 kg DM per ewe or 593 kg DM per cow
		(LFA upland)	89 kg DM per ewe or 593 kg DM per cow
winter	housing	(lowland)	sheep 0 days cattle 151 days (0.41 year)
		(upland)	sheep 0 days cattle 151 days (0.41 year)
		(LFA upland)	sheep 0 days cattle 151 days (0.41 year)

A2.0. Grassland CS option management

Grassland	GS2	GS2	GS3	GS4	GS5
	Permanent grassland with very low inputs (outside SDAs)	Permanent grassland with very low inputs (outside SDAs)	Ryegrass seed-set as winter food for birds	Legume and herb-rich swards	Permanent grassland with very low inputs in SDAs
Baseline	semi Improved grassland - lowland sheep	semi Improved grassland - lowland cattle	temporary grassland silage	temporary grassland silage	semi-improved grassland - upland LFA sheep
Machinery					
	Herbicide - weedwipe	Herbicide - weedwipe	Herbicide - weedwipe	Herbicide - weedwipe	Herbicide - weedwipe
	Fertiliser (inorganic) application x 2.2	Fertiliser (inorganic) application x 2.2	Fertiliser (inorganic) application x 4.2	Fertiliser (inorganic) application x 1.2	Fertiliser (inorganic) application x 2.2
	Chain harrow	Chain harrow	Pesticide spray		Brushwood cutter 1% area
			Mow x 2		
			Plough and reseed + roll every 5 years	Plough and reseed + roll every 5 years	
Other					
Seed					
			25 kg grass every 5 years	36 kg 80% grass + 10% clover + 10% herbs/wildflowers every 5 years	
Pesticides & PGRs					
	Herbicide - amidosulfuron	Herbicide - amidosulfuron	Herbicide - amidosulfuron	Herbicide - amidosulfuron	Herbicide - amidosulfuron
			Insecticide (leatherjackets) - chlorpyrifos		Herbicide stumps glyphosate 2 l ha-1 1% area
Supplementary nutrients					
Lime	0.75 t ave per year	0.75 t ave per year	0.75 t ave per year	0.75 t ave per year	0.75 t ave per year
N(+S)	9 kg N	9 kg N	20 kg N		9 kg N
N			30 kg N		
N					
P2O5	15 kg P_2O_5	15 kg P_2O_5	40 kg P_2O_5	15 kg P_2O_5	15 kg P_2O_5
K2O	15 kg K_2O	15 kg K_2O	60 kg K_2O	15 kg K_2O	15 kg K_2O
MgO					
FYM					
Slurry					
Harvest					
Crop yield			54 t fresh weight		
Livestock (as livestock units)					
Lowland sheep	1.2				
Lowland cattle		1.08		0.48	
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA					0.32
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grass silage kg DM per head	89 kg	651 kg		651 kg	104 kg
Concentrate kg DM per head	30 kg	250 kg		250 kg	75 kg
Deposition (proportion year)					
Grazing deposition - no land use change	1	0.59		0.59	1
Grazing deposition - land use change e.g. winter keep					
Housed - slurry					
Housed - FYM		0.41		0.41	

Grassland	GS5	GS9	GS10	GS13	GS13
	Permanent grassland with very low inputs in SDAs	Management of wet grassland for breeding waders	Management of wet grassland for wintering waders and wildfowl	Management of grassland for target features	Management of grassland for target features
Baseline	semi-improved grassland – upland LFA cattle	water meadow - cattle	water meadow - cattle	semi improved grassland - lowland sheep	semi improved grassland - lowland cattle
Machinery					
	Herbicide - weedwipe	Mow x 0.3	Mow x 0.3		
	Fertiliser (inorganic) application x 2.2				
	Brushwood cutter 1% area				
Other					
Seed					
Pesticides & PGRs					
	Herbicide - amidosulfuron				
	Herbicide stumps glyphosate 2 l ha^{-1} 1% area				
Supplementary nutrients					
Lime	0.75 t ave per year				
N (+S)	9 kg N				
N					
N					
N					
N					
N					
P_2O_5	15 kg P_2O_5				
K_2O	15 kg K_2O				
MgO					
FYM					
Slurry					
Harvest					
Crop yield					
Livestock (as livestock units)					
Lowland sheep				0.36	
Lowland cattle		0.1	0.1		0.48
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA					
Upland cattle LFA	0.63				
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					
Grass silage kg DM per head	593 kg			104 kg	651 kg
Concentrate kg DM per head	375 kg			75 kg	250 kg
Deposition (proportion year)					
Grazing deposition - no land use change	0.59	0.5	0.5	1	0.59
Grazing deposition - land use change e.g. winter keep		0.09	0.09		
Housed - slurry					
Housed - FYM	0.41	0.41	0.41		0.41

Grassland	GS16	GS16	GS16	GS16	GS17
	Rush infestation control supplement	Rush infestation control supplement	Rush infestation control supplement	Rush infestation control supplement	Lenient grazing supplement
Baseline	semi improved grassland - lowland sheep	semi improved grassland - upland sheep	unimproved grassland - lowland sheep	unimproved grassland - upland sheep	with GS2 + sheep
Machinery					
	Herbicide - weedwipe	Herbicide - weedwipe			
	Fertiliser (inorganic) application x 2.2	Fertiliser (inorganic) application x 2.2			
	Mow 10% area	Mow 10% area	Mow 10% area	Mow 10% area	
Other					
Seed					
Pesticides & PGRs					
	Herbicide - amidosulfuron	Herbicide - amidosulfuron			
Supplementary nutrients					
Lime	0.75 t ave per year	0.75 t ave per year			
N (+S)	30 kg N	30 kg N			
N					
N					
N					
N					
N					
P_2O_5	15 kg P_2O_5	15 kg P_2O_5			
K_2O	15 kg K_2O	15 kg K_2O			
MgO					
FYM					
Slurry					
Harvest					
Crop yield					
Livestock (as livestock units)					
Lowland sheep	1.2		0.36		1.2
Lowland cattle					
Upland sheep		0.72		0.32	
Upland cattle					
Upland sheep / hill flock LFA					
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					
Grass silage kg DM per head	104 kg	89 kg	104 kg	89 kg	53 kg
Concentrate kg DM per head	103 kg	50 kg	75 kg	40 kg	104 kg
Deposition (proportion year)					
Grazing deposition - no land use change	1	1	1	1	0.3
Grazing deposition - land use change e.g. winter keep					0.7
Housed - slurry					
Housed - FYM					

Grassland	GS17	GS17	GS17	HS7	HS9
	Lenient grazing supplement	Lenient grazing supplement	Lenient grazing supplement	Management of historic water meadows through traditional irrigation	Restricted depth crop establishment to protect archaeology under an arable rotation
Baseline	with GS2 + cattle	with GS5 + sheep	with GS5 + cattle	water meadow	temporary grassland silage
Machinery					
					reseed every 5 years – herbicide spray & direct drill
					Fertiliser (inorganic) application x 2.2
Other					
Seed					
					36 kg grass/clover mixture every 5 years
Pesticides & PGRs					
					Herbicide - glyphosate 3 L ha^{-1} every 5 years
Supplementary nutrients					
Lime					0.75 t ave per year
N (+S)					*4 years in 5:*
N					70 kg N
N					50 kg N
N					
N					
N					
P2O5					2.8 kg P_2O_5
K2O					
MgO					
FYM					17 t
Slurry					
Harvest					
Crop yield					32 t fresh weight
Livestock (as livestock units)					
Lowland sheep				0.15	
Lowland cattle	0.93				
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA		0.32	0.63		
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					
Grass silage kg DM per head	651 kg	89 kg	593 kg		
Concentrate kg DM per head	250 kg	30 kg	375 kg		
Deposition (proportion year)					
Grazing deposition - no land use change	0.3	0.3	0.3	0.59	
Grazing deposition - land use change e.g. winter keep	0.29	0.7	0.29	0.41	
Housed - slurry					
Housed - FYM	0.41		0.41		

Grassland	SW2	SW2	SW10	SW10	SW11
	4-6m buffer strip on intensive grassland [establishment]	4-6m buffer strip on intensive grassland	Seasonal livestock removal on grassland in SDAs next to streams, rivers and lakes	Seasonal livestock removal on grassland in SDAs next to streams, rivers and lakes	Riparian management strip
Baseline	temporary grassland silage	temporary grassland silage	semi-improved grassland lowland - sheep	semi-improved grassland lowland - cattle	semi-improved grassland lowland - sheep
Machinery					
	Plough, standard drill, roll 1st year only	Brushwood cutter 1% area	Chain harrow	Chain harrow	Herbicide - weedwipe
			Fertiliser (inorganic) application x 2.2	Fertiliser (inorganic) application x 2.2	
	Herbicide - weedwipe	Herbicide - weedwipe	Herbicide - weedwipe	Herbicide - weedwipe	Brushwood cutter 10% area
	Mow * 2.5 during years 1 and 2	Mow 50% area			
Other					
					Fencing
Seed					
	25 kg grass every 5 years				
Pesticides & PGRs					
	Herbicide - amidosulfuron	Herbicide - amidosulfuron	Herbicide - amidosulfuron	Herbicide - amidosulfuron	Herbicide - amidosulfuron
		Herbicide stumps glyphosate 2 l ha-1 1% area			Herbicide stumps glyphosate 2 l ha-1 10% area
Supplementary nutrients					
Lime			0.75 t ave per year	0.75 t ave per year	
N (+S)					
N			30 kg N	30 kg N	
N					
N					
N					
N					
P2O5			15 kg P_2O_5	15 kg P_2O_5	
K2O			15 kg K_2O	15 kg K_2O	
MgO					
FYM					
Slurry					
Harvest					
Crop yield					
Livestock (as livestock units)					
Lowland sheep			1.2		
Lowland cattle				1.08	
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA					
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					
Grass silage kg DM per head			104 kg	651 kg	
Concentrate kg DM per head			75 kg	250 kg	
Deposition (proportion year)					
Grazing deposition - no land use change			0.55	0.55	
Grazing deposition - land use change e.g. winter keep					
Housed - slurry					
Housed - FYM				0.45	

Grassland	SW11	SW12	SW12	SW12	SW13
	Riparian management strip	Making space for water	Making space for water	Making space for water	Very low nitrogen inputs to groundwaters
Baseline	semi-improved grassland lowland - cattle	temporary grassland silage	semi-improved grassland lowland - sheep	semi-improved grassland lowland - cattle	temporary grassland silage
Machinery					
	Herbicide - weedwipe	Chain harrow	Chain harrow	Chain harrow	Chain harrow
		Fertiliser (inorganic) application x 2.2	Fertiliser (inorganic) application x 2.2	Fertiliser (inorganic) application x 2.2	Fertiliser (inorganic) application x 2.2
	Brushwood cutter 10% area	Herbicide - weedwipe	Herbicide - weedwipe	Herbicide - weedwipe	Herbicide - weedwipe
Other					
	Fencing				
Seed					
Pesticides & PGRs					
	Herbicide - amidosulfuron	Herbicide - amidosulfuron	Herbicide - amidosulfuron	Herbicide - amidosulfuron	Herbicide - amidosulfuron
Supplementary nutrients					
Lime		0.75 t ave per year	0.75 t ave per year	0.75 t ave per year	0.75 t ave per year
N (+S)					
N		30 kg N	30 kg N	30 kg N	30 kg N
N					
N					
P2O5		15 kg P_2O_5	15 kg P_2O_5	15 kg P_2O_5	15 kg P_2O_5
K2O		15 kg K_2O	15 kg K_2O	15 kg K_2O	15 kg K_2O
MgO					
FYM					
Slurry					
Harvest					
Crop yield					
Livestock (as livestock units)					
Lowland sheep		1.2	1.2		1.0
Lowland cattle				1.08	
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA					
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					
Grass silage kg DM per head		104 kg	104 kg	651 kg	104 kg
Concentrate kg DM per head		75 kg	75 kg	250 kg	75 kg
Deposition (proportion year)					
Grazing deposition - no land use change		0.55	0.55	0.59	0.55
Grazing deposition - land use change e.g. winter keep		0.45	0.45		0.45
Housed - slurry					
Housed - FYM				0.41	

Grassland	SW13	UP1	UP1	UP2	UP2
	Very low nitrogen inputs to groundwaters	Enclosed rough grazing	Enclosed rough grazing	Management of rough grazing for birds	Management of rough grazing for birds
Baseline	temporary grassland silage	unimproved grassland - upland LFA sheep	unimproved grassland - upland LFA cattle	unimproved grassland - upland LFA sheep	unimproved grassland - upland LFA cattle
Machinery					
	Chain harrow	Brushwood cutter 10% area	Brushwood cutter 10% area	Mow 20% area	Mow 20% area
	Fertiliser (inorganic) application x 2.2				
	Herbicide - weedwipe				
Other					
		Burning 10% area	Burning 10% area		
Seed					
Pesticides & PGRs					
	Herbicide - amidosulfuron	Herbicide stumps glyphosate 2 l ha-1 10% area	Herbicide stumps glyphosate 2 l ha-1 10% area		
Supplementary nutrients					
Lime	0.75 t ave per year				
N(+S)					
N	30 kg N				
N					
N					
P2O5					
K2O					
MgO	15 kg P_2O_5				
FYM	15 kg K_2O				
Slurry					
Harvest					
Crop yield					
Livestock (as livestock units)					
Lowland sheep					
Lowland cattle	1.08				
Upland sheep				0.1	
Upland cattle					
Upland sheep / hill flock LFA		0.1			
Upland cattle LFA			0.3		0.3
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					
Grass silage kg DM per head	651 kg	89 kg	593 kg	89 kg	593 kg
Concentrate kg DM per head	250 kg	40 kg	190 kg	40 kg	190 kg
Deposition (proportion year)					
Grazing deposition - no land use change	0.55	0.59	0.59	0.59	0.59
Grazing deposition - land use change e.g. winter keep		0.41		0.41	
Housed - slurry					
Housed - FYM	0.45		0.41		0.41

Grassland	UP3	WD1	WD5	WD5	WD6
	Management of moorland	Woodland creation – Maintenance Payments	Restoration of wood pasture and parkland	Restoration of wood pasture and parkland	Creation of wood pasture
Baseline	unimproved grassland - upland LFA sheep	unimproved grassland (zero grazing)	semi-improved grassland with wood pasture - lowland sheep	semi-improved grassland with wood pasture - lowland cattle	semi-improved grassland lowland - cattle
Machinery					
	Mow 10% area	Herbicide - spot treat			
Other					
	Burning 10% area	Tree saplings and protectors x 1100	Tree saplings and protectors x 50	Tree saplings and protectors x 50	Tree saplings and protectors x 200
Seed					
Pesticides & PGRs					
		Herbicide - glyphosate 2 l ha^{-1} year 1			
Supplementary nutrients					
Lime					
N (+S)					
N					
N					
N					
N					
N					
P2O5					
K2O					
MgO					
FYM					
Slurry					
Harvest					
Crop yield					
Livestock (as livestock units)					
Lowland sheep			0.36		
Lowland cattle				0.48	0.48
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA	0.1				
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					
Grass silage kg DM per head	89 kg		104 kg	651 kg	651 kg
Concentrate kg DM per head	30 kg		75 kg	250 kg	250 kg
Deposition (proportion year)					
Grazing deposition - no land use change	0.42		1	0.59	0.59
Grazing deposition - land use change e.g. winter keep	0.16				
Housed - slurry					
Housed - FYM	0.41			0.41	0.41

Grassland	WD6	WD7	WD7		
	Creation of wood pasture	Management of successional areas and scrub	Management of successional areas and scrub		
Baseline	semi-improved grassland lowland - sheep	unimproved grassland - lowland sheep	unimproved grassland - lowland cattle		
Machinery					
		Herbicide - weedwipe	Herbicide - weedwipe		
		Mow 20% area	Mow 20% area		
Other					
	Tree saplings and protectors x 200				
Seed					
Pesticides & PGRs					
		Herbicide - amidosulfuron	Herbicide - amidosulfuron		
Supplementary nutrients					
Lime					
N (+S)					
N					
N					
N					
N					
N					
P2O5					
K2O					
MgO					
FYM					
Slurry					
Harvest					
Crop yield					
Livestock (as livestock units)					
Lowland sheep	0.36	0.36			
Lowland cattle			0.48		
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA					
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					
Grass silage kg DM per head	104 kg	104 kg	651 kg		
Concentrate kg DM per head	75 kg	75 kg	250 kg		
Deposition (proportion year)					
Grazing deposition - no land use change	1.0	0.42	0.42		
Grazing deposition - land use change e.g. winter keep		0.58	0.16		
Housed - slurry					
Housed - FYM			0.41		

Organic grassland	OP4	OR2	OR2		
	Multi Species Ley	organic conversion – unimproved permanent grassland	organic conversion – unimproved permanent grassland		
Baseline	organic temporary grassland	unimproved grassland - lowland sheep	unimproved grassland - lowland cattle		
Machinery					
	Plough, standard drill, roll year 1				
	Mow				
Other					
Seed					
	36 kg multi-species ley organic mixture				
Pesticides & PGRs					
Supplementary nutrients					
Lime					
N (+S)					
N					
N					
N					
N					
N					
P2O5					
K2O					
MgO					
FYM					
Slurry					
Harvest					
Crop yield					
Livestock (as livestock units)					
Lowland sheep		0.36			
Lowland cattle			0.48		
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA					
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					
Grass silage kg DM per head		61 kg	593 kg		
Concentrate kg DM per head		30 kg	190 kg		
Deposition (proportion year)					
Grazing deposition - no land use change		1.0	0.59		
Grazing deposition - land use change e.g. winter keep					
Housed - slurry					
Housed - FYM			0.41		

A3.0. Habitat specific baselines

A3.1. Traditional orchard in production

Trees receive 50% of the typical 20 sprays of commercial production.

Table A3.1. Traditional orchards in production.

	Date	**Activity**	**Product / active ingredient**
Rotationally	4 years	lime	ground limestone 4 tha^{-1}
Annualy	March	P & K fertiliser	20 kg P_2O_5 + 80 kg K_2O
	March	N fertiliser	100 kg N
	mid Apr	insecticide	pirimicarb (50% w/w)
	early June	fungicide (powdery mildew)	penconazole (100 gl^{-1} 10.6%w/w)
	mid June	fungicide (scab, *Gloeosporium* rot)	captan (80%w/w)
	late June	insecticide	chlorpyrifos (75% w/w)
	late June	fungicide (powdery mildew)	penconazole (100 gl^{-1} 10.6%w/w)
	early July	fungicide (scab, *Gloeosporium* rot)	captan (80%w/w)
	mid July	fungicide (powdery mildew)	penconazole (100 gl^{-1} 10.6%w/w)
	mid July	insecticide	fenoxycarb (25% w/w)
	late July	fungicide (scab, *Gloeosporium* rot)	captan (80%w/w)
	early Aug	fungicide (powdery mildew)	penconazole (100 gl^{-1} 10.6%w/w)
	mid Aug	fungicide (scab, *Gloeosporium* rot)	captan (80%w/w)
	late Aug	fungicide (powdery mildew)	penconazole (100 gl^{-1} 10.6%w/w)
	early Sept	fungicide (scab, *Gloeosporium* rot)	captan (80%w/w)
		transport to on farm storage (2 km) 25 t ha^{-1} yield	

A3.2. Other habitats

Habitat specific baseline	Fen (degraded)	Fen (maintenance)	Scrub	Water meadow - sheep	Water meadow - cattle
Baseline					
Machinery					
	Brushwood cutter 10% area				
Other					
Seed					
Pesticides & PGRs					
	Herbicide stumps glyphosate 2 l ha^{-1} 10% area				
Supplementary nutrients					
Lime					
N(+S)					
N					
N					
N					
N					
N					
P2O5					
K2O					
MgO					
FYM					
Slurry					
Harvest					
Crop yield					
Livestock (as livestock units)					
Lowland sheep	0.5	0.05		0.05	
Lowland cattle					0.1
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA					
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					
Grass silage kg DM per head					651 kg
Concentrate kg DM per head					250 kg
Deposition (proportion year)					
Grazing deposition - no land use change	1.0	0.17		1.0	0.59
Grazing deposition - land use change e.g. winter keep		0.83			
Housed - slurry					
Housed - FYM					0.41

Habitat specific baseline	Lowland heathland - sheep	Lowland heathland - cattle	Salt marsh - sheep	Salt marsh - cattle	Sand dune - sheep
Baseline					
Machinery					
	Mow 10% area	Mow 10% area			
Other					
Seed					
Pesticides & PGRs					
Supplementary nutrients					
Lime					
N(+S)					
N					
N					
N					
N					
N					
P2O5					
K2O					
MgO					
FYM					
Slurry					
Harvest					
Crop yield					
Livestock (as livestock units)					
Lowland sheep	0.05		0.05		0.1 [or ungrazed]
Lowland cattle		0.1		0.1	
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA					
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					
Grass silage kg DM per head		651 kg		651 kg	104 kg
Concentrate kg DM per head		250 kg		250 kg	75 kg
Deposition (proportion year)					
Grazing deposition - no land use change	1.0	0.59	0.59	0.59	1.0
Grazing deposition - land use change e.g. winter keep			0.41		
Housed - slurry					
Housed - FYM		0.41		0.41	

Habitat specific baseline	Reed bed	Raised bog - drained	Raised bog (maintenance)	Woodland	
Baseline					
Machinery					
	Brushwood cutter 10% area		Brushwood cutter 10% area		
Other					
Seed					
Pesticides & PGRs					
			Herbicide stumps glyphosate 2 l ha^{-1} 10% area		
Supplementary nutrients					
Lime					
N(+S)					
N					
N					
N					
N					
N					
P2O5					
K2O					
MgO					
FYM					
Slurry					
Harvest					
Crop yield					
Livestock (as livestock units)					
Lowland sheep					
Lowland cattle					
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA					
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					
Grass silage kg DM per head					
Concentrate kg DM per head					
Deposition (proportion year)					
Grazing deposition - no land use change					
Grazing deposition - land use change e.g. winter keep					
Housed - slurry					
Housed - FYM					

A4.0. Habitat specific CS option management

Habitat specific	CT1	CT6	GS9	GS10	HS4
	Management of coastal sand dunes and vegetated shingle	Coastal vegetation management supplement	Management of wet grassland for breeding waders	Management of wet grassland for wintering waders and wildfowl	Scrub control on historic and archaeological features
Baseline	sand dune	sand dune	water meadow – cattle + sheep	water meadow - cattle + sheep	scrub
Machinery					
	Brushwood cutter 10% area	Brushwood cutter 10% area	Mow x 0.3	Mow x 0.3	Brushwood cutter 25% area years 1 to 3
Other					
Seed					
Pesticides & PGRs					
	Herbicide stumps glyphosate 2 l ha^{-1} 10% area	Herbicide stumps glyphosate 2 l ha^{-1} 10% area			Herbicide stumps glyphosate 2 l ha^{-1} 25% area years 1 to 3
Supplementary nutrients					
Lime					
N(+S)					
N					
N					
N					
N					
N					
P2O5					
K2O					
MgO					
FYM					
Slurry					
Harvest					
Crop yield					
Livestock (as livestock units)					
Lowland sheep	0.05	0.05			
Lowland cattle			0.1	0.1	
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA					
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					
Grass silage kg DM per head					
Concentrate kg DM per head					
Deposition (proportion year)					
Grazing deposition - no land use change	1.0	1.0	0.5	0.5	
Grazing deposition - land use change e.g. winter keep			0.09	0.09	
Housed - slurry					
Housed - FYM			0.41	0.41	

Habitat specific	HS6	HS7	LH1	WD2	WT6
	Maintenance of designed/ engineered water bodies	Management of historic water meadows through traditional irrigation	Management of lowland heathland	Woodland Improvement	Management of reedbed
Baseline	scrub	water meadow	lowland heathland	woodland	(degraded) reedbed
Machinery					
	Brushwood cutter 10% area		Mow 10% area	Brushwood cutter 10% area	Brushwood cutter 5% area
	Mow		Shallow tine 5% area	Pesticide application - spot treat 20% area	
Other					
				Tree saplings and protectors x 1100 year 3	
Seed					
Pesticides & PGRs					
	Herbicide stumps glyphosate 2 l ha^{-1} 10% area			Herbicide stumps glyphosate 2 l ha^{-1} 20% area	Herbicide stumps glyphosate 2 l ha^{-1} 5% area
Supplementary nutrients					
Lime					
N(+S)					
N					
N					
N					
N					
N					
P2O5					
K2O					
MgO					
FYM					
Slurry					
Harvest					
Crop yield					
Livestock (as livestock units)					
Lowland sheep		0.05	0.05		
Lowland cattle					
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA					
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					
Grass silage kg DM per head					
Concentrate kg DM per head					
Deposition (proportion year)					
Grazing deposition - no land use change		0.59	0.59		
Grazing deposition - land use change e.g. winter keep		0.41	0.41		
Housed - slurry					
Housed - FYM					

Habitat specific	WT8	WT10			
	Management of fen	Management of lowland raised bog			
Baseline	(degraded) fen	(degraded) lowland raised bog			
Machinery					
	Brushwood cutter 10% area	Brushwood cutter 10% area			
Other					
Seed					
Pesticides & PGRs					
	Herbicide stumps glyphosate 2 l ha^{-1} 10% area	Herbicide stumps glyphosate 2 l ha^{-1} 10% area			
Supplementary nutrients					
Lime					
N(+S)					
N					
N					
N					
N					
N					
P2O5					
K2O					
MgO					
FYM					
Slurry					
Harvest					
Crop yield					
Livestock (as livestock units)					
Lowland sheep					
Lowland cattle					
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA					
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					
Grass silage kg DM per head					
Concentrate kg DM per head					
Deposition (proportion year)					
Grazing deposition - no land use change					
Grazing deposition - land use change e.g. winter keep					
Housed - slurry					
Housed - FYM					

Orchards	AB8	AB8	AB12	AB16	BE4
	Flower-rich margins and plots - spring sown	Flower-rich margins and plots - autumn sown	Supplementary winter feeding for farmland birds	Autumn sown bumblebird mix	Management of traditional orchards
Baseline	bush orchards	bush orchards	bush orchards	bush orchards	traditional orchard
Machinery					
	Plough, power harrow, standard drill year 1	Plough, power harrow, standard drill year 1	ATV 2 km x 22	Plough, power harrow, standard drill year 1	Mow
				Top x 2	
	Top (cut) x3 year 1	Top (cut) x2 year 2			
Other					
				15 kg wildflower seed + 15 kg grass seed year 1	
Seed					
	20 kg wildflower mixture year 1	20 kg wildflower mixture year 1	500 kg supplementary bird feed mixture		
Pesticides & PGRs					
					Fungicide – scab, captan x 7
					Fungicide - powdery mildew, penconazole x 7
Supplementary nutrients					
Lime					
N (+S)					
N				50 kg N year 1	100 kg N
N					
N					
N					
N					
P_2O_5					20 kg P_2O_5
K_2O					80 kg K_2O
MgO					50 kg MgO
FYM					
Slurry					
Harvest					
Crop yield					25 t
Livestock (as livestock units)					
Lowland sheep					
Lowland cattle					
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA					
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					
Grass silage kg DM per head					
Concentrate kg DM per head					
Deposition (proportion year)					
Grazing deposition - no land use change					
Grazing deposition - land use change e.g. winter keep					
Housed - slurry					
Housed - FYM					

A5.0. Organic arable baselines and CS option management

A5.1. Organic winter wheat

Table 5.1. Organic winter wheat.

	Date	Activity	Product / active ingredient
Rotation	supplies 3 crops	2 year clover (undersown) - drill	
		2 year clover (undersown) - roll	
	supplies 4 crops	P_2O_5	rock phosphate (28.5%) 0.63 t ha^{-1}
		K_2O	Sylvinite (24%) 0.42 t ha^{-1}
		lime	ground limestone 4 t ha^{-1}
Annually	Aug	FYM	17 t ha^{-1}
	Aug	plough & Press (20 cm)	
	Sept -Oct	power harrow	
	Sept -Oct	shallow cultivation	
	Sept -Oct	shallow cultivation	
	Oct	drill (200 kg seed tha^{-1})	
	August	harvest (4 tha^{-1})	
		transport to on farm storage (2 km) (4 t ha^{-1})	
		drying (to 86% dry matter)	

A5.2. Organic spring barley

Table A5.2. Organic spring barley.

	Date	Activity	Product / active ingredient
Rotation	supplies 3 crops	2 year clover (undersown) - drill	
		2 year clover (undersown) - roll	
	supplies 4 crops	P_2O_5	rock phosphate (28.5%) 0.63 t ha^{-1}
		K_2O	sylvinite (24%) 0.42 t ha^{-1}
	supplies 4 crops	lime	ground limestone 4 t ha^{-1}
Annually	Feb	FYM	17 t ha^{-1}
	Feb	plough & press (20 cm)	
	Feb	power harrow	
	Feb	shallow cultivation	
	Feb	shallow cultivation	
	Feb	drill (200 kg seed t ha^{-1})	
	August	harvest (3.2 t ha^{-1})	
		transport to on farm storage (2 km) (3.2 t ha^{-1})	
		drying (to 86% dry matter)	

A5.3. Organic arable CS option management

Organic arable	OP1	OP3	OP4	OP5	
	Overwintered stubble	Supplementary feeding for farmland birds	Multi Species Ley	Undersown cereal	
Baseline	organic spring barley	organic winter wheat	organic winter wheat	organic winter wheat	
Machinery					
	Shallow disc cultivation 30%	ATV 2 km x 22 weeks	Plough, standard drill, roll year 1	Plough, standard drill year 1 and 4	
	Plough, standard drill		Mow	Shallow tine x 2 year 1 and 4	
	Shallow tine x 2			Mechanical weeding year 1 and 4	
	Mechanical weeding				
Other					
Seed					
	6 kg Overwinter cover crop (e.g. mustard or fodder radish) 30% area	500 kg Supplementary organic bird feed mixture	36 kg Multi-species ley organic mixture year 1	200 kg winter wheat year 1 and 4	
	200 kg Spring barley seed			36 kg multi-species ley organic mixture year 1 and 4	
Pesticides & PGRs					
Supplementary nutrients					
Lime				0.75 t ave per year	
N(+S)					
N					
N					
P2O5					
K2O					
MgO					
FYM					
Slurry					
Harvest					
Crop yield	3.2 t			4.0 t year 1	
Livestock (as livestock units)					
Lowland sheep					
Lowland cattle					
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA					
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					
Grass silage kg DM per head					
Concentrate kg DM per head					
Deposition (proportion year)					
Grazing deposition - no land use change					
Grazing deposition - land use change e.g. winter keep					
Housed - slurry					
Housed - FYM					

A6.0. Arable baselines and CS option management

Sandy clay loam soil of soil nitrogen supply (SNS) index 1 and a P and K index 2

A6.1. Winter wheat

Table A6.1. Winter wheat.

	Date	Activity	Product / active ingredient
Rotationally	every 4 years	lime	ground limestone 1 t ha^{-1} yr^{-1}
Annually	Aug	0.68 plough (20 cm)	
	Sept -Oct	0.68 power harrow	
	Sept -Oct	0.32 shallow cultivation	
		drill	180 kg seed ha^{-1}
	Sept -Oct	seed Treatment (150ml / 100 kg seed)	20 g L^{-1} fluopyram (1.8% w/w), 100 g L^{-1} (8.9% w/w) prothioconazole and 60 g L^{-1} (5.4% w/w) tebuconazole 2.9 L ha^{-1}
	Oct - Nov	herbicide - grassweed	3 L pendimethalin (2,6-dinitroaniline) (400 g L^{-1})
	Oct - Nov	insecticide - aphids (BYDV risk)	0.2 L cypermethrin (100 g L^{-1})
	Nov- Mar	P and K fertiliser base maintenance	0:21:32 @ 300kg 63 kg P_2O_5 + 96 kg K_2O
	March	N and S Fertiliser	25 kg N
	Mar	growth regulation	1.25 L Agriguard Chlormequat 700 (quaternary ammonium) (700 g L^{-1}) + 1.25 L Moddus (Trinexapac-ethyl) (250 g L^{-1})
	Mar - Apr	herbicide - broad-leaved weeds	0.03 kg amidosulfuron (75%w/w)
	Apr	N fertiliser	100 kg N
	Apr	herbicide - wild oats	0.1 L clodinafop propargyl ((240 g L^{-1}) + 1 L mineral oil
	April	fungicide - Septoria	0.5 L epoxiconazole (125 g L^{-1}) + 0.6 L azoxystrobin (250 g L^{-1})
		fungicide - mildew	0.1 L quinoxyfen (500 g L^{-1})
	May	N Fertiliser	67 kg N
	May	fungicide - Septoria + rusts	0.5 L epoxiconazole (125 g L^{-1}) + 1.2 L trifloxystrobin (125 g L^{-1})
	June	fungicides	0.3 L azoxystrobin (250 g L^{-1}) + 0.5 L tebuconazole (250 g L^{-1})
	August	harvest 8.5 t ha^{-1}	
		transport to on farm storage (2 km)	
		drying (to 86% dry matter)	

A6.2. Spring Barley

Table A6.2. Spring barley.

	Date	Activity	Product / active ingredient
Rotationally	every 4 years	lime	ground limestone 4 tha^{-1}
Annually	Feb	0.68 plough (20 cm)	
	Feb	0.68 power harrow	

	Feb	0.32 shallow cultivation	
	Feb	drill	160 kg seed ha^{-1}
	March	seed treatment (150 ml / 100 kg seed)	20 g L^{-1} fluopyram (1.8% w/w) + 100 g L^{-1} (8.9% w/w) prothioconazole + 60 g L^{-1} (5.4% w/w) tebuconazole 2.9 L ha^{-1}
	March	P and K base fertiliser maintenance	0:23:30 150 kg ha^{-1}. 34.5 kg P_2O_5 + 45 kg K_2O
	March	N and S fertiliser	25 kg N
	Apr	herbicide + adjuvent	1 L (tralkoxydim) (250 g L^{-1}) + 0.4 L adjuvant (60% mineral oil, 40% surfactant)
	Apr	herbicide - broad-leaved weeds	0.03 kg amidosulfuron (sulfonylurea) (75%w/w)
	April	N fertiliser	81 kg N
	August	fungicide - Septoria	0.5 l epoxiconazole (125 g L^{-1}) + 1.2 L trifloxystrobin (125 g L^{-1})
	August	fungicides	0.3 l azoxystrobin (250 g L^{-1})
		fungicide - Septoria + rusts	0.5 l epoxiconazole (125 g L^{-1})
		harvest 5.7 t ha^{-1}	
		transport to on farm storage (2 km)	
		drying (to 86% dry matter)	

A6.3. Winter oilseed rape

Table A6.3. Winter oilseed rape.

	Date	**Activity**	**Product / active ingredient**
Rotationally	every 4 years	lime	ground limestone 4 t ha^{-1}
Annually	Aug	0.68 plough (20 cm)	
	Aug	0.32 shallow cultivation	
		drill	6 kg seed ha^{-1}
	Aug	seed treatment - flea beetle control	beta-cyfluthrin (100 g ha^{-1})
		roll	
	Sept	herbicide - weed control (post-drill, pre-emerge)	Prosulfocarb + S-metolachlor (500 g L^{-1}) 1.5 L
		slug control	methiocarb (3% w/w) 5.5 kg
		herbicide - weed control (post emerge grass / cereals)	fluazifop-P-butyl (125 g L^{-1}) 0.5 L
		insecticide (flea beetle)	cypermethrin (100 g L^{-1}) 0.4 L (tank mix)
	Oct	N fertiliser	30 kg N
		P & K fertiliser	30 kg P_2O_5 (65.9 kg TSP) + 30 kg K_2O (50 kg MOP)
	Nov	Fungicide - stem canker	200 g L^{-1} boscalid + 200 g L^{-1} dimoxystrobin 0.5 L ha^{-1}
	Feb	Fungicide - stem canker / light leaf spot	tebuconazole (250 g L^{-1}) 1 L
		N & S fertiliser	25 kg N
	March	N fertiliser	90 kgN
	April	N fertiliser	85 kgN
	May	fungicide Sclerotinia	iprodione (167 g L^{-1}) + thiophanate-methyl (167 g L^{-1}) 3 L
		insecticide - seed weevil / pod midge	deltamethrin (25 g L^{-1}) 0.2 L (tank mix)

		dessicate	glyphosate (360 g L^{-1}) 3 L
		harvest 3 t ha^{-1}	
		transport to on farm storage (2 km)	
		drying (to 86% dry matter)	

A6.4. Fodder brassica

Table A6.4. Fodder brassica (turnip rape)

	Date	Activity	Product / active ingredient
Rotationally	every 4 years	lime	ground limestone 4 t ha^{-1}
	Aug	0.68 plough (20 cm)	
Annually	Aug	0.32 shallow cultivation	
		drill	6 kg seed ha^{-1}
	Aug	seed treatment - flea beetle control	beta-cyfluthrin (100 g ha^{-1})
		roll	
	Sept	herbicide - weed control (post-drill, pre-emerge)	metazachlor (500 g L^{-1}) 1.5 L
		slug control	methiocarb (3% w/w) 5.5 kg
		herbicide - weed control (post emergence grass / cereals)	fluazifop-P-butyl (125 g L^{-1}) 0.5 L
		insecticide - flea beetle	cypermethrin (100 g L^{-1}) 0.4 L (tank mix)
	Oct	N fertiliser	30 kg N
		P & K fertiliser	50 kg P_2O_5 + 40 kg K_2O
		drying (to 86% dry matter)	

A6.5. Arable CS option management

Arable	AB8	AB8	AB11	AB12	AB13
	Flower-rich margins and plots - spring sown	Flower-rich margins and plots - autumn sown	Cultivated areas for arable plants	Supplementary winter feeding for farmland birds	Brassica fodder crop
Baseline	spring barley	winter wheat	winter wheat	winter wheat	winter wheat
Machinery					
	Plough, power harrow, standard drill year 1	Plough, power harrow, standard drill year 1	Plough, power harrow, shallow tine	ATV 2 km x 22	Plough, power harrow, standard drill
					Fertiliser (inorganic) application x 4.2
	Top (cut) x3 year 1	Top (cut) x2 year 2	Top		
			Herbicide - weedwipe		
Other					
Seed					
	20 kg wildflower mixture year 1	20 kg wildflower mixture year 1		500 kg supplementary bird feed mixture	6 kg oilseed rape
Pesticides & PGRs					
			Herbicide - amidosulfuron		
Supplementary nutrients					
Lime					1.0 t ave per year
N(+S)					30 kg N
N					
N					
N					
P2O5					50 kg P_2O_5
K2O					40 kg K_2O
MgO					
FYM					
Slurry					
Harvest					
Crop yield / transport off field	5 t	5 t			
Livestock (as livestock units)					
Lowland sheep					
Lowland cattle					
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA					
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					+10%
Grass silage kg DM per head					
Concentrate kg DM per head					
Deposition (proportion year)					
Grazing deposition - no land use change					
Grazing deposition - land use change e.g. winter keep					
Housed - slurry					
Housed - FYM					

Arable	AB14	AB15	AB16	GS1	GS4
	Harvested low input cereal	Two year sown legume fallow	Autumn sown bumblebird mix	Take field corners out of management	Legume and herb-rich swards
Baseline	winter wheat	winter wheat	winter wheat	winter wheat	winter wheat
Machinery					
	Plough, power harrow, standard drill	Plough, power harrow, standard drill year 1	Plough, power harrow, standard drill year 1	Mow 1 year in 5	Shallow disc cultivation, shallow tine, standard drill 3 years in 5
	Fertiliser (inorganic) application x 2.2	Top x 2 year 1, x 1 year 2	Top x 2 year 1, x 1 year 2		Herbicide – spot spray
	Pesticide spray x 4	Pesticide spray - non-selective herbicide year 2			
Other					
	75 kg winter wheat	30 kg wildflower seed	15 kg wildflower seed + 15 kg grass seed		
Seed					
					36 kg grass / clover mixture 3 years in 5
Pesticides & PGRs					
	Seed treatment	Non-selective herbicide year 2			Herbicide - amidosulfuron
	Fungicide x 4				
Supplementary nutrients					
Lime	1 t ave per year				0.75 t ave per year
N (+S)	25 kg N				
N			50 kg N year 1		
N					
N					
P_2O_5	60 kg P_2O_5				15 kg P_2O_5
K_2O	45 kg K_2O				15 kg K_2O
MgO					
FYM					
Slurry					
Harvest					
Crop yield	4.25 t				
Livestock (as livestock units)					
Lowland sheep					0.36
Lowland cattle					
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA					
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					
Grass silage kg DM per head					104 kg
Concentrate kg DM per head					75 kg
Deposition (proportion year)					
Grazing deposition - no land use change					1.0
Grazing deposition - land use change e.g. winter keep					
Housed - slurry					
Housed - FYM					

Arable	GS4	HS3	HS9	SW1	SW1
	Legume and herb-rich swards	Reduced-depth, non-inversion cultivation on historic and archaeological features	Restricted depth crop establishment to protect archaeology under an arable rotation	4-6m buffer strip on cultivated land	4-6m buffer strip on cultivated land
Baseline	winter wheat	winter wheat	winter wheat	winter wheat	existing buffer strip
Machinery					
	Shallow disc cultivation, shallow tine, standard drill 3 years in 5	Shallow disc cultivation, standard drill	Shallow disc cultivation, standard drill 1 year in 5	Plough, standard drill, roll year 1	
	Herbicide – spot spray	Fertiliser (inorganic) application x 4.2			
		Pesticide spray x 9		Mow x 2.5 years 1 and 2; x 0.5 after	Mow x 0.5
				Herbicide - weedwipe	
Other					
Seed					
	36 kg grass / clover mixture 3 years in 5	180 kg winter wheat	36 kg grass / clover mixture 1 year in 5	25 kg grass year 1	
Pesticides & PGRs					
	Herbicide - amidosulfuron	Seed treatment		Herbicide - amidosulfuron	
		Herbicide – diclofop-methyl + fenoxaprop-P-ethyl x 2			
		Herbicide - amidosulfuron			
		Herbicide - clodinafop propargyl			
		Fungicide x 4			
		PGR			
Supplementary nutrients					
Lime	0.75 t ave per year	1 t ave per year			
N(+S)		25 kg N			
N		105 kg N			
N		90 kg N			
P2O5	15 kg P_2O_5	60 kg P_2O_5			
K2O	15 kg K_2O	45 kg K_2O			
MgO					
FYM					
Slurry					
Harvest					
Crop yield		-10%			
Livestock (as livestock units)					
Lowland sheep					
Lowland cattle	0.48				
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA					
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grass silage kg DM per head	651 kg				
Concentrate kg DM per head	250 kg				
Deposition (proportion year)					
Grazing deposition - no land use change	0.59				
Grazing deposition - land use change e.g. winter keep					
Housed - slurry					
Housed - FYM	0.41				

Arable	SW7	SW12	WD6	WD6	
	Arable reversion to grassland with low fertiliser input	Making space for water	Creation of wood pasture	Creation of wood pasture	
Baseline	winter wheat	winter wheat	winter wheat	winter wheat	
Machinery					
	Plough, standard drill, roll year 1	Fertiliser (inorganic) application x 2.2			
	Herbicide - weedwipe	Herbicide – spot spray			
	Mow x 1 from year 2 onwards	Mow			
		Bale			
Other					
			Tree saplings and protectors x 200	Tree saplings and protectors x 200	
Seed					
	25 kg grass year 1				
Pesticides & PGRs					
	Herbicide - amidosulfuron	Herbicide - amidosulfuron			
Supplementary nutrients					
Lime	0.75 t ave per year	0.75 t ave per year			
N (+S)					
N	30 kg N	30 kg N			
N					
N					
P2O5	15 kg P_2O_5	15 kg P_2O_5			
K2O	15 kg K_2O	15 kg K_2O			
MgO					
FYM					
Slurry					
Harvest					
Crop yield					
Livestock (as livestock units					
Lowland sheep	1.2			0.36	
Lowland cattle			0.48		
Upland sheep					
Upland cattle					
Upland sheep / hill flock LFA					
Upland cattle LFA					
Supplementary Diet (in addition to grassland grazing)					
Grazing - brassica forage crop					
Grass silage kg DM per head	104 kg		651 kg	104 kg	
Concentrate kg DM per head	75 kg		250 kg	75 kg	
Deposition (proportion year)					
Grazing deposition - no land use change	0.59		0.59	0.42	
Grazing deposition - land use change e.g. winter keep	0.41			0.58	
Housed - slurry					
Housed - FYM			0.41		

Appendix 2. Emissions breakdown by CS option

Table A2.1. Breakdown of greenhouse gas emissions (t CO_2e ha^{-1} yr^{-1}) for options where there is no change in land use.

	AB11	AB12	AB13	AB13	AB14	AB14	AB15	AB15	BE4	BE6
	Cultivated areas for arable plants	Supplementary winter feeding for farmland birds	Brassica fodder crop	Brassica fodder crop	Harvested low input cereal	Harvested low input cereal	Two year sown legume fallow	Two year sown legume fallow	Management of traditional orchards	Veteran tree surgery
Baseline	WW	WW	WOSR	TGS	WW	TGS	WW	TGS	TO	VT
Machinery - application	0.201	0.065	0.137	0.137	0.206	0.206	0.111	0.111	0.015	0.000
Machinery - depreciation	0.105	0.031	0.089	0.089	0.152	0.152	0.055	0.055	0.003	0.000
Other	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Seed	0.000	0.115	0.001	0.001	0.017	0.017	0.004	0.004	0.000	0.000
Pesticides & PGRs	0.001	0.000	0.000	0.000	0.058	0.058	0.009	0.009	0.434	0.000
Supplementary nutrients	0.000	0.000	0.107	0.107	0.110	0.110	0.000	0.000	0.729	0.000
Harvest - application	0.000	0.000	0.000	0.000	0.029	0.029	0.000	0.000	0.045	0.000
Harvest - depreciation	0.000	0.000	0.000	0.000	0.248	0.248	0.000	0.000	0.060	0.000
Livestock - N_2O deposition	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Livestock - CH_4 deposition	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Livestock - CH_4 enteric	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Livestock - Supplementary diet	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Soils - N_2O	0.140	0.000	0.149	0.151	0.562	0.564	0.534	0.534	0.023	0.000
Soils - CO_2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Soils - CH_4	-0.016	0.000	-0.016	-0.016	-0.016	-0.016	-0.018	-0.018	-0.029	-0.018
Burning	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Carbon sequestration - soil	0.000	0.000	0.000	0.234	0.000	0.234	-0.117	0.000	0.000	0.000
Carbon sequestration - biomass	0.865	0.000	0.000	0.543	0.000	0.543	-0.271	0.271	0.000	0.000
Total emissions	0.430	0.211	0.467	0.469	1.365	1.367	0.695	0.695	1.280	-0.018
Total C sequestration	0.865	0.000	0.000	0.777	0.000	0.777	-0.388	0.271	0.000	0.000
	1.296	**0.211**	**0.467**	**1.246**	**1.365**	**2.144**	**0.307**	**0.967**	**1.280**	**-0.018**

Table A2.2. Breakdown of greenhouse gas emissions (t CO_2e ha^{-1} yr^{-1}) for options where there is no change in land use.

	GS2	**GS2**	**GS3**	**GS4**	**GS4**	**GS5**	**GS5**	**GS16**	**GS16**	**GS17**
	Permanent grassland with very low inputs (outside SDAs)	**Permanent grassland with very low inputs (outside SDAs)**	**Ryegrass seed-set as winter food for birds**	**Legume and herb-rich swards**	**Legume and herb-rich swards**	**Permanent grassland with very low inputs in SDAs**	**Permanent grassland with very low inputs in SDAs**	**Rush infestation control supplement**	**Rush infestation control supplement**	**Lenient grazing supplement**
Baseline	SIGLS	SIGLC	TGS	WW	TGS	SIGULFAS	SIGULFAC	SIGLS	UIGLS	GS2
Machinery - application	0.035	0.035	0.076	0.058	0.086	0.023	0.023	0.036	0.002	0.000
Machinery - depreciation	0.027	0.027	0.049	0.048	0.057	0.019	0.019	0.027	0.000	0.000
Other	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Seed	0.000	0.000	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000
Pesticides & PGRs	0.001	0.001	0.001	0.000	0.000	0.001	0.001	0.001	0.000	0.000
Supplementary nutrients	0.076	0.076	0.489	0.019	0.019	0.076	0.076	0.208	0.000	0.000
Harvest - application	0.000	0.000	0.070	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Harvest - depreciation	0.000	0.000	0.093	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Livestock - N_2O deposition	0.011	0.197	0.000	0.003	0.003	0.002	0.134	0.011	0.003	0.217
Livestock - CH_4 deposition	0.000	0.017	0.000	0.000	0.000	0.000	0.012	0.000	0.000	0.017

Livestock - CH_4 enteric	0.022	0.582	0.000	0.007	0.007	0.005	0.411	0.022	0.007	0.582
Livestock - Supplementary diet	0.013	0.317	0.000	0.004	0.004	0.002	0.196	0.013	0.004	0.317
Soils - N_2O	0.091	0.091	0.504	0.029	0.029	0.091	0.091	0.302	0.000	0.000
Soils - CO_2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Soils - CH_4	-0.016	-0.016	-0.016	-0.018	-0.018	-0.016	-0.016	-0.016	-0.018	-0.018
Burning	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Carbon sequestration - soil	0.000	0.000	0.000	-1.047	0.000	0.000	0.000	0.000	0.000	0.000
Carbon sequestration - biomass	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total emissions	0.260	1.327	1.267	0.151	0.188	0.202	0.946	0.603	-0.003	1.114
Total C sequestration	0.000	0.000	0.000	-1.047	0.000	0.000	0.000	0.000	0.000	0.000
	0.260	**1.327**	**1.267**	**-0.896**	**0.188**	**0.202**	**0.946**	**0.603**	**-0.003**	**1.114**

Table A2.3. Breakdown of greenhouse gas emissions (t CO_2e ha^{-1} yr^{-1}) for options where there is no change in land use.

	HS3	**HS4**	**HS6**	**HS9**	**HS9**	**SW10**	**SW10**	**SW13**
	Reduced-depth, non-inversion cultivation on historic and archaeological features	**Scrub control on historic and archaeological features**	**Maintenance of designed/ engineered water bodies**	**Restricted depth crop establishment to protect archaeology under an arable rotation**	**Restricted depth crop establishment to protect archaeology under an arable rotation**	**Seasonal livestock removal on grassland in SDAs next to streams, rivers and lakes.**	**Seasonal livestock removal on grassland in SDAs next to streams, rivers and lakes.**	**Very low nitrogen inputs to groundwaters**
Baseline	WW	SCB	SCB	WW	TGS	SIGULFAS (WS)	SIGULFAC (WS)	TGS
Machinery - application	0.135	0.001	0.015	0.122	0.130	0.034	0.034	0.042
Machinery - depreciation	0.137	0.001	0.003	0.116	0.744	0.026	0.026	0.031
Other	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Seed	0.041	0.000	0.000	0.033	0.001	0.000	0.000	0.000

Pesticides & PGRs	0.091	0.006	0.000	0.062	0.004	0.001	0.001	0.001
Supplementary nutrients	1.160	0.000	0.000	0.928	0.605	0.208	0.208	0.208
Harvest - application	0.052	0.000	0.000	0.045	0.033	0.000	0.000	0.000
Harvest - depreciation	0.446	0.000	0.000	0.387	0.044	0.000	0.000	0.000
Livestock - N_2O deposition	0.000	0.000	0.000	0.000	0.000	0.003	0.165	0.010
Livestock - CH_4 deposition	0.000	0.000	0.000	0.000	0.000	0.000	0.013	0.000
Livestock - CH_4 enteric	0.000	0.000	0.000	0.000	0.000	0.005	0.411	0.018
Livestock - Supplementary diet	0.000	0.000	0.000	0.000	0.000	0.002	0.196	0.011
Soils - N_2O	1.715	0.000	0.000	1.372	1.112	0.302	0.302	0.302
Soils - CO_2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Soils - CH_4	-0.016	-0.018	0.000	-0.017	-0.017	-0.016	-0.016	-0.016
Burning	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Carbon sequestration - soil	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.930
Carbon sequestration - biomass	0.000	-0.046	-0.046	0.000	0.000	0.000	0.000	0.000
Total emissions	3.761	-0.010	0.018	3.049	2.656	0.564	1.340	0.606
Total C sequestration	0.000	-0.046	-0.046	0.000	0.000	0.000	0.000	-0.930
	3.761	**-0.057**	**-0.028**	**3.049**	**2.656**	**0.564**	**1.340**	**-0.324**

Table A2.4. Breakdown of greenhouse gas emissions (t CO_2e ha^{-1} yr^{-1}) for options where there is a change in land use on a proportion of the area.

	AB8	**AB8**	**AB8**	**AB8**	**AB8**	**AB8**	**AB16**	**AB16**	**AB16**	**GS1**
	Flower-rich margins and plots -	**Flower-rich margins and plots -**	**Flower-rich margins and plots -**	**Flower-rich margins and plots -**	**Flower-rich margins and plots -**	**Flower-rich margins and plots -**	**Autumn sown bumblebird mix**	**Autumn sown bumblebird mix**	**Autumn sown bumblebird mix**	**Take field corners out of management**
Baseline	SB	TGS	BO	WW	TGS	BO	WW	TGS	BO	WW
Machinery - application	0.130	0.130	0.130	0.143	0.143	0.143	0.136	0.136	0.136	0.003
Machinery - depreciation	0.052	0.052	0.052	0.062	0.062	0.062	0.063	0.063	0.063	0.001
Other	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Seed	0.001	0.001	0.001	0.003	0.003	0.003	0.004	0.004	0.004	0.000
Pesticides & PGRs	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Supplementary nutrients	0.000	0.000	0.000	0.000	0.000	0.000	0.189	0.189	0.189	0.000
Harvest - application	0.006	0.006	0.006	0.006	0.006	0.006	0.000	0.000	0.000	0.000
Harvest - depreciation	0.009	0.009	0.009	0.009	0.009	0.009	0.000	0.000	0.000	0.000
Livestock - N_2O deposition	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Livestock - CH_4 deposition	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Livestock - CH_4 enteric	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Livestock - Supplementary diet	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Soils - N_2O	0.140	0.140	0.004	0.140	0.140	0.004	0.001	0.001	0.004	0.000
Soils - CO_2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Soils - CH_4	-0.016	-0.016	-0.016	-0.016	-0.016	-0.016	-0.016	-0.016	-0.016	-0.018
Burning	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Carbon sequestration - soil	-0.117	0.000	0.449	-0.117	0.000	0.449	-0.117	0.000	0.449	-1.047

Carbon sequestration - biomass	-0.271	-0.005	0.271	-0.271	0.271	0.638	-0.271	-0.005	0.271	-0.543
Total emissions	0.323	0.323	0.186	0.348	0.348	0.211	0.376	0.376	0.380	-0.015
Total C sequestration	-0.388	-0.005	0.721	-0.388	0.271	1.087	-0.388	-0.005	0.721	-1.590
	-0.066	**0.318**	**0.907**	**-0.041**	**0.619**	**1.298**	**-0.012**	**0.371**	**1.100**	**-1.604**

Table A2.5. Breakdown of greenhouse gas emissions (t CO_2e ha^{-1} yr^{-1}) for options where there is a change in land use on a proportion of the area.

	SW1	**SW1**	**SW2**	**SW2**	**SW11**	**SW12**	**SW12**	**SW12**	**SW12**
	4-6m buffer strip on cultivated land	**4-6m buffer strip on cultivated land**	**4-6m buffer strip on intensive grassland**	**4-6m buffer strip on intensive grassland**	**Riparian management strip**	**Making space for water**	**Making space for water**	**Making space for water**	**Making space for water**
Baseline	WW	BS	TGS	BS	SIGLS(RO)	WW	TGS	SIGLS(WS)	SIGLC(WS)
Machinery - application	0.048	0.012	0.049	0.012	0.005	0.042	0.042	0.042	0.042
Machinery - depreciation	0.027	0.010	0.027	0.010	0.008	0.031	0.031	0.031	0.031
Other	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000
Seed	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
Pesticides & PGRs	0.001	0.001	0.000	0.000	0.001	0.001	0.001	0.001	0.001
Supplementary nutrients	0.000	0.000	0.000	0.000	0.000	0.208	0.208	0.208	0.208
Harvest - application	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Harvest - depreciation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Livestock - N_2O deposition	0.000	0.000	0.000	0.000	0.000	0.000	0.011	0.019	0.235
Livestock - CH_4 deposition	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.017
Livestock - CH_4 enteric	0.000	0.000	0.000	0.000	0.000	0.000	0.022	0.022	0.582

Livestock - Supplementary diet	0.000	0.000	0.000	0.000	0.000	0.000	0.013	0.013	0.317
Soils - N_2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.302	0.302
Soils - CO_2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Soils - CH_4	-0.016	-0.016	-0.016	-0.016	-0.018	-0.018	-0.018	-0.016	-0.016
Burning	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Carbon sequestration - soil	-1.047	-1.047	-0.930	-0.930	0.000	-1.047	-0.930	0.000	0.000
Carbon sequestration - biomass	-0.543	-0.543	0.000	0.000	0.000	-0.543	0.000	0.000	0.000
Total emissions	0.061	0.006	0.061	0.006	-0.002	0.263	0.309	0.621	1.718
Total C sequestration	-1.590	-1.590	-0.930	-0.930	0.000	-1.590	-0.930	0.000	0.000
	-1.528	**-1.583**	**-0.869**	**-0.924**	**-0.002**	**-1.327**	**-0.620**	**0.621**	**1.718**

Table A2.6. Breakdown of greenhouse gas emissions (t CO_2e ha^{-1} yr^{-1}) for options on semi-natural habitat.

	CT1	**CT1**	**CT6**	**CT6**	**GS9**	**GS10**	**GS13**	**GS13**	**HS7**	**LH1**
	Management of coastal sand dunes and vegetated shingle	**Management of coastal sand dunes and vegetated shingle**	**Coastal vegetation management supplement**	**Coastal vegetation management supplement**	**Management of wet grassland for breeding waders**	**Management of wet grassland for wintering waders and wildfowl**	**Management of grassland for target features**	**Management of grassland for target features**	**Management of historic water meadows through traditional irrigation**	**Management of lowland heathland**
Baseline	SD	VS	SD	VS	WM	WM	SIGLS	SIGLC	WM	LH
Machinery - application	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.002
Machinery - depreciation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
Other	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Seed	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pesticides & PGRs	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Supplementary nutrients	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Harvest - application	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Harvest - depreciation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Livestock - N_2O deposition	0.000	0.000	0.000	0.000	0.025	0.025	0.011	0.197	0.001	0.000
Livestock - CH_4 deposition	0.000	0.000	0.000	0.000	0.002	0.002	0.000	0.017	0.000	0.000
Livestock - CH_4 enteric	0.001	0.001	0.001	0.001	0.063	0.063	0.022	0.582	0.001	0.001
Livestock - Supplementary diet	0.001	0.001	0.001	0.001	0.034	0.034	0.013	0.317	0.001	0.001
Soils - N_2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Soils - CO_2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Soils - CH_4	-0.018	-0.018	-0.018	-0.018	0.318	0.318	-0.018	-0.018	0.318	-0.018
Burning	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.072
Carbon sequestration - soil	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Carbon sequestration - biomass	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total emissions	-0.015	-0.015	-0.015	-0.015	0.441	0.441	0.028	1.095	0.320	0.059
Total C sequestration	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	-0.015	**-0.015**	**-0.015**	**-0.015**	**0.441**	**0.441**	**0.028**	**1.095**	**0.320**	**0.059**

Table A2.7. Breakdown of greenhouse gas emissions (t CO_2e ha^{-1} yr^{-1}) for options on semi-natural habitat.

	SW7	UP1	UP1	UP2	UP2	UP3	UP3	UP3	UP3
	Arable reversion to grassland with low fertiliser input	Enclosed rough grazing	Enclosed rough grazing	Management of rough grazing for birds	Management of rough grazing for birds	Management of moorland	Management of moorland	Management of moorland	Management of moorland
Baseline	WW(Er)	UIGULFAS	UIGULFAC	UIGULFAS	UIGULFAC	UIGULFAS(WS)	UIGULFAC(WS)	UIGULFAS	UIGULFAC
Machinery - application	0.041	0.001	0.001	0.003	0.003	0.002	0.002	0.002	0.002
Machinery - depreciation	0.026	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000
Other	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Seed	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pesticides & PGRs	0.001	0.002	0.002	0.000	0.000	0.000	0.000	0.000	0.000
Supplementary nutrients	0.208	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Harvest - application	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Harvest - depreciation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Livestock - N_2O deposition	0.000	0.001	0.064	0.001	0.064	0.001	0.076	0.001	0.064
Livestock - CH_4 deposition	0.000	0.000	0.006	0.000	0.006	0.000	0.006	0.000	0.006
Livestock - CH_4 enteric	0.000	0.001	0.196	0.001	0.196	0.001	0.196	0.001	0.196
Livestock - Supplementary diet	0.000	0.001	0.093	0.001	0.093	0.001	0.093	0.001	0.093
Soils - N_2O	0.302	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Soils - CO_2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Soils - CH_4	-0.016	-0.018	-0.018	-0.018	-0.018	-0.018	-0.018	-0.018	-0.018
Burning	0.000	0.014	0.000	0.000	0.000	0.014	0.000	0.014	0.000
Carbon sequestration - soil	-1.047	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Carbon sequestration - biomass	-0.543	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total emissions	0.562	0.002	0.343	-0.012	0.344	0.001	0.354	0.001	0.342
Total C sequestration	-1.590	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	-1.027	**0.002**	**0.343**	**-0.012**	**0.344**	**0.001**	**0.354**	**0.001**	**0.342**

Table A2.8. Breakdown of greenhouse gas emissions (t CO_2e ha^{-1} yr^{-1}) for options on semi-natural habitat.

	WD1	**WD2**	**WD2**	**WD2**	**WD5**	**WD5**	**WD6**	**WD6**	**WD6**
	Woodland creation – Maintenance Payments	**Woodland Improvement year 5**	**Woodland Improvement year 25**	**Woodland Improvement year 50**	**Restoration of wood pasture and parkland**	**Restoration of wood pasture and parkland**	**Creation of wood pasture**	**Creation of wood pasture**	**Creation of wood pasture**
Baseline	UIG(ZG)	WD	WD	WD	SIGLC	SIGLS	WW	SIGLC	SIGLS
Machinery - application	0.000	0.031	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Machinery - depreciation	0.000	0.014	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other	0.000	0.011	0.000	0.000	0.000	0.000	0.002	0.002	0.002
Seed	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pesticides & PGRs	0.024	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Supplementary nutrients	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Harvest - application	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Harvest - depreciation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Livestock - N_2O deposition	0.000	0.000	0.000	0.000	0.102	0.003	0.102	0.102	0.003
Livestock - CH_4 deposition	0.000	0.000	0.000	0.000	0.009	0.000	0.009	0.009	0.000
Livestock - CH_4 enteric	0.000	0.000	0.000	0.000	0.300	0.007	0.300	0.300	0.007
Livestock - Supplementary diet	0.000	0.000	0.000	0.000	0.164	0.004	0.164	0.164	0.004

Soils - N_2O	0.047	0.047	0.047	0.047	0.023	0.023	0.023	0.023	0.023
Soils - CO_2	0.000	0.759	1.771	0.000	0.000	0.000	0.000	0.000	0.000
Soils - CH_4	-0.041	-0.041	-0.041	-0.041	-0.032	-0.032	-0.032	-0.032	-0.032
Burning	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Carbon sequestration - soil	-0.752	0.000	0.000	0.000	-0.075	-0.075	-1.122	-0.075	-0.075
Carbon sequestration - biomass	-0.927	-0.093	-3.098	-0.970	-0.042	-0.042	-0.531	-0.042	-0.042
Total emissions	0.030	0.826	1.777	0.006	0.566	0.005	0.568	0.568	0.007
Total C sequestration	-1.678	-0.093	-3.098	-0.970	-0.117	-0.117	-1.653	-0.117	-0.117
	-1.648	**0.733**	**-1.321**	**-0.964**	**0.449**	**-0.112**	**-0.587**	**0.451**	**-0.110**

Table A2.9. Breakdown of greenhouse gas emissions (t CO_2e ha^{-1} yr^{-1}) for options on semi-natural habitat.

	WD7	**WD7**	**WT6**	**WT6**	**WT8**	**WT8**	**WT10**	**WT10**
	Management of successional areas and scrub	**Management of successional areas and scrub**	**Management of reedbed**	**Management of reedbed**	**Management of fen**	**Management of fen**	**Management of lowland raised bog**	**Management of lowland raised bog**
Baseline	SIGLS	SIGLC	RB	RB(Dg)	F	F(Dg)	RBO	RBO(Dg)
Machinery - application	0.006	0.006	0.000	0.000	0.001	0.001	0.001	0.000
Machinery - depreciation	0.009	0.009	0.000	0.000	0.000	0.000	0.000	0.000
Other	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Seed	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pesticides & PGRs	0.001	0.001	0.000	0.000	0.002	0.002	0.002	0.000
Supplementary nutrients	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Harvest - application	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Harvest - depreciation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Livestock - N_2O deposition	0.003	0.102	0.000	0.000	0.000	0.000	0.000	0.000
Livestock - CH_4 deposition	0.000	0.009	0.000	0.000	0.000	0.000	0.000	0.000
Livestock - CH_4 enteric	0.007	0.300	0.000	0.000	0.000	0.000	0.000	0.000
Livestock - Supplementary diet	0.004	0.164	0.000	0.000	0.000	0.000	0.000	0.000
Soils - N_2O	0.023	0.023	0.000	0.000	0.000	0.000	0.000	0.060
Soils - CO_2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	7.084
Soils - CH_4	-0.029	-0.029	2.813	3.394	4.750	4.750	0.534	2.644
Burning	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Carbon sequestration - soil	0.000	0.000	0.000	0.000	-0.730	-0.730	-0.730	-0.730
Carbon sequestration - biomass	-0.046	-0.046	0.000	0.638	0.000	0.005	0.000	0.005
Total emissions	0.023	0.584	2.813	3.394	4.753	4.753	0.538	9.788
Total C sequestration	-0.046	-0.046	0.000	0.638	-0.730	-0.725	-0.730	-0.725
	-0.023	**0.537**	**2.813**	**4.032**	**4.023**	**4.028**	**-0.192**	**9.063**

Appendix 3. Database update options

A3.1. Option 1. Manual update of Excel workbook

As described in Table 6.2, the uptake data are embedded in the Excel workbook (on 'CS Data (averaged)' worksheet) and these are linked to the 'CS Data (scaled)' and 'Compare (uptake)' worksheets. Thus if the uptake data are updated in the 'CS Data (averaged)' worksheet the other sheets are automatically updated. However, the amount of data is substantial, i.e. there are 169 regions (incl. England as a whole) which when multiplied by 106 CS options results in 17914 data items. It may be practical to update one region manually, e.g. England a whole, but probably not feasible to update all regions.

A3.2. Option 2. UH to process new uptake data

The second option would be for AERU to process new uptake data, using the steps outlined in Section 2, to generate a new version of the Excel workbook. The process is largely automated, but it would take about 1-2 hours to import and the data and generate the new workbook. This option would be reliant on the format of the raw uptake data remaining the same. Any deviation from this format would require an amendment to the processing routines, thus would entail more time.

This option does create a legacy issue for UH, but it is one that we would be willing to undertake at no extra cost, as it would be considered part of the communication costs element of our overhead, which often go beyond the official end date of the project to cover costs of, for example, dissemination.

A3.3. Option 3. UH provide software to process uptake data

The processes outlined in Section 2 have been undertaken via the development of bespoke software (the NESCarD Builder) that has been created for this project. This software has been designed and developed for in-house use only, but in theory could be further developed so that anyone could use it to process the uptake data and generate the Excel workbook. However, this would require the following tasks:

- Refinement/development of the user interface to make it more logical and user friendly.
- Development of help and support features.
- Development of error handling routines to prevent user errors and/or catch instances when the software fails, e.g. due to issues in the input data.
- Thorough testing of the software to ensure that it will as error free as possible.
- The development of an installation/deployment routine. The software is a standalone windows based application, thus would need to be installed on a user's computer. In relation to this, it would be wise to check Natural England's IT policies, i.e. will NE staff be able install a bespoke software application on their computers? If not, then this option may not be viable.

This option is likely to be the most costly option due to the tasks outlined above. It would also need to be separately costed as it would not be covered by the existing resources of the project. There would also be some legacy issues to consider, such as maintaining the software for the duration of its use.

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Establishing a field-based evidence base for the impact of agri-environment options on soil carbon and climate change mitigation – phase 2

Final report

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Figure A2.4. Agreement map for Cobbs Wood Farm tenancy, ES options and resampling locations (©Natural England).......... 85

Figure A2.5. Agreement map for Rectory Farm tenancy, ES options and resampling locations (©Natural England).......... 86

List of abbreviations

A-08_Itp-14-BH	Arable land converted to Itemp in 2014 on Broomhouse
A-08_Itp-18-BH	Arable land converted to Itemp in 2018 on Broomhouse
A-EEF-CF1	Arable on Eight Elms Farm counterfactual 1
A-KPF-CF2	Arable on Kingston Pastures Farm counterfactual 2
A-NB-CF2	Arable on Newbiggin Farm counterfactual 2
A-OU1-DR	Arable + option OU1 on Donkin Rigg Farm
A-OU1-NB	Arable + option OU1 on Newbiggin Farm
A-PH-CF1	Arable on Prior Hall counterfactual 1
A-PH-FYM	Arable on Prior Hall + farmyard manure
BH	Broomhouse Farm
CA	Catcherside Farm
CRF	Cambridge Road Farm
CWF	Cobbs Wood Farm
DR	Donkin Rigg Farm
EE3 / OE3	6m grass buffer strip
EEF	Eight Elms Farm
EK2	Permanent grassland with low inputs
EK3	Permanent grassland with very low inputs
EL2	Permanent grassland with low inputs in SDAs
EL3	Permanent grassland with very low inputs in SDAs
ES	Environmental Stewardship
GH	Gallows Hill Farm
GLM	General Linear Model
HC13	Restoration of wood pasture and parkland
HC9	Creation of woodland in SDAs
HE10	Floristically enhanced grass margin
HF20R	Cultivated fallow plots or margins for arable plants
HJ3	Arable reversion to unfertilised grassland to prevent erosion or run-off
HJ3	Arable reversion to grassland
HVF	Home Valley Farm
Iperm	Improved permanent grassland
Iperm-BH-EK2	Improved permanent grassland on Broomhouse Farm + option EK2
Iperm-BH-EK3	Improved permanent grassland on Broomhouse Farm + option EK3
Iperm-CA-EL2-UL18	Improved permanent grassland on Catcherside Farm + options EL2, UL18
Iperm-GH-EL2	Improved permanent grassland on Gallows Hill + option EL2
Iperm-PH-CF	Improved permanent grassland on Prior Hall counterfactual
Iperm-WA	Improved permanent grassland on Wimpole Avenue
Itemp	Improved temporary grassland
Itemp-OU1-DR	Improved temporary grassland + option OU1 on Donkin Rigg
Itemp-PH-CF	Improved temporary grassland on Prior Hall counterfactual
Itp-08_A-10_Itp-14-BH	Improved temporary grassland in 2008 recorded as arable in 2010 and improved temporary grassland in 2014 on Broomhouse Farm
Itp-08_A-10_Itp-18-BH	Improved temporary grassland in 2008 recorded as arable in 2010 and improved temporary grassland in 2018 on Broomhouse Farm
Itp-08-Ip-10-CA-EL2-UL18	Improved temporary grassland in 2008 recorded as improved permanent grassland in 2010 on Catcherside Farm + options EL2 + UL18

Itp-08-Ip-18-GH	Improved temporary grassland in 2008 recorded as improved permanent grassland in 2018 on Gallows Hill Farm
Itp-08-Ip-18-GH-EL3	Improved temporary grassland in 2008 recorded as improved permanent grassland in 2018 on Gallows Hill Farm + option EL3
KPF	Kingston Pastures Farm
NB	Newbiggen Farm
NSRI	National Soil Resources Institute
OB2	Hedgerow management (margin)
OHD3	Reduced-depth, non-inversion cultivation on archaeological features
OHF7	Beetle banks (on organic arable conversion
OU1	Conversion to organic management
OU1-2008-CWF	Option OU1 since 2008 on Cobbs Wood Farm
OU1-2008-HF20R-CWF	Option OU1 + HF20R since 2008 on Cobbs Wood Farm
OU1-2008-HVF	Option OU1 since 2008 on Home Valley Farm
OU1-2008-OHD3-CWF	Option OU1 + OHD3 since 2008 on Cobbs Wood Farm
OU1-2008-RF	Option OU1 since 2008 on Rectory Farm
OU1-2012-CRF	Option OU1 since 2008 on Cambridge Road Farm
PH	Prior Hall Farm
RCF	Relative to the counterfactual
RF	Rectory Farm
Rperm	Rough permanent grassland
Rperm_marshy	Rough permanent grassland / marshy grassland
Rperm_marshy-OU1-DR-OL3-UOL18	Rough permanent marshy grassland on Donkin Rigg Farm + options OU1, OL3, UOL18
Rperm_marshy-OU1-DR-OL3-UOL18-HL8-OHK15	Rough permanent marshy grassland on Donkin Rigg Farm + options OU1, OL3, UOL18, HL8, OHK15
Rperm_remnant	Rough permanent grassland / remnant habitat grassland
Rperm-CA-EL2-UL18	Rough permanent grassland on Catcherside Farm + options EL2, UL18
Rperm-GH-EL2	Rough permanent grassland on Gallows Hill + option EL2
Rperm-GH-EL2-EL3	Rough permanent grassland on Gallows Hill + options EL2, EL3
Rperm-GH-EL3	Rough permanent grassland on Gallows Hill + option EL3
Rperm-HC13-HR2-WA	Rough permanent grassland + option HC13 + HR2 on Wimpole Avenue
Rperm-NB	Rough permanent grassland on Newbiggen Farm
Rperm-OU1-DR-OL3-UOL18	Rough permanent grassland on Donkin Rigg Farm + options OU1, OL3, UOL18
Rperm-OU1-DR-OL3-UOL18-HL8	Rough permanent grassland on Donkin Rigg Farm + options OU1, OL3, UOL18, HL8
Rperm-OU1-DR-OL3-UOL18-HL8-OHK15	Rough permanent grassland on Donkin Rigg Farm + options OU1, OL3, UOL18, HL8, OHK15
Rperm-OU1-DR-OL3-UOL18-UOL20	Rough permanent grassland on Donkin Rigg Farm + options OU1, UOL18, UOL20
SOC	Soil Organic Carbon
UL18 / OUL18	Cattle grazing on upland grassland and moorland
UOL20	Haymaking

Summary

Defra project BD2302 (Warner et al., 2008; 2011b) assessed the impact of implementing each individual Environmental Stewardship (ES) 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). The project applied a life-cycle assessment approach and utilised published data from a variety of sources. Bell (2011) and Bell and Worrall (2009) quantified the SOC at a depth of 20 cm on agricultural land throughout two National Trust estates contrasting in geographic location and local site variables: the Wallington Estate (n = 230 after the removal of outliers) in the north-east of England east of Newcastle, and the Wimpole Estate (n = 48 after the removal of outliers) in south-east England south-west of Cambridge. Variables accounted for included soil group, soil series, land use, management practice, pH and altitude. Ten years later, this study has re-assessed the SOC content of selected sites originally sampled by Bell (2010) on the Wallington Estate. The objective was to ascertain the potential impact of ES options implemented at Wallington on SOC over a 10 year period. The values obtained could then be compared with data cited from the published literature used by Warner et al. (2008; 2011b) and update them if appropriate. The ES options assessed were limited to those present on the Wallington Estate, although further sampling was undertaken at the Wimpole Estate in order to maximise the diversity of the ES options assessed. It does not attempt to evaluate all ES options. The soil sampling methods have been replicated in order to allow a direct comparison to be made and to quantify the change in SOC over the previous 10 year period. Laboratory analysis of the soil samples derived % SOC from loss on ignition and total organic carbon by carbon-nitrogen analysis.

The statistical analysis follows the method of Bell (2011) and Bell and Worrall (2009). Soil series and land use are designated as factors within a Generalised Linear Model (GLM) with covariates of altitude, soil pH, aspect and years in current land use. Land use has been analysed at two different levels of aggregation: 1. estate scale land use (Bell, 2010); 2. land use scale, tenancy and ES option + management practice. The change in SOC between 2008 and 2018 varied depending on land use. The original study of Bell (2011) that acts as a baseline for this work found that a significant difference in SOC was observed due to land use [$F(8,201)= 5.312$, $p=0.001$]. The SOC increased in the following sequence: arable < improved temporary grassland < improved permanent grassland < rough permanent grassland. In 2018 a significant difference remained evident for land use [$F(8,201)=2.957$, $p=0.004$]. While the hierarchy of SOC content due to land use was maintained, there was no longer a significant difference between the SOC of arable land and grassland for the tenancies evaluated on the Wallington Estate.

The arable land on both the Wallington and Wimpole estates increased in SOC since 2008 (0.39 and 1.50 g kg^{-1} soil respectively). This was significant at the Wimpole Estate ($p<0.001$). The management of arable land at both locations includes practices conducive with the enhancement of SOC such as grass/clover leys (as part of but not exclusively to option OU1-Organic management), and organic amendments such as straw or farmyard manure. A pairwise comparison of each management scenario individually with the two counterfactual (control) scenarios on arable land identified a significant difference where a grass/clover ley is included in the rotation (A-OU1-DR: $p=0.003$ and $p=0.005$), the addition of 15 - 20 t ha^{-1} FYM biennially (A-PH-FYM: $p=0.029$) and the conversion to permanent grass as option HJ3 ($p=0.004$ and $p=0.013$). Options that take a proportion of land out of agricultural production, for example HJ3-Arable reversion to grassland to prevent soil erosion, where appropriately targeted to protect sensitive habitat features or vulnerable soils also play an important role in the enhancement of SOC on

arable land. These management practices and changes in land use permit continued agricultural production, being categorised as low to moderate displacement risk.

The SOC in improved temporary grassland appeared relatively stable, declining by a mean -0.04 g kg^{-1}. There was no significant difference between scenarios grouped by tenancy, Environmental Stewardship option and management. The SOC of permanent grassland has declined significantly overall compared to measurements taken in 2008 within the improved permanent grassland (-4.62 g kg^{-1}; $p<0.001$), rough permanent grassland (-7.46 g kg^{-1}; $p<0.001$) and marshy grassland (-17.29 g kg^{-1}; $p=0.005$) land use categories. The decline on marshy grassland and rough permanent grassland in close proximity to such areas may indicate former wetland habitat where the SOC has continued to deteriorate due to remnant drainage systems. Although these drainage systems have been allowed to deteriorate and no longer function, the benefit of restoration options (for example option HL8-Restoration of rough grazing for birds) was not in this case realised during the 10 year ES agreement itself. The decline in SOC is however likely to be at a potentially slower rate than if a fully functioning drainage system were in place. Successful rewetting of organic soils where gains in SOC have been demonstrated are typically achieved in the medium-long term, suggesting longer term management agreements beyond the current 10 year maximum are required under such conditions.

No significant difference was evident between scenarios where SOC change is disaggregated to the tenancy, ES option and management practice level on grassland due to the variability in measured SOC change, -1.82 to 1.67 t C ha^{-1} yr^{-1} and -0.54 to 2.95 t C ha^{-1} yr^{-1} relative to the counterfactual scenario. Change could not be attributed with confidence to any of the variables cited in the published literature (low nitrogen inputs, provision of optimal crop nutrition, liming, the presence of a greater sward species diversity, improved productivity grass species, and low to moderate levels of grazing of 0.4 – 0.8 LU ha^{-1}) as having an impact on SOC in grassland. The zero change allocated to the low input grassland options (EK2/EL2/EK3/EL3) on existing permanent grassland in Defra project BD2302 (Warner et al., 2008; 2011b) remained unchanged. Options such as UOL20 haymaking aim to encourage sward species diversity, while mixed grazing (UOL18 / UL18) offer the potential to increase sward structural diversity. Since the sward species or structural diversity has not been measured directly these variables cannot be cited conclusively in the current analysis. No definitive change in SOC has been allocated to these options.

The creation of wood pasture (option HC13-Restoration of wood pasture and parkland) has a potential benefit for SOC on rough permanent grassland. It also maintains the production levels (low displacement risk) where implemented on existing low input grassland. The 0.17 t C ha^{-1} yr^{-1} accumulated at Wimpole is comparable to the 0.13 t C ha^{-1} yr^{-1} for grassland converted to forest on 10% of the area.

1.0. Introduction

In 2012 the National Trust sought to enter the majority of tenant farms on its Wallington Estate into the former Higher Level Stewardship (HLS) scheme. 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 (Natural England, 2013ab). 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 Environmental Stewardship were:

- 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 ES option is designed to contribute to one or more of the five primary objectives. In meeting these primary objectives an overarching priority of ES was originally to enhance the contribution made by agricultural land and to climate change mitigation (Natural England, 2013ab). This has since become one of the main priorities in proposals for future Environmental Land Management Policies (Agriculture Bill (292) 2017-2019; Draft Environment (Principles and Governance) Bill, 2018). Future development of stewardship schemes have greenhouse gas (GHG) emission reduction and the protection of carbon stores within soils or biomass embedded within them.

Defra project BD2302 (Warner et al., 2008; 2011b) assessed the impact of implementing each individual ES option on SOC and biomass C, and the greenhouse gases carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Bell (2011) and Bell and Worrall (2009) quantified SOC on agricultural land throughout the Wallington and Wimpole Estates to a depth of 20 cm. Variables accounted for included 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.*, 2008; Warner et al., 2011b) evaluated ES and other options most suited to each individual tenancy on the Wallington Estate and calculated their potential to enhance soil or biomass C. An output of the project was a land carbon management plan and recommendations of HLS options tailored specifically to each individual tenancy to maximise the carbon sequestration potential of the estate overall. Ten years later, this study has re-assessed the SOC content of selected sites originally sampled by Bell (2010) on the Wallington Estate. The objective was to ascertain the potential impact of ES options implemented at Wallington on SOC over a 10 year period. The values obtained could then be compared with data cited from the published literature used by Warner et al. (2008; 2011b) and update them if appropriate. The ES options assessed were limited to those present on the Wallington Estate, although further sampling was undertaken at the Wimpole Estate in order to maximise the diversity of the ES options assessed. It does not attempt to evaluate all ES options. The soil sampling methods have been replicated in order to allow a direct comparison to be made and to quantify the change in SOC over the previous 10 year period.

2.0. Methods

Sampling was conducted at two sites contrasting in geographic location and local site variables: the Wallington Estate in the north-east of England east of Newcastle, and the Wimpole Estate in south-east England south-west of Cambridge (Figure 2.1). Both estates are owned by the National Trust.

Figure 2.1. Location of the Wallington and Wimpole Estates.

2.1. Wallington Estate case study farms and sample sites

The Wallington Estate consists of a broad range of agricultural land uses and semi-natural habitats, each identified by Bell (2011) to contain different quantities of SOC. The original objective was to enter the entire estate into Higher Level Stewardship (HLS). Following discussion with tenants, a combination of HLS, Entry Level Stewardship (ELS) and Organic Entry Level Stewardship (OELS) options were implemented. Not all areas of the Wallington Estate were resampled in 2018, the focus has been on ES options implemented on arable land and improved grassland. The soil series (Cranfield University, 2019; Clayden and Hollis, 1984) included in the reanalysis are summarised in Table 2.1.1. The most frequent present in the areas resampled are the Brickfield and Nercwys series.

Table 2.1.1. Soil series present on the Wallington Estate.

Soil series	Abbr	Soil group	Compaction risk	NSRI %SOC
Brickfield	Br	surface-water gley soils	low-moderate	5.00
Dunkeswick	Dk	surface-water gley soils	low-moderate	5.00
Enborne	Eo	ground-water gley soils	low	5.79
Fladbury	Fa	ground-water gley soils	low	5.79
Greyland	gJ	surface-water gley soils	low-moderate	5.00
Heapy	Hj	brown earth	low	4.02
Nercwys	Nc	brown earth	low	4.02
Rivington	Rc	brown earth	low	4.02
Ticknall	tL	surface-water gley soils	low-moderate	5.00
Waltham	Wa	brown earth	low	4.02
Wilcocks	Wo	surface-water gley soils	low-moderate	5.00
Wigton Moor	ww	ground-water gley soils	low	5.79

Notes: 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). Ground-water gley soils: humose or peaty topsoil (low risk).

Maps showing the location of each ES option implemented at each Wallington tenancy were supplied by Natural England. Each map was digitised in ArcGIS® and overlaid onto the digitised maps of Wallington maps (Warner *et al.*, 2011a) showing the location of each sample taken by Bell (2011). A subsection of six tenancies was selected in consultation with stakeholders based on the number of sample sites of Bell (2011) that were identified as being located within the boundary of priority ES options listed in TIN107 (Natural England, 2012) and defined in the maps of the tenancies supplied by Natural England.

The sampling regime aimed to maximise the number of ES option types assessed although it is acknowledged that not all, once mapping of the ES options was complete. The precise number of ES options included was constrained by the existing sample locations (Bell, 2011). Not all options present had an existing underlying sample location due in part to the scale of the Wallington Estate and the spatial variability in concentration of the previous sampling effort within different areas and tenancies. The tenancies selected included those where the 2008 sampling intensity was greatest (Figure 2.1.1).

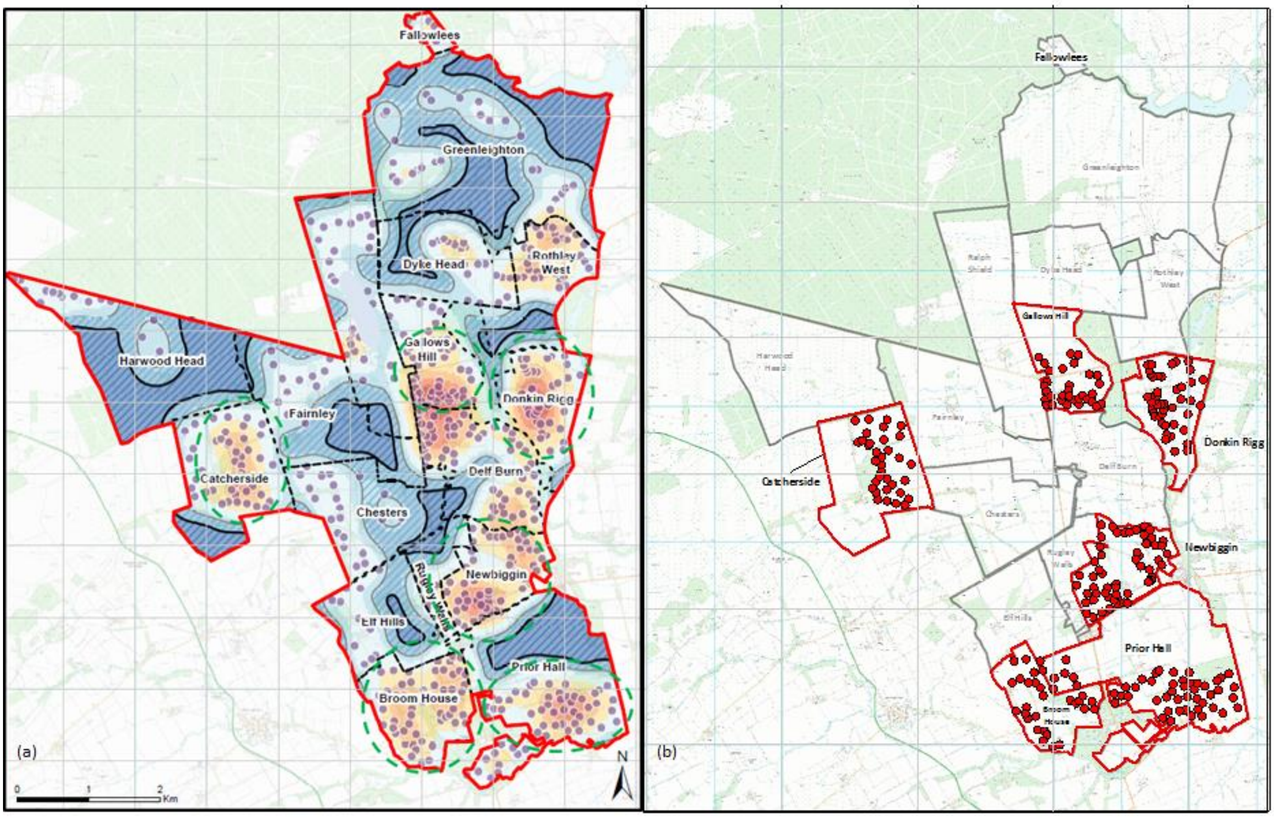

Figure 2.1.1. (a) Sampling intensity (Bell, 2011) at the Wallington Estate and chosen case study tenancies (green dashed circle) and (b) location of resampled sites.

Sample sites within each ES option type were further aggregated at two levels of soil classification: (1) soil class (Bell, 2011) and (2) dominant soil texture (Panagos *et al.*, 2012) in addition to land use history (Bell, 2011; Warner *et al.*, 2011a) and soil pH. The use of dominant soil texture will allow further extrapolation to an England-wide spatial scale (subject to associated caveats). Where ES has not been implemented the nearest adjacent sample location with comparable soil class, texture, pH and land use history was selected for establishing a counterfactual or control set of samples.

The changes in management regime between the sampling periods of 2008 and 2018 were established via interview with the farm managers following the protocol of Warner *et al.* (2011a, 2013), and review of option management prescriptions supplied by Natural England. This was applied to land parcels on individual tenancies within the Wallington Estate where ES options of interest had been identified and mapped coupled with the presence of a sample location taken in 2008. Environmental Stewardship options were limited to those implemented on the Wallington Estate and those where sampling had occurred in 2008. It does not represent a comprehensive study of all options available under the ES scheme. Farm input data was sourced in liaison with the selected agreement holders to include, on a field by field basis in reference to farm maps and a review of farm records, the following layers of detail (1 to 4 in ascending level of detail) as used previously by Warner *et al.* (2011a) when undertaking interviews with farm mangers. Records applicable to original management (pre-option) and current management (post option) identified changes in farm inputs and outputs related to the uptake of options: (1) General management practices (yes or no) (e.g. application of NPK, organic manures, use of particular type of machinery, herbicides), difference in management of improved and unimproved grassland; (2) Timing (when inputs are applied or stock grazed, crops sown, grassland reseeded) or duration (e.g. time since last reseed); (3) Stocking rates (livestock units per ha), depth of tillage on arable or reseeded grassland, seed mix; and (4) Precise application rates (NPK, FYM, herbicides), dietary constituents of livestock and quantities per animal. Stocking rates may vary throughout the year, e.g. on temporary and permanent grassland if stock are moved (e.g. removed from temporary grassland and added to improved permanent grassland when cut for silage, or added to improved permanent grassland if removed from unimproved permanent grassland during the winter). The number of stock and baseline productivity may require aggregation between multiple fields where such management is applicable. Observations of grass species / clover mix while on farm visits and counts of stock in the fields were noted at the time of sampling.

The following section provides and overview of the tenancies on the Wallington Estate. A total of 259 of the original 648 sample sites (Bell, 2011) were resampled. A summary of the options included in the assessment, their baseline land use and their potential impact on SOC for that baseline land use are summarised in Table 2.1.2.

Table 2.1.2. Environmental Stewardship options assessed at the Wallington and Wimpole Estates, key management of relevance to SOC, change in management practice or land use, and change in SOC in the published literature. CMP: change in management practice; LUC: land use change.

Option	Key management	Equivalent mode of potential C sequestration	t C ha^{-1} yr^{-1}
Arable / organic arable land			
OHD3 Reduced-depth, non-inversion cultivation on archaeological features	non-inversion cultivation maximum 10cm depth or zero tillage, no sub-soil or mole-plough	CMP: shallow or zero cultivation	0[a]
OU1	conversion to organic management	CMP: variable, typically a grass/clover ley	0.30
HF20R Cultivated fallow plots or margins for arable plants	annual cultivation, zero crop drilling	CMP: natural regeneration (annual)	-0.25
HJ3 Arable reversion to unfertilised grassland to prevent erosion or run-off	removal of compaction, sown grass mixture, no supplementary nutrients, no overgrazing	LUC: to unimproved permanent grassland	0.3 – 1.9
OB2 Hedgerow management (margin)	no cultivation or supplementary nutrients within 2 m of hedge centre	LUC: to unimproved grass strip (part)	0.3 – 1.9
HE10 Floristically enhanced grass margin		LUC: to unimproved grass strip	0.3 – 1.9
EE3 / OE3 6m grass buffer strip	establish grass strip by sowing or natural regeneration, no supplementary nutrients, control woody growth	LUC: to unimproved grass strip	0.3 – 1.9
OHF7 Beetle banks (on organic arable conversion	establish raised grass bank / strip by sowing with a mixture of perennial and tussock forming grasses	LUC: to unimproved grass strip	0.3 – 1.9
Improved temporary grassland			
UL18 Cattle grazing on upland grassland and moorland	minimum of 30% LUs as grazing cattle averaged over 2 year period	CMP: sheep and cattle grazing	No data
EL2 Permanent grassland with low inputs in SDAs	no cultivation, maximum 50 kg N ha^{-1} inorganic / 100 kg N ha^{-1} total N limit (no increase), existing lime permitted	LUC: to improved permanent grassland +	0.2 – 0.5

EL3 Permanent grassland with very low inputs in SDAs	no cultivation, maximum 12.5 t ha^{-1} farmyard manure, existing lime permitted	restrictions on supplementary nutrients LUC: to improved permanent grassland + restrictions on supplementary nutrients	0.2 – 0.5
Improved permanent grassland			
UL18 Cattle grazing on upland grassland and moorland	minimum of 30% LUs as grazing cattle averaged over 2 year period	CMP: sheep and cattle grazing	
EK2 Permanent grassland with low inputs	maximum 50 kg N ha^{-1} inorganic / 100 kg N ha^{-1} total N limit (no increase), existing lime permitted	CMP: restriction on supplementary nutrients	*0.08 – 0.3*
EK3 Permanent grassland with very low inputs	maximum 12.5 t ha^{-1} farmyard manure, existing lime permitted	CMP: restriction on supplementary nutrients	*0.08 – 0.3*
EL2 Permanent grassland with low inputs in SDAs	maximum 50 kg N ha^{-1} inorganic / 100 kg N ha^{-1} total N limit (no increase), existing lime permitted	CMP: restriction on supplementary nutrients	*0.08 – 0.3*
EL3 Permanent grassland with very low inputs in SDAs	maximum 12.5 t ha^{-1} farmyard manure, existing lime permitted	CMP: restriction on supplementary nutrients	*0.08 – 0.3*
Rough permanent grassland			
UOL20 Haymaking	cut and remove hay or haylage once per annum after 5th July, exclude livestock minimum 7 weeks before cutting	CMP: cutting, temporary livestock exclusion	No data
HC13 Restoration of wood pasture and parkland	tree planting to replace lost trees, scrub removal, grazing to maintain diverse sward structure	LUC (part): to 10% woodland	0.13
HC9 Creation of woodland in SDAs	tree planting	LUC: to woodland	0.1 – 1.3

Note: [a]as net increase overall due to redistribution of SOC within deeper soil layers

The options and management associated with each tenancy at Wallington, and the number of samples taken is summarised in Table 2.1.3. The number of samples was limited by there being spatial coincidence between the sample site as defined by Bell (2011) in 2008 and the ES options subsequently implemented. Maps of the sampling locations are provided in Appendix 1.

Table 2.1.3. Land management an Environmental Stewardship options assessed at the Wallington Estate. Text in italics and parentheses refers to options present in close proximity to sample sites but not sampled.

Management and option code	N	Description
Prior Hall		
A-PH-CF1	9	Arable counterfactual 1
A-08_Itp-14-PH	6	Arable conversion to temporary grassland in 2014
A-PH-FYM	4	Arable + FYM
Itemp-PH-CF	9	Temporary grassland counterfactual
Iperm-PH-CF	22	Improved permanent grassland counterfactual
Newbiggen		
A-NB-CF2	9	Arable counterfactual 2

A-OU1-NB	32	Arable OU1 Organic management
HJ3	2	HJ3 Reversion to unfertilised grassland prevent erosion on arable land
OB2	1	OB2 Hedgerow management landscape (1 side)
Rperm-OU1-NB	7	OU1 Organic management on rough permanent grassland
		(EE3 / OE3 6m grass buffer strip)
		(HE10 Floristically enhanced buffer strip)
Donkin Rigg		
A-OU1-DR	13	Arable OU1 Organic management
Itemp-OU1-DR	5	OU1 Organic management on temporary grassland
Rperm_marshy-OU1-DR-OL3-UOL18	2	UOL18 Cattle grazing upland grassland & moorland; OL3 In-bye grassland very low inputs on rough permanent marshy grassland
Rperm_marshy-OU1-DR-OL3-UOL18-HL8-OHK15	4	UOL18 Cattle grazing upland grassland & moorland; OL3 In-bye grassland very low inputs; HL8 Restoration of rough grazing for birds; OHK15 Maintenance grassland target features on rough permanent marshy grassland
Rperm-OU1-DR-OL3-UOL18	10	UOL18 Cattle grazing upland grassland & moorland; OL3 In-bye grassland very low inputs on rough permanent grassland
Rperm-OU1-DR-OL3-UOL18-HL8	2	UOL18 Cattle grazing upland grassland & moorland; OL3 In-bye grassland very low inputs; HL8 Restoration of rough grazing for birds on rough permanent grassland
Rperm-OU1-DR-OL3-UOL18-HL8-OHK15	2	UOL18 Cattle grazing upland grassland & moorland; OL3 In-bye grassland very low inputs; HL8 Restoration of rough grazing for birds; OHK15 Maintenance grassland target features on rough permanent grassland
Rperm-OU1-DR-OL3-UOL18-UOL20	3	UOL18 Cattle grazing upland grassland & moorland; OL3 In-bye grassland very low inputs; UOL20 Haymaking on rough permanent grassland
Broomhouse		
A-08_Itp-14-BH	7	Arable conversion to temporary grassland in 2014
A-08_Itp-18-BH	4	Arable conversion to temporary grassland in 2018
Itp-08_A-10_Itp-14-BH	3	Improved temporary grassland conversion to arable in 2010 to improved temporary grassland in 2014
Itp-08_A-10_Itp-18-BH	3	Improved temporary grassland conversion to arable in 2010 to improved temporary grassland in 2018
Ip-08_A-10_Itp-14-BH	2	Improved permanent grassland conversion to arable in 2010 to improved temporary grassland in 2014
Iperm-BH-EK2	5	EK2 Permanent grassland with low inputs on improved permanent grassland
Iperm-BH-EK3	4	EK3 Permanent grassland with very low inputs on improved permanent grassland
Gallows hill		
Itp-08-Ip-18-GH	11	Documented as improved temporary grassland in 2008, improved permanent grassland in 2018
Itp-08-Ip-18-GH-EL3	3	Improved temporary grassland conversion to improved temporary grassland in 2011
Iperm-GH-EL2	3	EL2 Permanent in-bye grassland low inputs on improved permanent grassland
Rperm_marshy-GH-EL3	2	EL3 In-bye grassland and meadows very low inputs on rough permanent marshy grassland
Rperm-GH-EL2	5	EL2 Permanent in-bye grassland low inputs on rough permanent grassland
Rperm-GH-EL2-EL3	3	EL2 Permanent in-bye grassland low inputs; EL3 In-bye grassland and meadows very low inputs on rough permanent grassland
Rperm-GH-EL3	2	EL3 In-bye grassland and meadows very low inputs on rough permanent grassland

Catcherside		
Itemp-CA-UL18	8	UL18 Cattle grazing upland grassland & moorland
Itp-08-Ip-10-CA-EL2-UL18	3	EL2 Permanent in-bye grassland low inputs; UL18 Cattle grazing upland grassland & moorland
Iperm-CA-EL2-UL18	7	EL2 Permanent in-bye grassland low inputs; UL18 Cattle grazing upland grassland & moorland on improved permanent grassland
Rperm-CA-EL2-UL18	11	EL2 Permanent in-bye grassland low inputs; UL18 Cattle grazing upland grassland & moorland on rough permanent grassland on improved temporary grassland

2.2. Wimpole Estate case study farms and sample sites

The Wimpole Estate located in Cambridgeshire consists of multiple tenancies, mostly arable, managed as part of the National Trust Home Farm (blue highlighted areas in Figure 2.2.1). These tenancies have been entered into ES agreements and have undergone organic conversion as a component of being entered into option OU1.

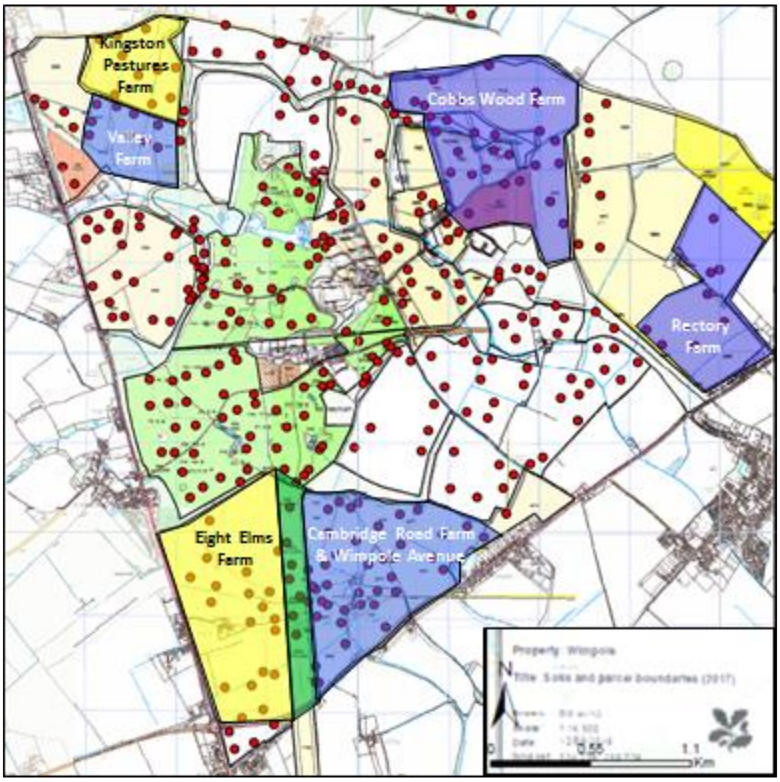

Figure 2.2.1. Map of the Wimpole Estate (yellow fill - arable counterfactual; blue fill – arable + ES; green fill – grassland).

The Estate also includes tenancies where ES is not present (yellow filled areas in Figure 2.2.1) and these have been resampled in order to establish counterfactuals for comparison. The soil series (Cranfield University, 2019; Clayden and Hollis, 1984) present at Wimpole and included in the analysis are summarised in Table 2.2.1. The estate is dominated by the Hanslope (Hn) series.

Table 2.2.1. Soil series present at the Wimpole Estate.

Soil series	Abbr	Description	Compaction risk
Abington	AB	loam or clay subsoils without significant clay enrichment	moderate
Didmarton (gully)	dB	loam or clay subsoils without significant clay enrichment	moderate
Drayton	dT	clay	high
Evesham3	Ea	clay	high
Hanslope	Hn	clay	high
Lode	Lo	shallow humose or peaty topsoil over bedrock	low
Wantage	Wb		low

The following section provides and overview of the tenancies on the Wimpole Estate. A total of 51 of the original 378 sample sites (Bell, 2011) were resampled. The options and management associated with each tenancy on the Wimpole Estate, and the number of samples taken are summarised in Table 2.2.2. Similarly to the Wallington Estate, the number of samples was limited to those included within agreements and there being spatial coincidence between the original sample sites as defined by Bell (2011) in 2008 and those ES options. Maps of the sampling locations on each tenancy are provided in Appendix 2.

Table 2.2.2. Land management an Environmental Stewardship options assessed at the Wimpole Estate. Text in italics and parentheses refers to options present in close proximity to sample sites but not sampled.

Management and option code	N	ES option
Eight Elms		
A-EEF-CF1	5	Arable counterfactual 1
Kingston Pastures		
A-KPF-CF2	6	Arable counterfactual 2
Cobbs Wood		
OU1-2008-CWF	9	Arable OU1 Organic management
OU1-2008-OHD3-CWF	3	OHD3 Low depth, non-inversion cultivation on archaeological features
OU1-2008-HF20R-CWF	1	HF20R Cultivated fallow plots or margins for arable plants *(HE10 Floristically enhanced grass margin)*
Cambridge Road		
OU1-2012-CRF	6	Arable OU1 Organic management *(OHF7 Beetle banks)*
Rectory		
OU1-2008-RF	6	Arable OU1 Organic management *(OHF4NR Nectar flower mixture)*
Home Valley		
OU1-2008-HVF	6	Arable OU1 Organic management *(HE10 Floristically enhanced grass margin)*
Wimpole Avenue		
Iperm-WA	2	Improved permanent grassland
Rperm-HC13-HR2-WA	4	HC13 Restoration of wood pasture and parkland + HR2 Grazing supplement for native breeds at risk on rough permanent grassland

2.3. Soil sampling and analysis

2.3.1. Soil sampling

Soil sampling followed the methodology of Bell (2011) at a total of 302 sample locations located using GPS with reference to the coordinates specified by Bell (2011). At each sample location a rectangular pit 50 cm in length, 20 cm wide and 18.0 cm deep was dug and the soil removed (Figure 2.3.1).

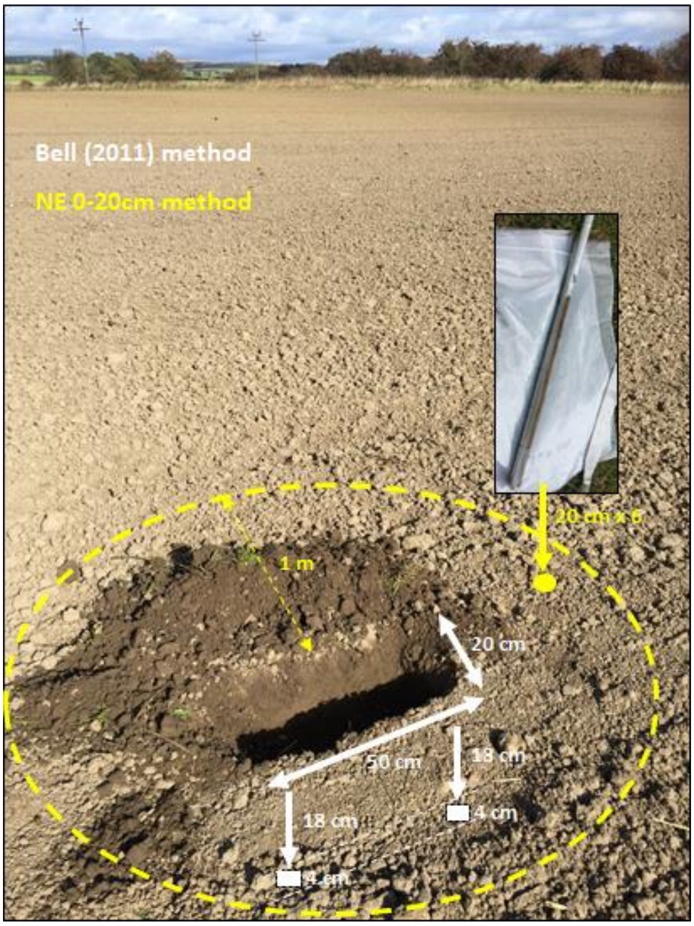

Figure 2.3.1. Sampling protocol at each resampled location.

Two bulk density measurements per sample location were taken by extracting soil at each end of the soil pit using a soil ring hammered into the 18.0 – 22.0 cm layer. Further soil was removed from the 18.0 – 22.0 cm layer from within the soil pit for analysis of percent organic matter (OM) by loss on ignition (LOI), total percent organic carbon (TOC) by CN analysis and soil pH. Samples were stored at 4^{o}C until despatch to the laboratory. Sample analysis was undertaken by Forest Research, Alice Holt, UK. A further set of samples were taken in the 0-20cm layer by soil auger. Six soil cores 20cm deep were extracted within a 1m radius of the soil pit centre. The 20-25cm layer within the auger which may potentially be compacted during the extraction process was discarded from the sample. Analysis for %OM by LOI was conducted by NRM laboratories, Bracknell, UK.

2.3.2. Statistical analysis

The statistical analysis follows the method of Bell (2011) and Bell and Worrall (2009). Soil series and land use are designated as factors within a Generalised Linear Model (GLM) with covariates of altitude, soil pH, aspect and years in current land use. Land use has been analysed at two different levels of aggregation: 1. estate scale land use (Bell, 2010); 2. land use scale, tenancy and ES option + management practice. An Analysis of CoVariance (ANCOVA) was performed using SPSS® Statistical Software (version 25) with results of significance subject to further post-hoc analysis with the Tukey test. The %SOC data from the laboratory analysis was log transformed before the ANCOVA analysis in order provide a normally distributed dataset. A bivariate analysis determined that the covariates within the ANCOVA did not have a correlation above 0.8. An initial boxplot analysis of the change in SOC between the 2008 and 2018 datasets identified outliers. Samples determined as outliers were removed from the main component of the analysis. A further analysis at the land use, tenancy and ES option + management practice scale using an independent samples t-test compared the change SOC in response to changes in management and ES option relative to the counterfactual scenarios (two different sets of sampling points, different years). A paired sample t-test determined the change in SOC between years for each land use category (identical sets of sampling points, different years).

2.3.3. Sample calibration

Bell (2011) derived %SOC from LOI and the Walkley-Black method. The current assessment derived %SOC from LOI and TOC by C:N analysis. The analysed sample data reported here (section 2.3.1) is a direct comparison of the two approaches. Reversal of the calibration equation of the Walkley-black approach of Bell (2011) compared with the 2018 %SOC from OM by LOI yielded similar results, as did a comparison of the reversed %SOC from OM by LOI calibrated with the 2018 %TOC dataset compared directly with the %TOC 2018 dataset.

2.3.3. Conversion to carbon weight per unit area

For the final stage of the analysis to compare the measured change with changes reported in the published literature the %SOC data provided by the laboratory analysis was converted to t C ha^{-1} using the method described in Ravindranath and Ostwald (2008) and Bell (2011) (*Equation 1*):

Equation 1:

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

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

Bell (2011) also calculates SOC (t C ha^{-1}) using average National Soil Resources Institute (NSRI) bulk density values for each soil group. This has been replicated with the resampled data for comparison. The change in SOC between sample periods is calculated using Equation 2.

Equation 2.

$$\Delta_{(SOC)} = (SOC_{(option)} - SOC_{(baseline)}) / T$$

where: T = Time in years between samples (10 years)

$SOC_{(option)}$ = *SOC (t C ha^{-1}) of the option (resample)*

$SOC_{(baseline)}$ = SOC ($t\ C\ ha^{-1}$) of the baseline scenario (Bell, 2010)
$\Delta_{(SOC)}$ = mean change in SOC per annum ($t\ C\ ha^{-1}\ yr^{-1}$)

The timeframe is change in SOC per annum over 10 years. It is acknowledged that the ES options have not been in place for 10 years however it is unknown what the baseline SOC was at the time of option implementation. It is only known what the SOC quantities were in 2008.

3.0. Results and Discussion

3.1. Wallington Estate

3.1.1. Estate scale: land use

3.1.1.1. Difference between years (2008 and 2018)

The results in this section are reported primarily as g SOC kg^{-1} soil, reflecting the data as provided by the analysis laboratory. The change in SOC has also been converted to t C ha^{-1} using NSRI soil bulk density values (Bell, 2011) in order to enable a comparison with values in the published literature in section 3.3. The original land use classifications of Bell (2011) were replicated with the addition of marshy and remnant acid grassland (Wallington Biological Survey, 1999; Warner et al., 2011a). For each land use category, a paired sample t-test (SPSS® version 25) compared the difference in SOC between samples taken in 2008 and 2018 accounting for change in land use since 2008 (Table 3.1.1).

Table 3.1.1. Total change in SOC (g kg^{-1}) between 2008 and 2018 to 20 cm depth (text in italics and parentheses denotes t C ha^{-1} yr^{-1}) and summary output of a paired sample t-test for the main land use classifications present in 2018.

Current land use (2018)	N	Mean change 2008 - 2018	Standard error of mean change	t	df	Sig
arable	67	0.39 (*0.08*)	0.50	1.122	66	0.266
Itemp	45	-0.04 (*-0.01*)	0.79	-0.206	44	0.838
Iperm	60	-4.62 (*-0.91*)	0.83	-5.221	59	<0.001*
Rperm	45	-7.46 (*-1.52*)	1.41	-5.499	44	<0.001*
Rperm_marshy	6	-17.29 (*-3.41*)	3.49	-4.737	5	0.005*
Rperm_remnant	2	-15.86 (*-3.00*)	2.90	-3.942	1	0.158
conifer	2	0.74 (*0.15*)	2.44	0.275	1	0.829
HJ3	2	7.12 (*1.34*)	2.69	3.971	1	0.157
OB2	1	5.21 (*0.87*)	-	-	-	-

*significant difference (p<0.05) between years

There is no significant change in SOC on arable land or Itemp overall between 2008 and 2018. A significant decline is observed for each permanent grassland land use category with the exception of the Rperm[remnant], mainly due to a small sample size. Notable declines in SOC are present in the Iperm and Rperm grassland classifications. Fewer samples were present within the arable land use category in 2018 relative to 2008 (n=20), in part due to the conversion to Itemp and the entering into ES agreements. A proportion of Itemp (n=17) had been converted to Iperm since 2008. Arable land is disaggregated further by individual land management category and tenancy in section 3.1.1.2.

3.1.1.2. Difference between land use categories

Figure 3.1a represents the SOC (g kg^{-1}) of sample sites (n = 230 after the removal of outliers) in 2008 as obtained by Bell (2011). The data is displayed using the land use classifications present in

2018. It is shown with the SOC measured in 2018 (Figure 3.1b) and the change in SOC within the 10 year period (Figure 3.1c). Figure 3.1c has the associated caveat that individual ES options have not been in place for the full duration of this 10 year period. The analysis and boxplots exclude sample sites removed as outliers from the original change in SOC dataset.

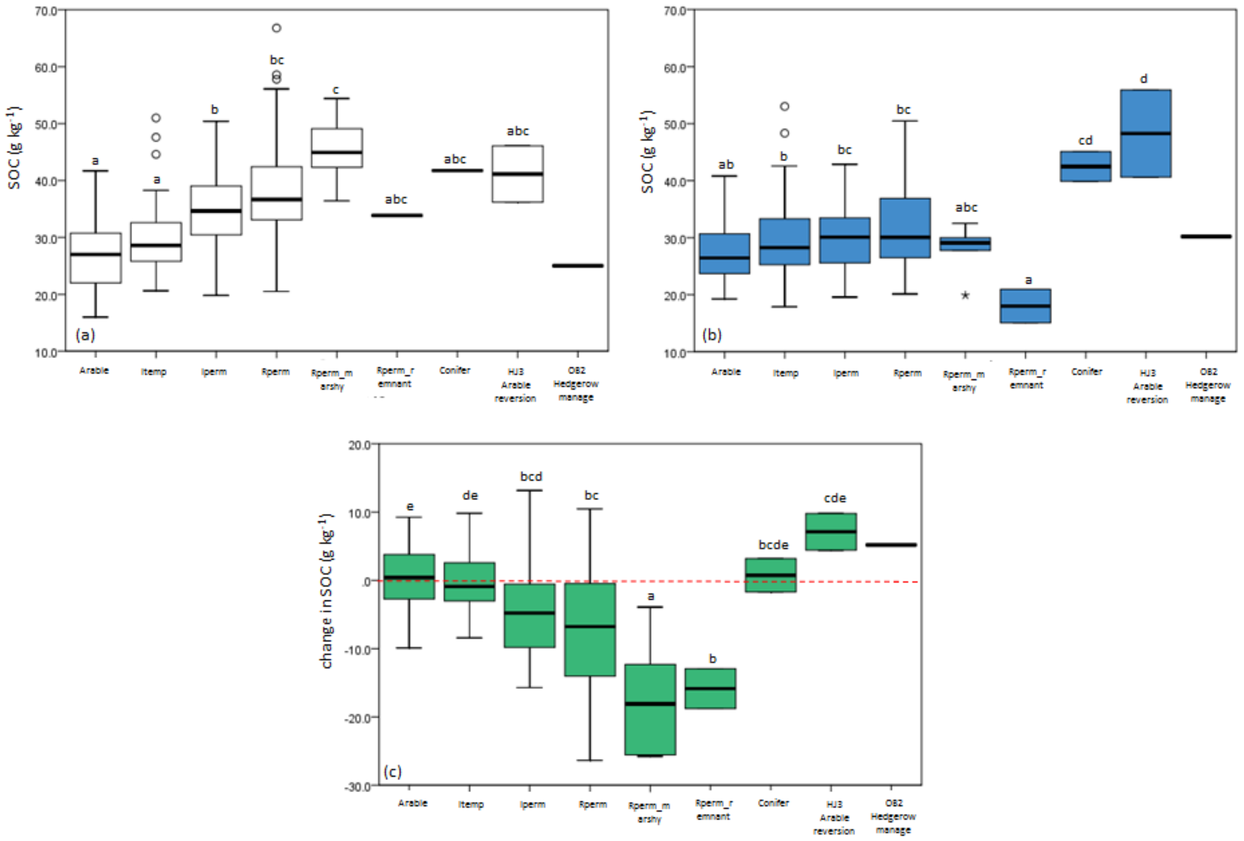

Figure 3.1.1. Boxplot of SOC (g kg^{-1}) 2018 land use classification in the resampled sites (n=230) as measured (a) in 2008 by Bell (2011), (b) in 2018 and (c) change 2008-2018 (red dashed line indicates zero change in SOC). Data points with different letters indicate a significant (*p*<0.05) difference. Acronyms: Itemp - Improved temporary grassland; Iperm - Improved permanent grassland; Rperm - Rough permanent grassland; Rperm_marshy - Rough permanent grassland / marshy grassland; Rperm_remnant - Rough permanent grassland / remnant habitat grassland; HJ3 Arable reversion to grassland; OB2 - Hedgerow management (margin).

Bell (2011) found that for sampling of all tenancies on the Wallington Estate the SOC increased in the following sequence: arable < improved temporary grassland (Itemp) < improved permanent grassland (Iperm) < rough permanent grassland (Rperm). This sequence was applicable when the 2008 data was analysed for the sample locations re-assessed in 2018 (Figure 3.1.1a). Warner et al. (2011a) included sites classified as marshy grassland and unimproved acid grassland, which for the original Bell (2011) dataset contained higher SOC than Rperm. This was observed when the 2008 data was analysed for the sites reassessed in 2018 (Figure 3.1.1a). For the sites reassessed excluding outliers, using the 2008 data a significant difference in SOC was observed due to land use [F(8,201)= 5.312, *p*=0.001] and altitude [F(1,201)= 4.793, p=0.030] (Table 3.2). The remaining variables, soil series, pH years in land use and aspect were not significant for this particular set of samples.

Table 3.1.2. General linear model summary statistics within dominant land use categories for log transformed SOC ($g\ kg^{-1}$) to 20 cm depth in 2008.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	1.142[a]	22	0.052	5.854	0.000	0.391
Intercept	5.649	1	5.649	636.846	0.000	0.760
Land use	0.377	8	0.047	5.312	<0.001*	0.175
Soil series	0.091	10	0.009	1.024	0.424	0.048
Altitude	0.043	1	0.043	4.793	0.030*	0.023
pH	0.001	1	0.001	0.126	0.723	0.001
Years land use	0.000	1	0.000	0.013	0.910	0.000
Aspect	0.033	1	0.033	3.669	0.057	0.018
Error	1.783	201	0.009			
Total	505.623	224				
Corrected Total	2.925	223				

[a] R Squared = 0.391 (Adjusted R Squared = 0.324); *significant difference ($p<0.05$)

Post-hoc testing (Tukey test) indicates a significant difference between SOC in 2008 between arable land and Iperm, Rperm and Rperm[marshy] ($p< 0.001$); Itemp and Iperm ($p=0.017$), Rperm ($p< 0.001$) and Rperm[marshy] ($p< 0.001$) and Iperm and Rperm[marshy] ($p=0.047$) (Table 3.1.3)

Table 3.1.3. General linear model summary post-hoc test (Tukey HSD) within dominant land use categories of log transformed SOC ($g\ kg^{-1}$) to 20 cm depth measured in 2008 for the main land use classifications present in 2018.

	arable	Itemp	Iperm	Rperm	Rperm_ marshy	Rperm_ remnant	conifer	HJ3
arable	n/a							
Itemp	0.390	n/a						
Iperm	<0.001*	0.017*	n/a					
Rperm	<0.001*	<0.001*	0.194	n/a				
Rperm_marshy	<0.001*	<0.001*	0.047*	0.555	n/a			
Rperm_remnant	0.778	0.978	1.000	0.998	0.760	n/a		
conifer	0.082	0.306	0.874	0.998	1.000	0.980	n/a	
HJ3	0.116	0.387	0.924	0.999	0.999	0.990	1.000	n/a

*significant difference ($p<0.05$) between years; OB2 excluded from post-hoc analysis due to one sample

Several authors report a similar hierarchy for SOC associated with land use, both in the UK and Europe (for example Bradley, 2005; Cantarello et al., 2011; Dyson et al., 2009; Panagos et al., 2013ab; Scharleman et al., 2014). In 2018 (Figure 3.1.1b) a significant difference remained evident for land use [F(8,201)=2.957, $p=0.004$] (Table 3.1.4).

Table 3.1.4. General linear model summary statistics within dominant land use categories for log transformed SOC ($g\ kg^{-1}$) to 20 cm depth in 2018.

Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**	**Partial Eta Squared**
Corrected Model	0.472[a]	22	0.021	2.805	0.000	0.235
Intercept	4.890	1	4.890	639.973	0.000	0.761
Land use	0.181	8	0.023	2.957	0.004*	0.105
Soil series	0.124	10	0.012	1.628	0.101	0.075
Altitude	0.015	1	0.015	2.008	0.158	0.010
pH	0	1	0	0.025	0.875	0

Years land use	0.006	1	0.006	0.753	0.387	0.004
Aspect	0	1	0	0.028	0.867	0.000
Error	1.536	201	0.008			
Total	478.934	224				
Corrected Model	0.472[a]	22	0.021	2.805	0.000	0.235

[a]R Squared = 0.235 (Adjusted R Squared = 0.151); *significant difference (*p*<0.05)

Post hoc tests (Table 3.1.5) indicate that the quantity of SOC within each land use category no longer follows significantly the hierarchy reported by Bell (2011) and Bell and Worrall (2009) as summarised in Table 3.3. There was no significant difference between arable land and grassland for the tenancies evaluated although one exists between option HJ3 and all other land use categories except the conifer dominated woodland.

Table 3.1.5. General linear model summary post-hoc test (Tukey HSD) within dominant land use categories for log transformed SOC (g kg^{-1}) to 20 cm depth measured in 2018 for the main land use classifications present in 2018.

	arable	Itemp	Iperm	Rperm	Rperm_ marshy	Rperm_ remnant	conifer	HJ3
arable	n/a							
Itemp	0.745	n/a						
Iperm	0.379	1.000	n/a					
Rperm	0.072	0.929	0.984	n/a				
Rperm_marshy	1.000	1.000	0.998	0.969	n/a			
Rperm_remnant	0.076	0.023*	0.016*	0.007*	0.129	n/a		
conifer	0.047*	0.151	0.184	0.311	0.175	0.001*	n/a	
HJ3	0.003*	0.016*	0.022*	0.048*	0.027*	<0.001*	0.999	n/a

*significant difference (*p*<0.05)

In terms of the change in SOC between 2008 and 2018 (Table 3.1.6), land use was the only significant factor [F(8,201)= 6.194, *p*<0.001].

Table 3.1.6. General linear model summary statistics within dominant land use categories for change in log transformed SOC (g kg^{-1}) to 20 cm depth.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	2.340[a]	22	0.106	6.283	0.000	0.407
Intercept	3.620	1	3.620	213.812	0.000	0.515
Land use	0.839	8	0.105	6.194	<0.001*	0.198
Soil series	0.282	10	0.028	1.665	0.091	0.077
Altitude	0.004	1	0.004	0.226	0.635	0.001
pH	0.011	1	0.011	0.661	0.417	0.003
Years land use	$3.147E^{-5}$	1	$3.147E^{-5}$	0.002	0.966	0.000
Aspect	0.053	1	0.053	3.140	0.078	0.015
Error	3.403	201	0.017			
Total	458.849	224				
Corrected Total	5.743	223				

[a]R Squared = 0.407 (Adjusted R Squared = 0.343); *significant difference (*p*<0.05)

Post hoc tests of SOC change (Table 3.1.7) indicate a significant difference between Rperm[marshy] and all other land uses, mainly due to the high level of SOC decline in

Rperm[marshy]. The decrease measured for Iperm and Rperm results in a significant difference in SOC change between these land uses and arable land.

Table 3.1.7. General linear model post-hoc Tukey HSD test for similarity in change in log transformed SOC (g kg^{-1}) to 20 cm depth between dominant land use categories present in 2018.

	arable	Itemp	Iperm	Rperm	Rperm_ marshy	Rperm_ remnant	conifer	HJ3
arable	n/a							
Itemp	1.000	n/a						
Iperm	0.009*	0.072	n/a					
Rperm	<0.001*	<0.001*	0.029	n/a				
Rperm_marshy	<0.001*	<0.001*	<0.001*	<0.001*	n/a			
Rperm_remnant	0.018*	0.026*	0.201	0.750	<0.001*	n/a		
conifer	1.000	1.000	0.978	0.588	<0.001*	0.204	n/a	
HJ3	0.984	0.974	0.615	0.133	<0.001*	0.045*	0.999	n/a

*significant difference ($p<0.05$) between years; OB2 excluded from post-hoc analysis due to one sample

Arable land (with options HJ3 and OB2 included separately) increased in SOC overall (Figure 3.1.1c) by a mean 0.39 g kg^{-1} soil (Table 3.1). Options HJ3 and OB2 represent options where a change in land use classification or a proportion of land use classification results on arable land. The remaining ES options represent a change in management practice i.e no change in land use classification but a change in the way that particular land use e.g. arable land is manged while staying as arable land. These options are analysed in section 3.1.2. An increase in SOC was observed in both HJ3 (7.12 g kg^{-1}) and OB2 (5.21 g kg^{-1}). Post-hoc tests indicated that these increases were not significantly different to that of arable land overall, in part due to the small sample sizes. Further, the baseline SOC in 2008 for option HJ3 was higher than the mean for arable land across the estate as a whole, therefore while the total SOC in 2018 was significantly greater, the increase was not. There is a significant difference observed when compared with individual land management practices on arable land upon disaggregation of the data (section 3.1.2). All samples taken on grassland declined (Figure 3.1.1c), this was most evident in the Rperm land use classification (-7.46 g kg^{-1}) and Rperm where marshy grassland (-17.29 g kg^{-1}) had been recorded by the Wallington Biological Survey (1999). The SOC in Itemp appeared relatively stable, declining by -0.04 g kg^{-1} while the mean SOC within the Iperm classification decreased by -4.62 g kg^{-1}.

Land use alone explains 19.8% of the variation within samples (Table 3.1.6). The main increase in SOC on arable land is associated with land use change, options HJ3 and the field margin of OB2, both of which are comparable to recently converted permanent grassland. The higher SOC values reported for grassland relative to arable land (Bell and Worrall, 2009; Bradley, 2005; Cantarello et al., 2011; Dyson et al., 2009; Panagos et al., 2013ab) suggest the potential to gain SOC where there is a change in land use of this nature (Brown et al., 2017), as required by options HJ3 and OB2. This was also predicted by Dawson and Smith (2007), Falloon et al. (2004), Ostle et al. (2009), Smith et al. (2000ab) and Warner et al. (2008; 2011b). An increase of 0.3 – 1.9 (mean 1.0) t C ha^{-1} yr^{-1} is reported in the literature, comparable to the 0.9 – 1.3 t C ha^{-1} yr^{-1} identified between 2008 and 2018 at Wallington.

Most permanent grassland classifications decline in SOC, such that in 2018 for the locations resampled, there is no longer a significant difference in SOC between this land use and that of arable land or Itemp. Arable land is subject to cultivation and this is attributed as the main cause for a lower SOC at equilibrium relative to permanent grassland (Bradley, 2005; Ostle et al., 2009; Smith et al., 2000ab). Although the 2008 data supported this assertion, it was no longer significantly different at Wallington in 2018. The permanent grassland options have not undergone a change in land use since 2008, which would have potentially accounted for any decline in SOC observed. Changes in management have occurred (section 3.1.2) but these would not, based on values in the published literature, be expected to result in declines of this magnitude. The exception is where grassland has been identified as marshy grassland or remnant unimproved acid grassland. Marshy grassland may indicate former wetland habitat that has been subject to agricultural improvement such as drainage. The draining of wetland is reported to decrease SOC on permanent grassland between -5.4 to -2.2 t C $ha^{-1}yr^{-1}$ (Evans et al., 2016; Ostle et al., 2009). These figures refer to deep peat and fen soils, the soil series considered here represent gley soils with shallower organic layers. Losses might be expected to be lower at Wallington relative to the figures of Evans et al. (2016) and Ostle et al. (2009) but this was not the case. Although the presence of marshy grassland may provide an explanation in part for the decline in SOC on Rperm, it does not explain the losses experienced on grassland elsewhere on the estate (section 3.1.2).

3.1.2. Land use scale: tenancy, management and ES option

The resampled locations classified within the land use categories of Arable, Itemp, Iperm and Rperm (section 3.1.1) in 2008 were analysed for changes in land use or management practice within the boundary of those classifications individually.

3.1.2.1. Arable land

The SOC (g kg^{-1}) for the arable land use category in the previous section but disaggregated by tenancy, management and option, is illustrated in Figures 3.1.2 a-c for 2008, 2018 and the difference in measured SOC between 2008 and 2018. Options HJ3 and OB2 are also included.

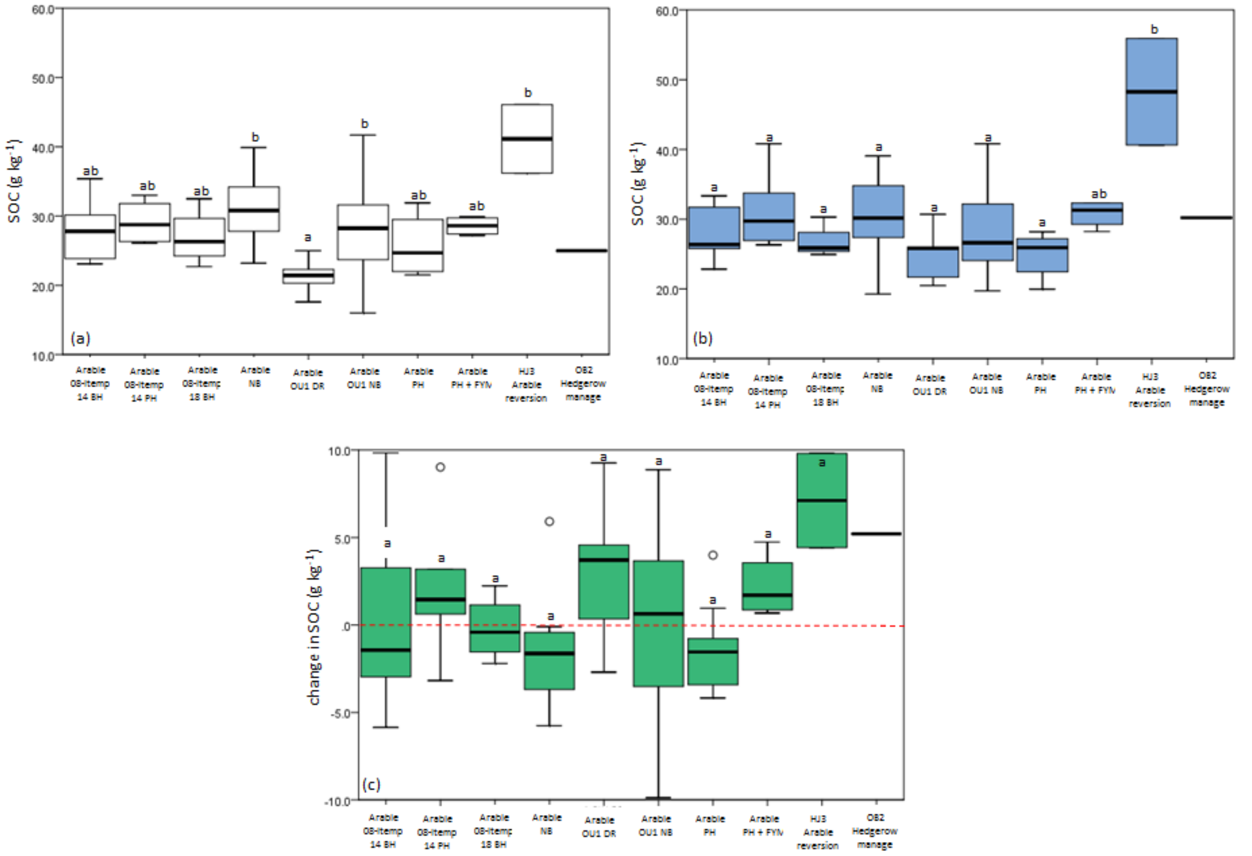

Figure 3.1.2. Boxplot of SOC (g kg^{-1}) on arable land in the resampled sites as measured (a) in 2008 by Bell (2011), (b) in 2018 and (c) change 2008-2018 (red dashed line indicates zero change in SOC). Data points with different letters indicate a significant (*p*<0.05) difference. Acronyms: A-08_Itp-14-BH – arable land converted to Itemp in 2014 on Broomhouse; A-08_Itp-18-BH – arable land converted to Itemp in 2018 on Broomhouse; A-NB – arable on Newbiggin counterfactual 2; A-OU1-DR – arable option OU1 on Donkin Rigg; A-OU1-NB – arable option OU1 on Newbiggin; A-PH – arable on Prior Hall counterfactual 1; A-PH-FYM - arable on Prior Hall + farmyard manure.

In addition to option HJ3 the other land use change on arable land was conversion to Itemp in 2014 on the Prior Hall tenancy (A-08_Itp-14-PH) and former Broomhouse tenancy (A-08_Itp-14-BH). The key management variables with the potential to effect SOC for each scenario on land classed as arable in 2008 are summarised in Table 3.1.8.

Table 3.1.8. Key management variables for management scenarios on land classified as arable on the Wallington Estate in 2008.

Management / option	Tillage + frequency	Ley (% rotation)	Organic fertiliser	Crop residue incorporation	Grazing
A-NB-CF2	1 (20cm)	1.5 year grass / clover ley (38%)	0	stubble	sheep (ley)
A-OU1-DR	1 (20cm)	2 – 3 year grass / clover / lucerne ley (50 – 60%)	25 t FYM	stubble	sheep (ley)

A-OU1-NB	1 (20cm)	1.5 year grass / clover ley (38%)	[b]2 t broiler manure + straw	stubble	sheep (ley)
A-PH-CF1	1 (20cm)	[a]2 – 5 year grass / clover ley (15 – 42%)	0	stubble	sheep (ley)
A-PH-FYM	1 (20cm)	[a]2 – 5 year grass / clover ley (15 – 42%)	15-20 t FYM biennially	stubble	sheep (ley)
A-08_ltp-14-BH	5 (20cm)	0	25 t FYM biennially	0	sheep
A-08_ltp-14-PH	5 (20cm)	0	15-20 t FYM biennially	0	sheep
A-08_ltp-18-BH	5 (20cm)	0	25 t FYM biennially	0	sheep
HJ3	0	0	0	0	0
OB2	0	0	0	0	0

Note: grazing of leys by sheep during the summer; [a]included instead of winter oilseed rape in alternate rotations; [b]when available (not annually)

A GLM analysis of total SOC measured in 2008 and 2018 using an identical approach to that described in section 3.1.1 but applied to arable land disaggregated by tenancy, and management and ES option identified that management practice was a significant factor [F(9,67)=3.333, *p*=0.003] and [F(9,67)=3.267, *p*=0.002] during both years (Table 3.1.9).

Table 3.1.9. General linear model summary statistics within arable land use categories for log transformed SOC (g kg^{-1}) to 20 cm depth measured in 2018.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	0.297[a]	19	0.016	3.395	0.001	0.491
Intercept	0.148	1	0.148	32.168	0.001	0.324
Management practice	0.135	9	0.015	3.267	0.002*	0.305
Soil series	0.047	6	0.008	1.694	0.136	0.132
Altitude	0.001	1	0.001	0.167	0.684	0.002
pH	0.000	1	0.000	0.047	0.830	0.001
Years land use	0.010	1	0.010	2.083	0.154	0.030
Aspect	0.023	1	0.023	5.051	0.028*	0.070
Error	0.309	67	0.005			
Total	182.207	87				
Corrected Total	0.606	86				

[a]R Squared = 0.491 (Adjusted R Squared = 0.346); *denotes significant ($p<0.05$)

The same GLM analysis of SOC change between 2008 and 2018 did not identify management [F(9,64)=1.914, *p*=0.066] as being significant (Table 3.1.10). Those management practice scenarios with higher SOC in 2018, option HJ3 in particular, did not increase sufficiently during the 10 year period to be classed as significant by the GLM analysis, reflecting a pre-existing higher baseline SOC in 2008. Further, the increase in SOC where grass / clover leys were integrated within the rotation in scenario A-OU1-DR eliminated the significant difference between this and the arable land on the Newbiggen tenancy in 2018 (Figure 3.1.2b).

Table 3.1.10. General linear model summary statistics within arable land use categories for change in log transformed SOC (g kg^{-1}) to 20 cm depth.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	0.101[a]	19	0.005	1.722	0.055	0.338
Intercept	0.230	1	0.230	74.560	0	0.538
Management practice	0.053	9	0.006	1.914	0.066	0.212
Soil series	0.040	6	0.007	2.188	0.056	0.170
Altitude	0	1	0	0.055	0.815	0.001
pH change	0.001	1	0.001	0.252	0.617	0.004
Years land use	0	1	0	0.096	0.758	0.001
Aspect	0.001	1	0.001	0.310	0.580	0.005
Error	0.197	64	0.003			
Total	188.618	84				
Corrected Total	0.298	83				

[a] R Squared = 0.338 (Adjusted R Squared = 0.142); *denotes significant ($p<0.05$)

A pairwise comparison of each management scenario individually with the two counterfactual scenarios using an independent samples t-test identified a significant difference where a grass/clover ley is included in the rotation (A-OU1-DR: $p=0.003$ and $p=0.005$), the addition of 15 - 20 t ha^{-1} FYM biennially (A-PH-FYM: $p=0.029$) and the conversion to permanent grass as option HJ3 ($p=0.004$ and $p=0.013$) (Table 3.1.11).

Table 3.1.11. Summary statistics from an independent samples t-test comparing arable land management practice categories present in 2018 with arable counterfactual 1 and counterfactual 2 scenarios for change in log transformed SOC (g kg^{-1}) to 20 cm depth.

	A-PH-CF1			A-NB-CF2		
	t	df	Sig (2-tailed)	t	df	Sig (2-tailed)
A-08_ltp-14-BH	[a]0.662	8.016	0.526	0.743	14	0.470
A-08_ltp-14-PH	2.076	13	0.058	1.910	13	0.078
A-08_ltp-18-BH	0.873	11	0.401	0.785	11	0.449
A-NB-CF2	-0.109	16	0.915	n/a	n/a	n/a
A-OU1-DR	3.329	20	0.003*	3.125	20	0.005*
A-OU1-NB	[a]1.099	25.183	0.282	0.863	39	0.393
A-PH-CF1	n/a	n/a	n/a	-0.109	16	0.915
A-PH-FYM	2.517	11	0.029*	2.095	11	0.060
HJ3	3.768	9	0.004*	3.076	9	0.013*
OB2	2.306	8	0.050	1.834	8	0.104

*significant difference ($p<0.05$) between years; [a]unequal variances assumed as indicated by Levene's test for equality of means

The significant difference ($p<0.05$) between A-PH-CF1 and the addition of FYM but not with A-NB-CF2 and FYM is a result of the higher SEM in A-NB-CF2 (Table 3.12). Moxley et al. (2014) evaluate four key themes associated with management practice on arable land that may impact SOC: the incorporation of crop residues, the frequency of tillage, the application of inorganic fertiliser and the application of manure. The frequency of tillage and the application of manure are variables considered at Wallington that, according to Table 3.1.11, are a significant factor. The incorporation of residues are evaluated as part of the arable management on the Wimpole Estate in section 3.2.

Table 3.1.12. Mean change in SOC (t C ha^{-1}) for management on arable land to 20 cm depth (text in italics and parentheses denotes g kg^{-1}).

Management / option	N	Mean 2018	Mean change 2008 - 2018	Standard error of mean change	Mean change yr^{-1}	Mean change yr^{-1} relative to CF
A-08_Itp-14-BH	7	56.19 *(28.21)*	0.56 *(0.45)*	4.38	0.06	0.33
A-08_Itp-14-PH	6	64.92 *(31.21)*	4.35 *(2.09)*	3.42	0.44	0.71
A-08_Itp-18-BH	4	53.15 *(26.75)*	-0.42 *(-0.20)*	1.79	-0.04	0.23
A-NB-CF2	9	58.43 *(30.12)*	-2.82 *(-1.47)*	2.17	-0.28	-0.01
A-OU1-DR	13	50.67 *(24.56)*	5.77 *(2.83)*	1.81	0.58	0.85*
A-OU1-NB	32	53.09 *(28.51)*	0.35 *(0.19)*	1.57	0.04	0.31
A-PH-CF1	9	47.39 *(24.50)*	-2.71 *(-1.38)*	1.65	-0.27	0.01
A-PH-FYM	4	64.03 *(30.78)*	4.59 *(2.21)*	1.91	0.46	0.74*
HJ3	2	91.02 *(48.27)*	13.43 *(7.12)*	5.11	1.34	1.62*
OB2	1	50.75 *(30.21)*	8.75 *(5.21)*	0.00	0.87	1.15

*significant difference (p<0.05) from counterfactual scenarios as indicated by an independent samples t-test

The mean SOC increase of 0.06 – 0.44 t C ha^{-1} yr^{-1} (scenarios A-08_Itp-14-BH and A-08_Itp-14-PH in Table 3.1.12) for arable land converted to Itemp in 2014 was not significantly different to the counterfactual scenarios and lower than the 1.44 t C ha^{-1} yr^{-1} of Vleeshouwers and Verhagen (2002) (cited Lugato *et al.*, 2014b). The scenario A-08_Itp-18-BH recently converted to Itemp in 2018 has been excluded. The figure from Vleeshouwers and Verhagen (2002) refers to conversion to permanent grassland rather than temporary grassland. Warner et al. (2011a) estimate an increase of 0.35 t C ha^{-1} yr^{-1} on temporary grassland, adjusting the increase in response to the cultivation every five years.

On arable land that remains as arable land the two counterfactual scenarios decline in SOC (-2.82 to -2.71 t C ha^{-1}). An increase in the mean SOC is observed on arable land converted to organic management where grass / clover leys have been introduced (A-OU1-DR) and where FYM is applied biennially (A-FYM-PH). The presence of winter oilseed rape in November 2018 in the field where FYM is applied indicates a minimum 4 years since the previous grass / clover ley was removed from this parcel. A pairwise comparison using an independent samples t-test identified a significant difference (p=0.029) between the addition of 15 – 20 t ha^{-1} FYM biennially (A-FYM-PH) and counterfactual 1 (A-PH-CF1). The SOC increased by a mean 0.46 t C ha^{-1} yr^{-1} (a mean 0.74 t C ha^{-1} yr^{-1} relative to the counterfactual scenarios), 0.37 t C ha^{-1} yr^{-1} is reported by Ostle et al. (2009) for annual applications.

All arable land on the Wallington Estate, including both counterfactual scenarios, contain a grass/clover ley in the rotation, varying from 18 months (scenarios A-NB and A-OU1-NB), 2-3 years (A-OU1-DR) to 3-5 years (A-PH). The inclusion of a grass/clover ley is reported to increase the SOC of arable land by 0.26 – 0.54 t C ha^{-1} yr^{-1} in the UK, through a decrease in the frequency of cultivation (Dawson and Smith, 2007; Ostle et al., 2009; Smith et al., 2000ab). Although included within the two counterfactual scenarios where management has not changed since 2008, the SOC has declined. There is no obvious explanation for this decline as it would be expected to have remained relatively stable. The sequence in the rotation in which sampling was conducted is likely to be different between 2008 and 2018, this data is not however available for 2008 for a comparison to be made.

The impact of introducing this management can be measured more directly in the A-OU1-DR scenario that implemented a 2-3 year grass/clover ley as a replacement source of nitrogen from inorganic fertiliser upon conversion to organic land post 2008. Both the pre-organic and current organic management regimes applied FYM in equal quantities, the method and timing of application were therefore excluded as variables. The SOC increased by a mean 0.58 t C ha^{-1} yr^{-1} on this tenancy, towards the higher end of the range cited in the published literature. Although the mean change was comparable to values in the published literature, the GLM analysis did not identify the SOC as being significantly different from the counterfactual scenarios. A pairwise comparison using an independent samples t-test identified a significant difference between A-OU1-DR and both counterfactual scenarios, A-PH-CF1 (p=0.003) and A-NB-CF2 (p=0.005).

The A-NB-CF2 and A-OU1-NB scenarios have the same rotation, they differ in terms of supplementary nutrient application. Scenario A-NB applies ammonium nitrate, A-OU1-NB applies broiler manure with straw. The mean change in A-OU1-NB is small, 0.04 t C ha^{-1} yr^{-1} but represents an increase of 0.31 t C ha^{-1} yr^{-1} when compared with the A-NB scenario, albeit not significantly different. Existing data on the impact of broiler manure is limited although the straw component is likely to be the main contributing factor to any increase in SOC (Ostle et al., 2009; Smith et al., 2000ab). For the incorporation of straw Ostle et al. (2009) and Vleeshouwers and Verhagen (2002) cite values of 0.15 – 0.69 t C ha^{-1} yr^{-1} with a UK mean of 0.4 t C ha^{-1} yr^{-1}. The increase relative to the A-NB counterfactual (0.31 t C ha^{-1} yr^{-1}) is within this range.

3.1.2.2. Temporary grassland

The SOC (g kg^{-1}) for Itemp disaggregated by tenancy, management and option is illustrated in Figures 3.1.3 a-c for 2008, 2018 and difference in measured SOC between 2008 and 2018.

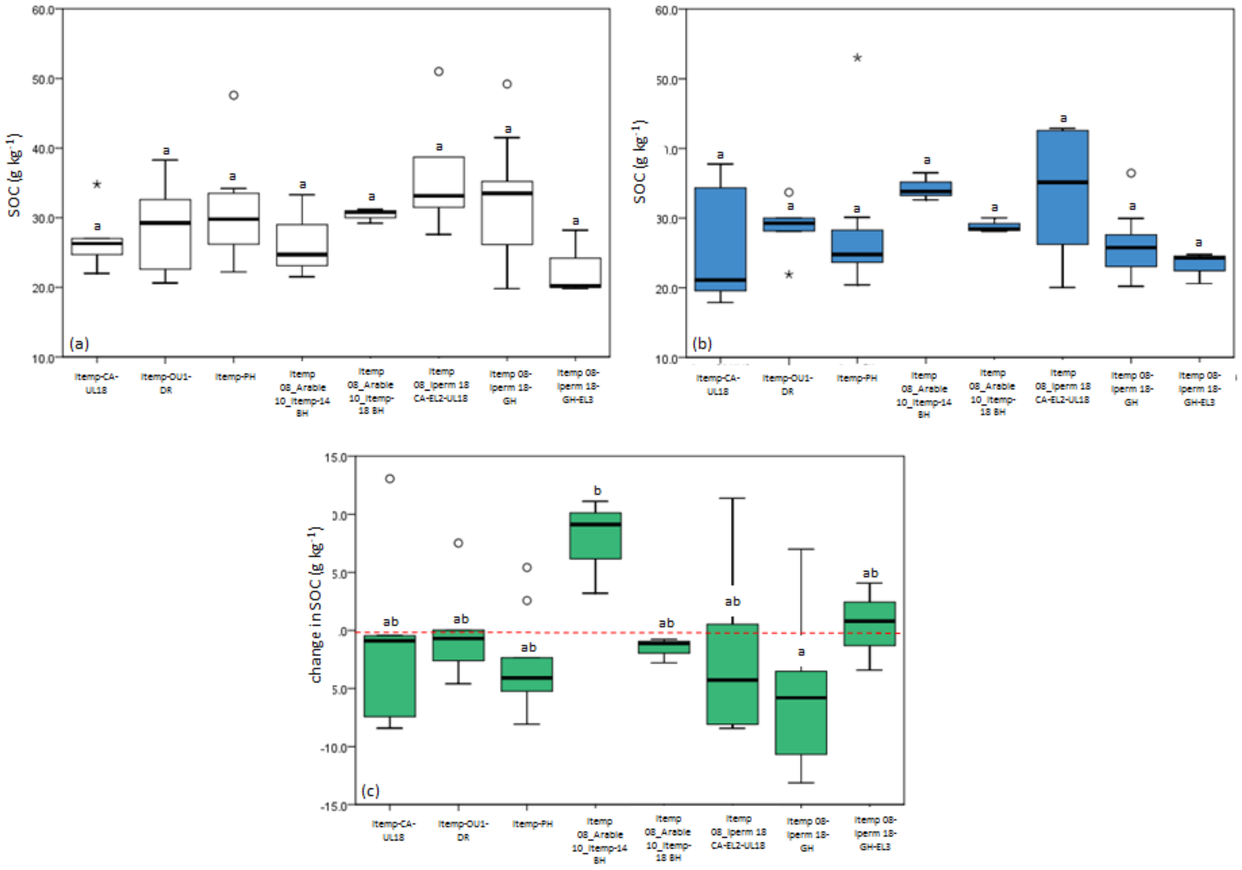

Figure 3.1.3. Boxplot of SOC (g kg^{-1}) on Itemp in the resampled sites as measured (a) in 2008 by Bell (2011), (b) in 2018 and (c) change 2008-2018 (red dashed line indicates zero change in SOC). Data points with different letters indicate a significant (*p*<0.05) difference. Acronyms: CA – Catcherside; DR – Donkin Rigg; PH – Prior Hall; BH – Broomhouse; GH – Gallows Hill; Itemp 08-Arable 10_Itemp 14 – land uses in 2008, 2010, 2014; EL2, EL3, UL18, OU1 – ES option

According to the GLM analysis there is no significant difference in SOC between scenarios grouped by tenancy, option and management on Itemp 2008 [F(7, 29)= 1.236, *p*=0.316], 2018 [F(7, 29)=1.451, *p*=0.224] or for the change in SOC [F(7, 29)= 0.714, *p*=0.660].

Table 3.1.13. General linear model summary statistics within Itemp land use categories for change in log transformed SOC (g kg^{-1}) to 20 cm depth.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	0.128^{a}	15	0.009	0.946	0.530	0.329
Intercept	0.058	1	0.058	6.447	0.017	0.182
Management practice	0.045	7	0.006	0.714	0.660	0.147

Soil series	0.010	4	0.002	0.266	0.897	0.035
Altitude	0.001	1	0.001	0.078	0.782	0.003
pH change	0.000	1	0.000	0.026	0.872	0.001
Years land use	5.392E^{-07}	1	5.392E^{-07}	0.000	0.994	0.000
Aspect	0.001	1	0.001	0.140	0.711	0.005
Error	0.263	29	0.009			
Total	95.351	45				
Corrected Total	0.391	44				

[a]R Squared = 0.329 (Adjusted R Squared = -0.019); *denotes significant (p<0.05)

Post-hoc tests via a Tukey HSD identified a significant increase (p=0.19) on Itemp that had undergone conversion to arable land in 2010 then conversion back to Itemp in 2014 (Itp-08_A-10_Itp-14-BH). This was also noted by an independent samples t-test (Table 3.1.14). The t-test did not identify any significant difference between ES options (OU1, EL2, EL3 and UL18) and management on Itemp relative to the counterfactual scenario (Itemp-PH-CF).

Table 3.1.14. Summary statistics from an independent samples t-test comparing improved temporary grassland management practice categories present in 2018 with the counterfactual scenario (Itemp-PH-CF) for change in log transformed SOC (g kg-1) to 20 cm depth.

	Itemp-PH-CF		
	t	df	Sig (2-tailed)
Itemp-CA-UL18	[a]0.268	10.175	0.794
Itemp-OU1-DR	1.161	12	0.268
Itemp-PH-CF	n/a	n/a	n/a
Itp-08_A-10_Itp-14-BH	3.543	10	0.005*
Itp-08_A-10_Itp-18-BH	0.592	10	0.567
Itp-08-Ip-10-CA-EL2-UL18	0.052	10	0.960
Itp-08-Ip-18-GH	-1.569	18	0.134
Itp-08-Ip-18-GH-EL3	1.227	10	0.248

*significant difference (p<0.05) between years; [a]unequal variances assumed as indicated by Levene's test for equality of means

The counterfactual (Itemp-PH-CF) decreased by -5.44 t C ha^{-1} during the 10 year period under assessment (Table 3.1.15), more than most other management scenarios on Itemp.

Table 3.1.15. Change in SOC (t C ha^{-1}) for management on Itemp to 20 cm depth (text in italics and parentheses denotes g kg^{-1}).

Management / option	**N**	**Mean 2018**	**Mean change 2008 - 2018**	**Standard error of mean change**	**Mean change yr^{-1}**	**Mean change yr^{-1} relative to CF1**
Itemp-CA-UL18	8	59.88 *(30.29)*	-2.13 *(-1.16)*	6.18	-0.21	0.33
Itemp-OU1-DR	5	57.36 *(28.60)*	-0.05 *(-0.07)*	4.26	-0.01	0.54
Itemp-PH-CF	9	54.59 *(28.13)*	-5.44 *(-2.77)*	2.73	-0.54	n/a
Itp-08_A-10_Itp-14-BH	3	65.20 *(34.32)*	14.85 *(7.82)*	4.52	1.49	2.03*
Itp-08_A-10_Itp-18-BH	3	59.99 *(28.84)*	-3.24 *(-1.56)*	1.30	-0.32	0.22
Itp-08-Ip-10-CA-EL2-UL18	3	57.19 *(30.10)*	-5.06 *(-2.66)*	4.72	-0.51	0.04
Itp-08-Ip-18-GH	11	52.26 *(25.98)*	-12.25 *(-6.08)*	3.71	-1.22	-0.68
Itp-08-Ip-18-GH-EL3	3	45.93 *(23.22)*	0.82 *(0.49)*	4.24	0.08	0.63

*significant difference (p<0.05)

The Itemp placed into management under options EL2 (Itp-08-Ip-10-CA-EL2-UL18) or EL3 (Itp-08-Ip-18-GH-EL3) requires that no further cultivation and reseeding is undertaken, modifying the land use category to Iperm. Restrictions are also placed on the quantity or type of supplementary nutrients that may be applied. Relative to the counterfactual scenario, there is a mean increase of 0.04 and 0.68 t C $ha^{-1}yr^{-1}$ for options EL2 and EL3 on Itemp respectively. Due to the high variability within the data, the increase is not significant. Conversion from Itemp to Iperm yields variation between scenarios, from -12.25 to 0.63 t C $ha^{-1}yr^{-1}$. In reference to the published literature, eliminating a periodic cultivation every five years would be expected to increase the SOC (Ostle et al., 2009; Smith et al., 2000ab; Warner et al., 2008; 2011ab). This was not the case. With respect to the Itp-08-Ip-18-GH and Itp-08-Ip-18-GH-EL3 scenarios although classed as Itemp in 2008, much of this land had not been cultivated for over 20 years. A parcel to the north of the tenancy representing three of the sample locations was previously reseeded in 2009. The SOC for Itemp on this tenancy is lower than for most other scenarios within this land use. This area of the tenancy was noted to be below the mean for the Wallington Estate in 2008 (Bell, 2011; Warner et al., 2011a). Data relating to SOC on temporary grassland in the published literature are limited. Rutledge *et al.* (2015) in New Zealand note declines of 1.0 – 2.0 t C ha^{-1} within the first three months post cultivation of grassland, before CO_2 emission ceases and sequestration at rates of 1.65 t C ha^{-1} yr^{-1} begins. There is however no period over which this rate of accumulation occurs specified. The scenario Itemp-CA-UL18 consists of two parcels cultivated in 2016 and 2017, one and two years prior to resampling. The decline in SOC could be attributed to the relatively recent cultivation. This does not however explain the decrease in the counterfactual scenario or the somewhat dramatic decline on Itp-08-Ip-18-GH where conversion to Iperm had occurred over 20 years previously.

3.1.2.3. Improved permanent grassland

Improved permanent grassland disaggregated by tenancy, management and option the SOC (g kg^{-1}) in 2008, 2018 and the difference in measured SOC between 2008 and 2018 is illustrated in Figures 3.1.4 a-c.

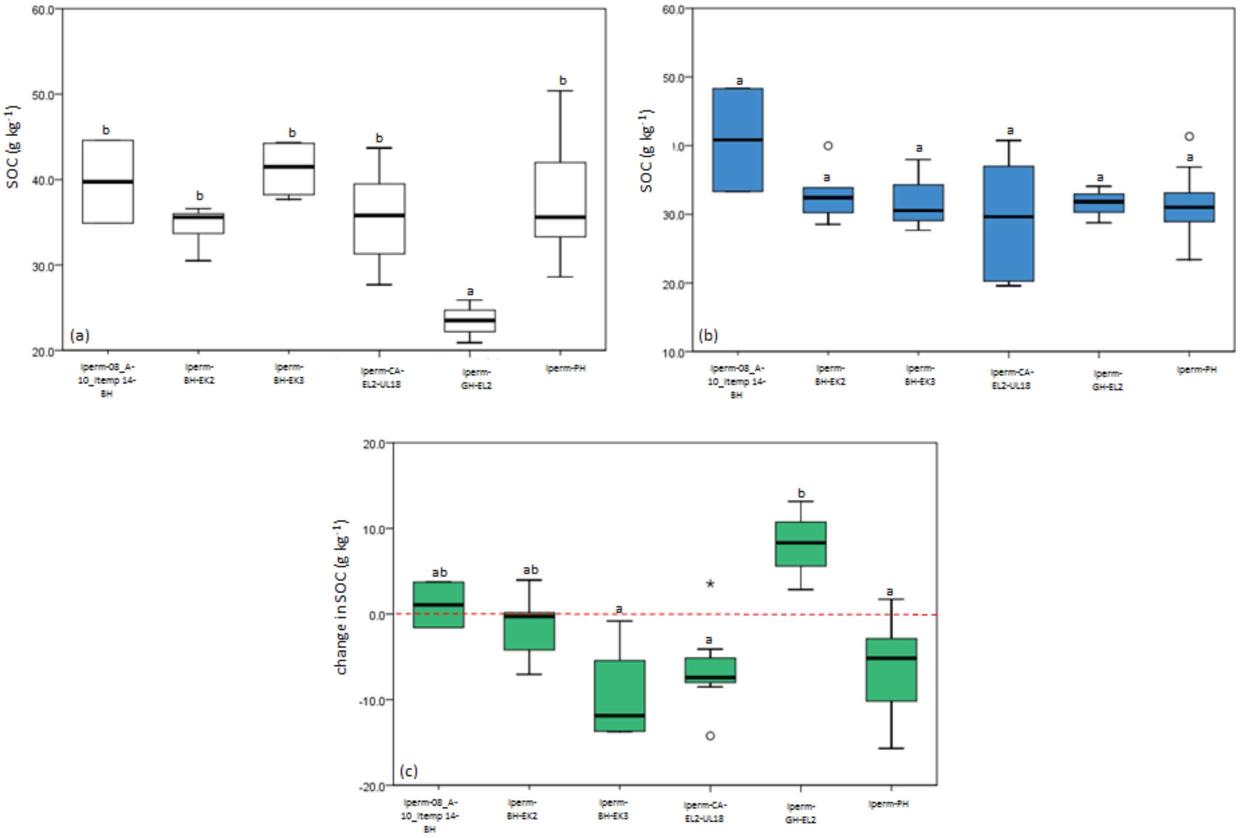

Figure 3.1.4. Boxplot of SOC (g kg^{-1}) on Iperm in the resampled sites as measured (a) in 2008 by Bell (2011), (b) in 2018 and (c) change 2008-2018 (red dashed line indicates zero change in SOC). Data points with different letters indicate a significant (*p*<0.05) difference. Acronyms: BH – Broomhouse; CA – Catcherside; GH – Gallows Hill; PH – Prior Hall; Iperm-08_A-10_Itemp-14 land use in 2008, 2010, 2014; ES options EK2, EK3, EL2, UL18.

The GLM analysis found a significant difference in 2008 [F(5, 31)= 3.295, *p*=0.017] but no significance difference in 2018 [F(5, 30)= 0.606, *p*=0.696] or with respect to the change in SOC for different management scenarios on Iperm [F(5, 30)= 2.209, *p*=0.079] (Table 3.1.16).

Table 3.1.16. General linear model summary statistics within Iperm land use categories for change in log transformed SOC (g kg^{-1}) to 20 cm depth.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	0.216[a]	12	0.018	2.071	0.052	0.453
Intercept	0.207	1	0.207	23.782	<0.001	0.442
Management practice	0.096	5	0.019	2.209	0.079	0.269
Soil series	0.017	3	0.006	0.652	0.588	0.061

Altitude	0.012	1	0.012	1.362	0.252	0.043
pH change	0.008	1	0.008	0.872	0.358	0.028
Years land use	0.007	1	0.007	0.858	0.362	0.028
Aspect	0.001	1	0.001	0.149	0.702	0.005
Error	0.261	30	0.009			
Total	85.521	43				
Corrected Total	0.477	42				

[a]R Squared = 0.453 (Adjusted R Squared = 0.234); *denotes significant (*p*<0.05)

The mean SOC of Iperm in 2018 is just above 30 g C kg^{-1} for most of the Iperm scenarios (Figure 3.1.4b), comparable to the broad Europe scale predictions of Brogniez et al. (2015) on mineral soils for the region. Post-hoc tests (Tukey HSD) identified a significant difference between scenario Iperm-GH-EL2 and scenarios Iperm-BH-EK3, Iperm-CA-EL2-UL18 and Iperm-PH-CF. This was confirmed by an independent samples t-test that compared each scenario pairwise with the counterfactual Iperm-PH-CF scenario (Table 3.1.17).

Table 3.1.17. Summary statistics from an independent samples t-test comparing improved permanent grassland management practice categories present in 2018 with the counterfactual scenario (Iperm-PH-CF) for change in log transformed SOC (g kg-1) to 20 cm depth.

	Iperm-PH-CF		
	t	df	Sig (2-tailed)
Ip-08_A-10_Itp-14-BH	1.858	22	0.077
Iperm-BH-EK2	1.961	25	0.061
Iperm-BH-EK3	-1.222	24	0.233
Iperm-CA-EL2-UL18	0.040	27	0.968
Iperm-GH-EL2	3.815	23	0.001*
Iperm-PH-CF	n/a	n/a	n/a

*significant difference (*p*<0.05); [a]unequal variances assumed as indicated by Levene's test for equality of means

The increase noted for Iperm-GH-EL2 (16.73 t C ha^{-1} – Table 3.1.18) coincides with a low baseline SOC in 2008 (Figure 3.1.4a) relative to other areas of Iperm resampled.

Table 3.1.18. Change in SOC (t C ha^{-1}) for management on improved permanent grassland to 20 cm depth (text in italics and parentheses denotes g kg^{-1}).

Management / option	N	Mean 2018	Mean change 2008 - 2018	Standard error of mean change	Mean change yr^{-1}	Mean change yr^{-1} relative to CF1
Ip-08_A-10_Itp-14-BH	2	84.92 *(40.83)*	2.24 *(1.08)*	5.52	0.22	1.50
Iperm-BH-EK2	5	68.66 *(33.01)*	-3.06 *(-1.47)*	3.96	-0.31	0.97
Iperm-BH-EK3	4	60.20 *(31.68)*	-18.18 *(-9.57)*	5.78	-1.82	-0.54
Iperm-CA-EL2-UL18	7	56.01 *(29.21)*	-12.40 *(-6.34)*	4.09	-1.24	0.04
Iperm-GH-EL2	3	65.00 *(31.56)*	16.73 *(8.12)*	6.19	1.67	2.95*
Iperm-PH-CF	22	62.13 *(31.23)*	-12.78 *(-6.43)*	2.06	-1.28	n/a

*significant difference (*p*<0.05)

The counterfactual scenario Iperm-PH decreased by a mean -12.78 t C ha^{-1} (Table 3.1.18). As a result most scenarios increased in SOC on Iperm relative to the counterfactual however a decline was evident for most management scenarios overall. Warner et al. (2008; 2011a) did not identify changes in SOC for ES options on grassland that remained within the same land use classification due to the limited availability of data. This included options that placed restrictions on fertiliser application (EL2, EL3, EK2 and EK3) or introduced mixed grazing (UL18). Grassland management practices cited in the published literature to potentially improve SOC accumulation rates include liming and appropriate supplementary nutrition (Fornara *et al.*, 2011; 2013) and avoidance of damage to the soil structure by livestock (Stockman *et al.*, 2013). Lime application is not permitted in options within the ES scheme, most of these fall within the Rperm classification (section 3.2.3.4). Over-grazing is cited as detrimental to SOC due to the excess removal of biomass, coupled with an increased risk of topsoil compaction and, because of reduced water infiltration capacity, water erosion (Conant *et al.*, 2001; 2005; Freibauer *et al.*, 2004; Louwagie *et al.*, 2009). Stockmann *et al.* (2013) assign 0.02 – 0.4 t C ha^{-1} yr^{-1} to ‘improved grazing’, grazing that does not cause land degradation through excessive stocking rates. Ostle et al. (2009) reports low to moderate stocking rates of 0.4 – 0.8 livestock units per ha increases SOC by 0.05 t C ha^{-1} yr^{-1}. Subtle changes in SOC such as this are however difficult to detect at the landscape scale and determine with confidence. The same is applicable to the low rates of fertiliser application (<50 kg N ha^{-1}) also reported by by Ostle et al. (2009) to increase SOC by 0.08 t C ha^{-1} yr^{-1}.

Several authors (for example Bell, 2011; Moxley et al., 2014; Smith et al., 2008a) highlight inconsistencies between studies assessing the impact of stocking rates and supplementary nutrient application on SOC on grassland such that no clear conclusions are evident. Bell (2011) reports no relationship between livestock type, stocking rate or grazing regime at Wallington. The presence of legumes within the grass sward and avoidance of soil compaction are two factors reported as being conducive with SOC accumulation not accounted for in the current assessment. On Iperm clover may be present but this will not be specifically sown such as on Itemp or in a ley on arable land. Compaction may be present in association with high stocking rates however this is subject to within field variation, associated with areas of livestock congregation such as feeding rings or gateways. While no samples were taken adjacent to gateways, the past siting of feeding rings could not be identified.

3.2.3.4. Rough permanent grassland

The greatest decrease in SOC of the land use categories analysed was on Rperm and Rperm[marshy] (Figure 3.1.5). An increase was observed for option EL3 on the Gallows Hill tenancy and OU1 on Newbiggin for which the GLM analysis was also significant relative to the declines on Rperm[marshy]. The SOC for the Rperm-GH-EL2-EL3 scenario during the initial sampling in 2008 was low (Figure 3.1.5a). In 2018, the SOC is comparable for this scenario to that of most other Rperm scenarios (Figure 3.1.5b) suggesting that the increase is mainly due to the initial low baseline. Most scenarios on Rperm have a mean SOC between 25 and 30 g C kg^{-1} in 2018.

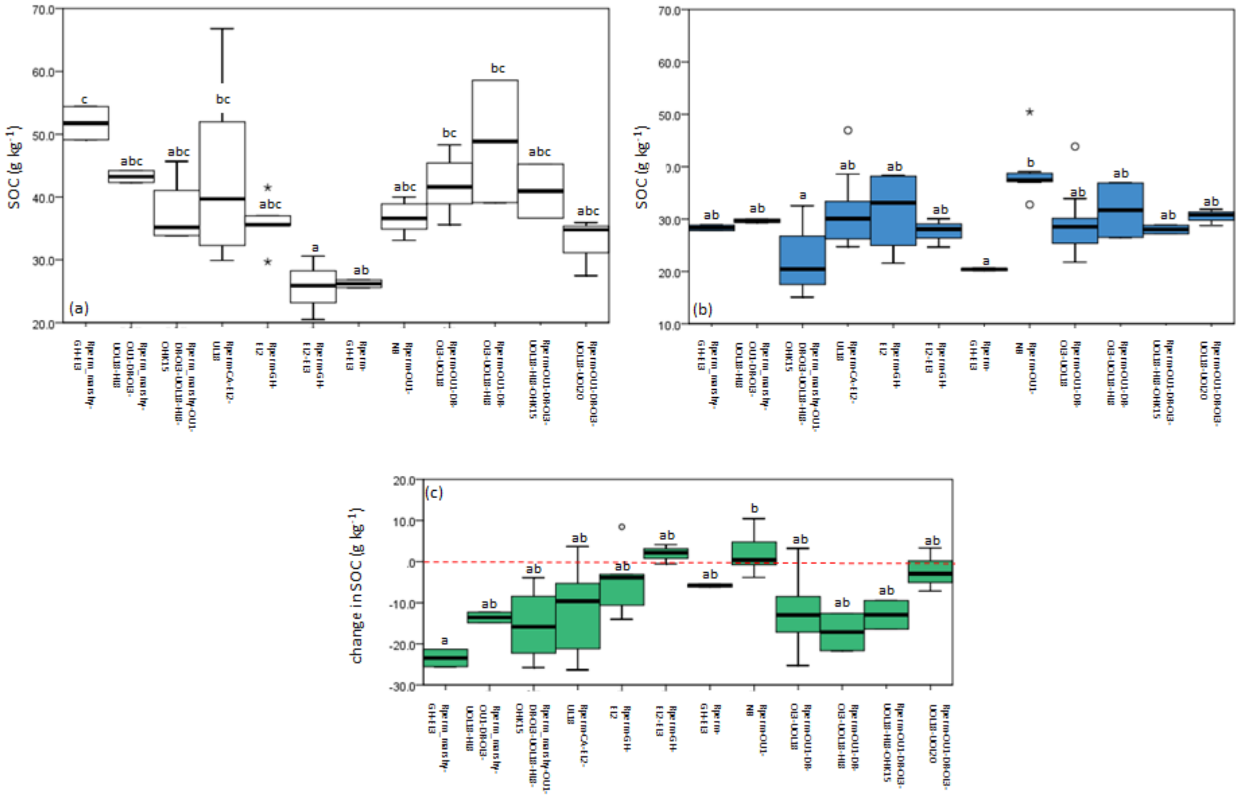

Figure 3.1.5. Boxplot of SOC (g kg-1) on Rperm in the resampled sites as measured (a) in 2008 by Bell (2011), (b) in 2018 and (c) change 2008-2018 (red dashed line indicates zero change in SOC). Data points with different letters indicate a significant ($p<0.05$) difference. Acronyms: GH – Gallows Hill, CA – Catcherside, DR – Donkin Rigg; ES options OU1, OL3, UOL18, HL8, OHK15, EL2, UL18, UOL20.

The options on Rperm do not instigate any form of land use change, rather a change in management. The GLM analysis of SOC identified a significant difference between management scenarios in 2008 on Rperm [F(9,31)=4.869, *p*<0.001] and for change in SOC [F(9,31)=2.792, *p*=0.016] (Table 3.1.19) but not in 2018 [F(9,31)=1.595, *p*=0.158].

Table 3.1.19. General linear model summary statistics within Rperm land use categories for change in log transformed SOC (g kg-1) to 20 cm depth.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	1.851[a]	19	0.097	2.434	0.013	0.599
Intercept	0.000	0	.	.	.	0.000
Management practice	1.006	9	0.112	2.792	0.016*	0.448
Soil series	0.305	5	0.061	1.523	0.211	0.197
Altitude	0.092	1	0.092	2.295	0.140	0.069
pH change	0.224	1	0.224	5.593	0.024*	0.153
Years land use	0.000	0	.	.	.	0.000
Aspect	0.008	1	0.008	0.192	0.664	0.006
Error	1.241	31	0.040			

Total	87.285	51
Corrected Total	3.092	50

[a]R Squared = 0.599 (Adjusted R Squared = 0.353); *significant ($p<0.05$)

Post-hoc testing with a Tukey HSD test (Table 3.1.20) indicated a significant difference between the change in SOC identified for both Rperm-NB and Rperm_marshy-GH-EL3 (P = 0.014) with borderline non-significance between Rperm-GH-EL2-EL3 and Rperm_marshy-GH-EL3 (*p*=0.05).

Table 3.1.20. General linear model summary post-hoc test (Tukey HSD) applied to change in log transformed SOC (g kg^{-1}) to 20 cm depth for management on rough permanent grassland present in 2018.

		1	2	3	4	5	6	7	8	9	10	11
Rperm_marshy-GH-EL3	1	n/a										
Rperm_marshy-OU1-DR-OL3-UOL18-HL8	2	0.795	n/a									
Rperm_marshy-OU1-DR-OL3-UOL18-HL8-OHK15	3	0.943	1.000	n/a								
Rperm-CA-EL2-UL18	4	0.567	1.000	1.000	n/a							
Rperm-GH-EL2	5	0.113	0.998	0.690	0.850	n/a						
Rperm-GH-EL2-EL3	6	0.050	0.943	0.382	0.515	1.000	n/a					
Rperm-GH-EL3	7	0.313	1.000	0.920	0.987	1.000	1.000	n/a				
Rperm-OU1-NB	8	0.014*	0.874	0.140	0.130	0.998	1.000	1.000	n/a			
Rperm-OU1-DR-OL3-UOL18	9	0.534	1.000	1.000	1.000	0.900	0.583	0.992	0.183	n/a		
Rperm-OU1-DR-OL3-UOL18-HL8	10	0.983	1.000	1.000	1.000	0.882	0.619	0.963	0.428	1.000	n/a	
Rperm-OU1-DR-OL3-UOL18-HL8-OHK15	11	0.772	1.000	1.000	1.000	0.999	0.954	1.000	0.896	1.000	1.000	n/a
Rperm-OU1-DR-OL3-UOL18-UOL20	12	0.111	0.991	0.639	0.809	1.000	1.000	1.000	1.000	0.857	0.821	0.994

*significant difference ($p<0.05$) between years

The mean change and change per year as t C ha^{-1} and g kg^{-1} are summarised in Table 3.1.21.

Table 3.1.21. Change in SOC (t C ha^{-1}) for management on Rperm to 20 cm depth (text in italics and parentheses denotes g kg^{-1}).

Management / option	N	Mean 2018	Mean change 2008 - 2018	Standard error of mean change	Mean change yr^{-1}
Rperm_marshy-GH-EL3	2	53.80 *(28.31)*	-44.53 *(-23.44)*	4.04	-4.45
Rperm_marshy-OU1-DR-OL3-UOL18	2	59.08 *(29.67)*	-26.91 *(-13.58)*	1.32	-2.69
Rperm_marshy-OU1-DR-OL3-UOL18-HL8-OHK15	4	44.79 *(22.11)*	-30.42 *(-15.35)*	9.37	-3.04
Rperm-CA-EL2-UL18	11	65.80 *(31.42)*	-23.21 *(-11.53)*	6.11	-2.32

Rperm-GH-EL2	5	63.10 *(31.24)*	-9.38 *(-4.64)*	7.81	-0.94
Rperm-GH-EL2-EL3	3	54.11 *(27.59)*	3.79 *(1.93)*	2.59	0.38
Rperm-GH-EL3	2	38.70 *(20.37)*	-11.08 *(-5.83)*	0.67	-1.11
Rperm-NB	7	61.58 *(38.91)*	3.49 *(2.16)*	2.95	0.35
Rperm-OU1-DR-OL3-UOL18	10	59.14 *(29.06)*	-26.41 *(-12.79)*	4.97	-2.64
Rperm-OU1-DR-OL3-UOL18-HL8	2	62.61 *(31.70)*	-33.73 *(-17.15)*	7.47	-3.37
Rperm-OU1-DR-OL3-UOL18-HL8-OHK15	2	53.22 *(28.01)*	-24.57 *(-12.93)*	6.59	-2.46
Rperm-OU1-DR-OL3-UOL18-UOL20	3	63.38 *(30.47)*	-4.70 *(-2.26)*	6.34	-0.47

Two scenarios increase in SOC within the Rperm land use classification, Gallows Hill where options EL2 and EL3 are present, and OU1 on Newbiggin. Neither scenario is located on marshy grassland. The Rperm on Newbiggin is more distinct with respect to its management relative to other tenancies. Sheep are not grazed for 12 months of the year. In 2008 grazing by lowland ewes (0.12 LU ha^{-1} per head – Natural England, 2013) spanned 6 months of the year from May to October. This has since been reduced to 3 months during the summer period only, but with no change to the stocking rate. The stocking rate when the animals are present on the Rperm exceeds the potentially beneficial moderate 0.8 LU ha^{-1} stocking rate cited by Ostle et al. (2009) but lies within this range when adjusted for the proportion of the year present. The absence of grazing during the winter reduces the risk of soil compaction due to the trampling of wet soils (Conant *et al.*, 2001; 2005; Freibauer *et al.*, 2004; Louwagie *et al.*, 2009) a variable not quantified in the current analysis. The remaining tenancies graze sheep throughout the year. There is no consistent change in SOC between scenarios on non-marshy grassland containing option EL2 (-23.21 to 3.79 t C ha^{-1}) or EL3 (-11.08 to 3.79 t C ha^{-1}). The Gallows Hill tenancy also grazes livestock within the 0.4 - 0.8 LU ha^{-1} range described as potentially beneficial (Ostle et al., 2009) yet a decrease in SOC is present on parcels within this land use. The impact of soil series is discussed in section 3.1.4.5.

Declines are observed on scenarios identified as ‘marshy grassland’ by the Wallington Biological Survey in 1999 (-44.53 to -26.91 t C ha^{-1}). Marshy grassland is situated in areas subject to improvements such as drainage and potentially represent areas of declining SOC due to drying of the soil and oxidation of SOC to CO_2 (Evans et al., 2016; Ostle et al., 2009). The restoration of rough grazing for birds on the Donkin Rigg tenancy targets the enhancement of populations of lapwing (*Vanellus vanellus*), curlew (*Numenius arquata*) and snipe (*Gallinago gallinago*). An indicator of success for this option is that by year two of the agreement, 30% of the area has moist soil or 3% is standing water in late March or early April. Although the wetland areas are under restoration through option HL8, the time taken to reverse the process of SOC loss through rewetting of land tends not to be immediate i.e. is subject to a lag effect (Freeman et al., 2003; Moorby, 2008). Further, the indicators of success are focused on modification to vegetation structure rather than enhancement of soil function. The decline in SOC observed where this option has been implemented are likely to be associated with the former management regime, the implementation of option HL8 as of 2018 either being yet to reverse the degradation process, or having reversed it insufficiently to result in a net gain. Overstocking would not appear to be a factor due to the previous (0.4 - 0.7 LU ha^{-1}) and current (0.75 LU ha^{-1}) maximum lying within the low to moderate stocking rate range of 0.4 – 0.8 LU ha^{-1} proposed by Ostle et al. (2009) to benefit SOC by 0.05 t C ha^{-1} yr^{-1}. While a decline on marshy grassland has been observed since 2008, the rate of decline may have slowed relative to if HL8 was not implemented. It may also be that accumulation has begun but was not measurable due to the time required for habitat restoration to be implemented and a potential lag effect. An unknown factor is the time that will be required to reverse the process. According to Ostle et al. (2009), IPCC (2014) and Worrall et al. (2011) SOC accumulation post restoration proceeds at a rate of 0.05 to 0.23 t C ha^{-1}. The SOC has on average declined at a rate of -3.04 to -2.46 t C ha^{-1} yr^{-1}, 10 – 60 times more rapidly than the rate of increase estimated by Ostle et al. (2009), IPCC (2014) and Worrall et al. (2011). If the SOC has begun to increase, the decline experienced in the early phases of the 10 year period will in all probability outweigh this, resulting in the net decline observed. The drainage system is not being maintained and is gradually silting up although the rate of decline suggests reliance on passive measures are insufficient alone. Option OHK15 (Maintenance of grassland for target features) also implemented on this land parcel aims to maintain the habitat as moderately species rich grassland. Target species include those associated with wet soils, for example purple moor grass (*Molinia caerulea*), bog asphodel (*Narthecium ossifragum*) and cross-leaved heath (*Erica tetralix*). Successful implementation of this option is sympathetic to maintaining wet grassland however the decline in SOC shifts the emphasis to the restoration mode of option HL8. It would also suggest the need for the artificial blocking of drainage channels to speed up the siltation process. There is unfortunately a potential conflict of interests between SOC enhancement and animal health. The liver fluke (*Fasciola hepatica*) a parasite of sheep requires a species of aquatic snail (*Galba truncULata*) as an intermediate host in order to complete its life-cycle. The rewetting of grassland in areas where sheep grazing is undertaken greatly increases the risk of liver fluke infection. Wetland restoration options may require coupling with supplementary options that facilitate stock removal.

Other ES options present on Donkin Rigg within areas of marshy or former marshy grassland, for example EL3 / OL3 do not increase the rate of SOC degradation on wet grassland further but are not specific to the restoration of such areas by for example, the specific removal of drainage. Neither are wetland plant species specified as indicators of success. This is also evident for a small number of samples on the Gallows Hill tenancy where a mean decline of -4.45 t C ha^{-1} has occurred since 2008 in the marshy grassland area to the north-east of this tenancy within option EL3. The option itself is not responsible for the SOC decline, rather the type and condition of the habitat on which it is implemented.

A second potential factor, and one identified by Bell (2011) is the application of phosphate to Rperm. This was formerly applied to Rperm on the Donkin Rigg tenancy as basic slag until conversion to organic land post 2008. The decline observed within Rperm excluding marshy grassland on Donkin Rigg (-20.97 to -33.79 t C ha^{-1}) is within the same range as the Catcherside tenancy (-23.21 t C ha^{-1}) where the fertiliser regime has not changed, with no significant difference between the two.

3.1.4. Field parcel scale: tenancy, management and ES option

The change in SOC is shown spatially for each tenancy in Figure 3.1.6.

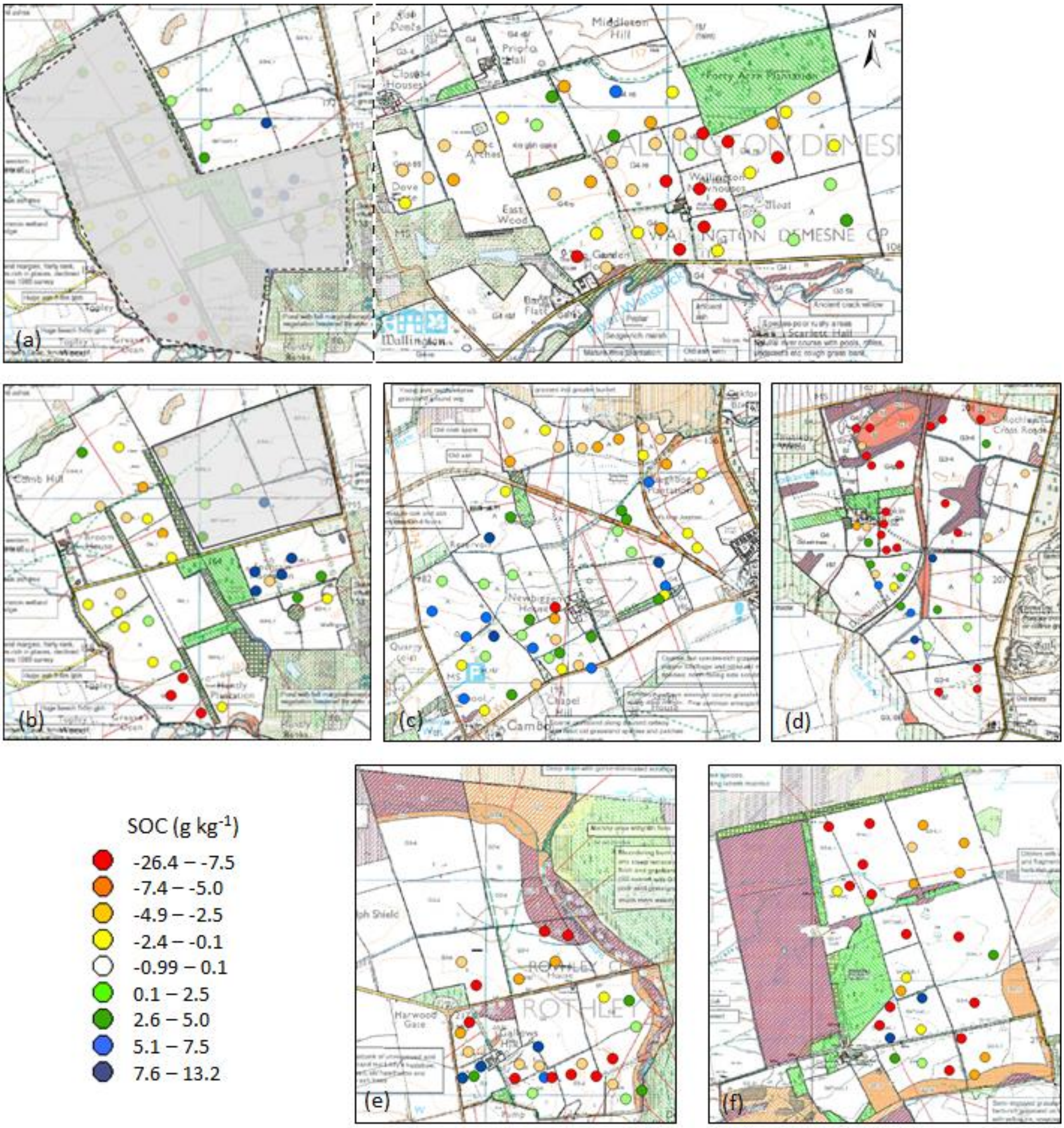

Figure 3.1.6. Spatial representation of change in SOC on each Wallington tenancy overlaid onto the Wallington Biological Survey (1999): (a) Prior Hall, (b) Broomhouse, (c) Newbiggen, (d) Donkin Rigg, (e) Gallows Hill, (f) Catcherside. Grey shaded area = samples outside the tenancy boundary.

Most of the fields in Figure 3.1.6a decline in SOC. An exception, also highlighted in Table 3.2, is the parcel to the east of the tenancy where farmyard manure is applied (scenario A-PH-FYM) at a rate of 15 – 20 t ha^{-1}. The field is split into two sections, with each half receiving an application biennially. An increase is also noted within the parcel to the west converted from arable to Itemp in 2014 (A-08_Itp-14-PH). Parts of Broomhouse Farm (Figure 3.1.6b) have undergone multiple changes in land use in the period 2008 – 2018, including conversion from grassland to arable before being returned to grassland. An increase in SOC is observed within parcels to the east of the tenancy. This increase does not appear to be explained by land use or changes of land use. The three parcels of land have different management histories and baseline land uses in 2008, consisting of arable (A-08_Itp-14-BH), Itemp (Itp-08_A-10_Itp-14-BH) and Iperm (Ip-08_A-10_Itp-14-BH). The latter two were converted to arable land post 2008 before all three were converted to Itemp in 2014.

Part of Newbiggin Farm (Figure 3.1.6c) was converted to organic management in 2010 (scenario A-OU1-NB). The area to the east of the tenancy is not under organic management (A-NB) although the crop rotation is the same, consisting of two crops of winter oats and a grass/clover ley. Spatially, gains in SOC are noted mainly in the south and east of the tenancy. The area to the north, irrespective of whether organic or non-organic land, experiences a decline in SOC. The main difference between the two land management regimes is the source of supplementary nutrients. Land within organic management receives broiler manure with added straw. The non-organic land receives ammonium nitrate and inorganic sources of phosphate and potash. Further nitrogen is supplied by an 18 month grass/clover ley grazed by sheep during the summer. Management overall was not significantly different. The Rperm located in the parcel to the south of the tenancy contains the Heapy (Hj) brown earth and Ticknall (tL) surface-water gley soil series. The Hj is classed as low compaction risk (Table 2.1) while the tL low-moderate risk due to the impermeable clay layer present. Soil compaction has not been quantified but is a low risk overall due to absence of livestock during the winter and early spring.

On the Donkin Rigg tenancy shown in Figure 3.1.6d the arable rotation changed from a four cereal rotation with a clover or brassica fodder crop to a rotation of two cereal crops combined with a 2-3 year grass/clover/lucerne ley (50-60% of the rotation). Both rotations received equal quantities of FYM, the variable under evaluation in this case is the addition of the ley. Other land use to the north of the tenancy includes Rperm where a decrease in SOC occurs, especially areas within or adjacent to marshy grassland (Rperm_marshy-OU1-DR-OL3-UOL18-HL8 (-OHK15)) (Figure 3.1.5c). The main change in management for this land use is the introduction of cattle grazing to areas formerly grazed only by sheep (UOL18) at a maximum stocking density combined of 0.75 LU ha^{-1} and the elimination of supplementary nutrients, mainly phosphate, in the form of basic slag. As part of the ES agreement grazing with sheep is permitted at stocking densities of between 0.4 and 1.0 LU ha^{-1} between 31st March and 20th June and a maximum 2.0 LU ha^{-1} with cattle in June and July. The 0.4 and 1.0 LU ha^{-1} lies broadly within the low-moderate stocking density range stated by Dawson and Smith (2007) as conducive with SOC increase. Where grazing potentially exceeds this level is during the summer. An indicator of success for option HL8 on this tenancy is that in late March or early April by year two of the agreement, 30% of the area has moist soil or 3% is standing water. Grazing wet soils risks soil compaction. If the target 30% moist soil in April is achieved the presence of cattle during June and July may coincide with wet soils during periods of above average rainfall during the spring and early summer. It would be advisable to not graze the maximum 2.0 LU ha^{-1} where soil conditions remain wet.

Gallows Hill (Figure 3.1.6e) consists of areas of former Itemp to the south of the tenancy which have not been reseeded for over 25 years. Declines in SOC are observed in these fields. Declines are also noted in areas within or in the same parcel as marshy grassland. The Itemp received low rates of inorganic NPK in 2008, this has been discontinued within parcels entered into EL3 (Itp-08-Ip-18-GH-EL3). One other land parcel to the north-west of the tenancy classed as Itemp was last cultivated in 2009. Overall there is a slight gain in SOC but this is not consistent within the parcel itself or significantly different to the counterfactual scenario. An increase in SOC is observed on Iperm in the south-west corner of the tenancy (Iperm-GH-EL2) however this parcel had a low baseline SOC in 2008 relative to other areas of Iperm resampled (Figure 3.1.4a). The increase aligns the current value with other Iperm on the estate (Figure 3.1.4).

Catcherside (Figure 3.1.6f) no longer applies slurry to Itemp but continues to apply FYM. Cattle grazing has been introduced into areas formerly grazed by solely by sheep as part of option UL18. The SOC on Catcherside declines on all grassland types, Itemp, Iperm and Rperm. Gains are noted in the south-west part of the tenancy on Rperm (scenario Rperm-CA-EL2-UL18). There is limited consistency in the results to attribute the entry of individual land parcels into ES (EL2) as a mechanism to impact SOC on this tenancy.

3.1.4.7. Clusters and tenancy

A cluster analysis (ArcGIS Getis-Ord Gi* statistic) identified 'hot spots' (groups of samples where SOC has increased) and 'cold spots' (groups of samples where SOC has decreased). This is summarised in Figure 3.1.7.

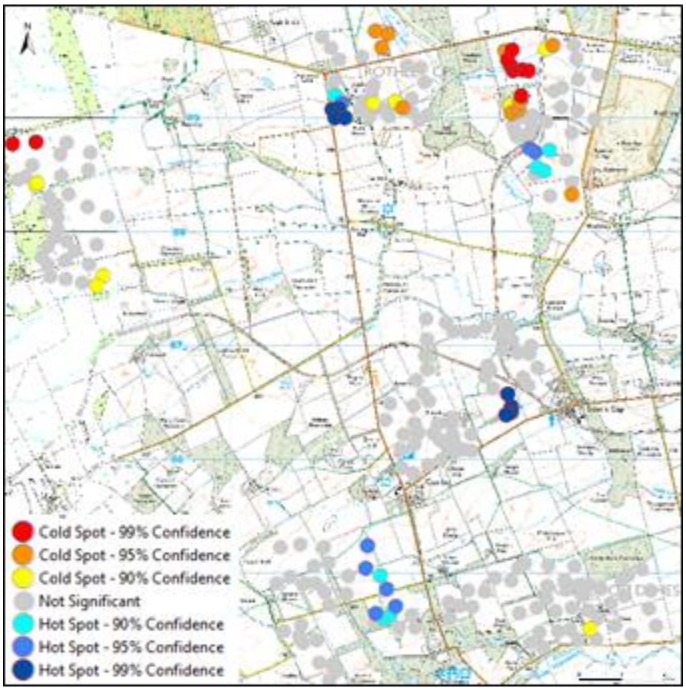

Figure 3.1.7. Overview of the Wallington Estate and clusters (ArcGIS® Getis-Ord Gi* statistic) of SOC gain and loss.

Figures 3.1.2.a and b identify arable land on the Donkin Rigg tenancy (A-OU1-DR) as having low SOC relative to other areas of arable land on the estate, but that this is increasing (Figure 3.1.2.c). The increase in SOC is identified in the cluster analysis, as are areas of arable land within the Newbiggin tenancy and the former arable land at Broomhouse. The 'cold spot' cluster to the north of Donkin Rigg highlight the decline in SOC on the Rperm and Rperm-marshy grassland classifications on this tenancy.

3.2. Wimpole Estate

3.2.1. Estate scale: land use

The following section reports on the SOC sampled at the Wimpole Estate. It follows the same format as reported at Wallington but for fewer samples (n = 51). A total of 372 samples were taken by Bell (2011). Boxplots of the original data collected in 2008 (Bell, 2011) are displayed (Figure 3.2.1a) adjacent to the measured SOC as g kg^{-1} from sample sites reassessed in 2018 (Figure 3.2.1b) and the change in SOC within the 10 year period (Figure 3.2.1c). The analysis and boxplots exclude sample sites removed as outliers from the original change in SOC dataset.

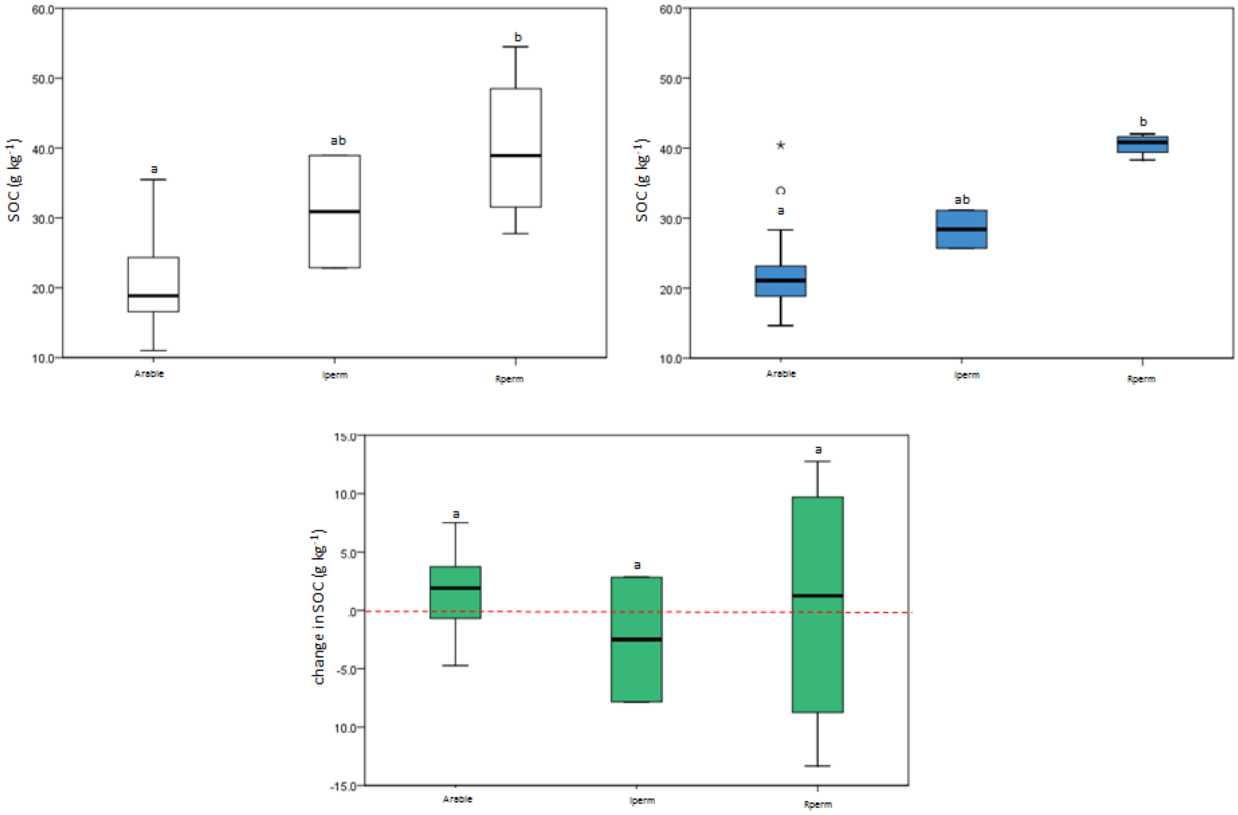

Figure 3.2.1. Boxplot of SOC (g kg^{-1}) in the resampled sites (n=51) as measured (a) in 2008 by Bell (2011), (b) in 2018 and (c) change 2008-2018 (red dashed line indicates zero change in SOC). Data points with different letters indicate a significant (*p*<0.05) difference.

The samples taken (n = 51) are dominated by the arable land use category (n = 42). A paired sample t-test indicated a significant increase in SOC between 2008 and 2018 on arable land (Table 3.2.1).

Table 3.2.1. Change in SOC (g kg^{-1}) to 20 cm depth (text in italics and parentheses denotes t C ha^{-1} yr^{-1}) and summary output of a paired sample t-test for the main land use classifications present in 2018.

Land use (2008)	N	Mean change 2008 - 2018	Standard error of mean change	t	df	Sig
arable	42	1.50 *(4.14)*	0.46	3.625	41	*0.001
Iperm	2	-2.50 *(-5.83)*	5.33	-0.316	1	0.805
Rperm	4	0.48 *(1.69)*	5.78	0.287	3	0.793

*significant difference (p<0.05) between years

A significant difference [F(2,35)= 6.722, *p*=0.003] between SOC and the land use classifications defined by Bell (2011) is observed in 2008 accounting for 27.8% of variation (Table 3.2.2).

Table 3.2.2. General linear model summary statistics within dominant land use categories for log transformed SOC (g kg^{-1}) to 20 cm depth measured in 2008.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	0.589[a]	12	0.049	4.063	0.001	0.582
Intercept	0.262	1	0.262	21.669	0.000	0.382
Land use	0.162	2	0.081	6.722	*0.003	0.278
Soil series	0.071	6	0.012	0.980	0.453	0.144
Altitude	0.000	1	0.000	0.023	0.881	0.001
pH	0.037	1	0.037	3.067	0.089	0.081
Years land use	0.001	1	0.001	0.101	0.753	0.003
Aspect	0.061	1	0.061	5.033	*0.031	0.126
Error	0.423	35	0.012			
Total	84.900	48				
Corrected Total	1.012	47				

[a] R Squared = 0.582 (Adjusted R Squared = 0.439); *significant (*p*<0.05)

It is also significant [F(2,35)= 6.514, *p*=0.004] in 2018 accounting for 27.1% of variation (Table 3.2.3).

Table 3.2.3. General linear model summary statistics within dominant land use categories for log transformed SOC (g kg^{-1}) to 20 cm depth measured in 2018.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	0.473[a]	12	0.039	10.940	0.000	0.790
Intercept	0.117	1	0.117	32.356	0.000	0.480
Land use	0.047	2	0.023	6.514	0.004*	0.271
Soil series	0.010	6	0.002	0.475	0.822	0.075
Altitude	0.002	1	0.002	0.447	0.508	0.013
pH	0.066	1	0.066	18.367	0.001*	0.344
Years land use	0.001	1	0.001	0.192	0.664	0.005
Aspect	0.011	1	0.011	2.967	0.094	0.078
Error	0.126	35	0.004			

Total	88.826	48				
Corrected Total	0.599	47				

^{a}R Squared = 0.790 (Adjusted R Squared = 0.717); *significant (*p*<0.05)

With respect to the change in SOC between the two sampling periods there is borderline non-significance [F(2,35)= 3.267, *p*=0.050] accounting for 15.7% of variation (Table 3.2.4).

Table 3.2.4. General linear model summary statistics within dominant land use categories for change in log transformed SOC (g kg^{-1}) to 20 cm depth.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	0.202^{a}	12	0.017	1.797	0.088	0.381
Intercept	1.452	1	1.452	154.991	0.000	0.816
Land use	0.061	2	0.031	3.267	0.050	0.157
Soil series	0.125	6	0.021	2.216	0.065	0.275
Altitude	0.022	1	0.022	2.375	0.132	0.064
pH	0.001	1	0.001	0.108	0.745	0.003
Years land use	0.000	1	0.000	0.050	0.825	0.001
Aspect	0.002	1	0.002	0.173	0.680	0.005
Error	0.328	35	0.009			
Total	83.711	48				
Corrected Total	0.530	47				

^{a}R Squared = 0.381 (Adjusted R Squared = 0.169); *significant (*p*<0.05)

3.2.2. Estate scale: land use, management and ES option

Disaggregation of the dominant land use classification defined by Bell (2011) to individual scenarios disaggregated by land use, tenancy and management and ES option is summarised for arable land in Figure 3.2.2. It explains a greater proportion of the variation for SOC in 2008 (*p*=0.006; 46.1% of variation) and 2018 (*p*=0.006; 44.7% of variation) (Table 3.2.5). Option HF20 is excluded from the post-hoc analysis due to there being one sample point. The two grassland scenarios are included in the Figure 3.2.2 for comparison purposes. Due to no variation in management within these two land uses they have not been subject to post-hoc analysis.

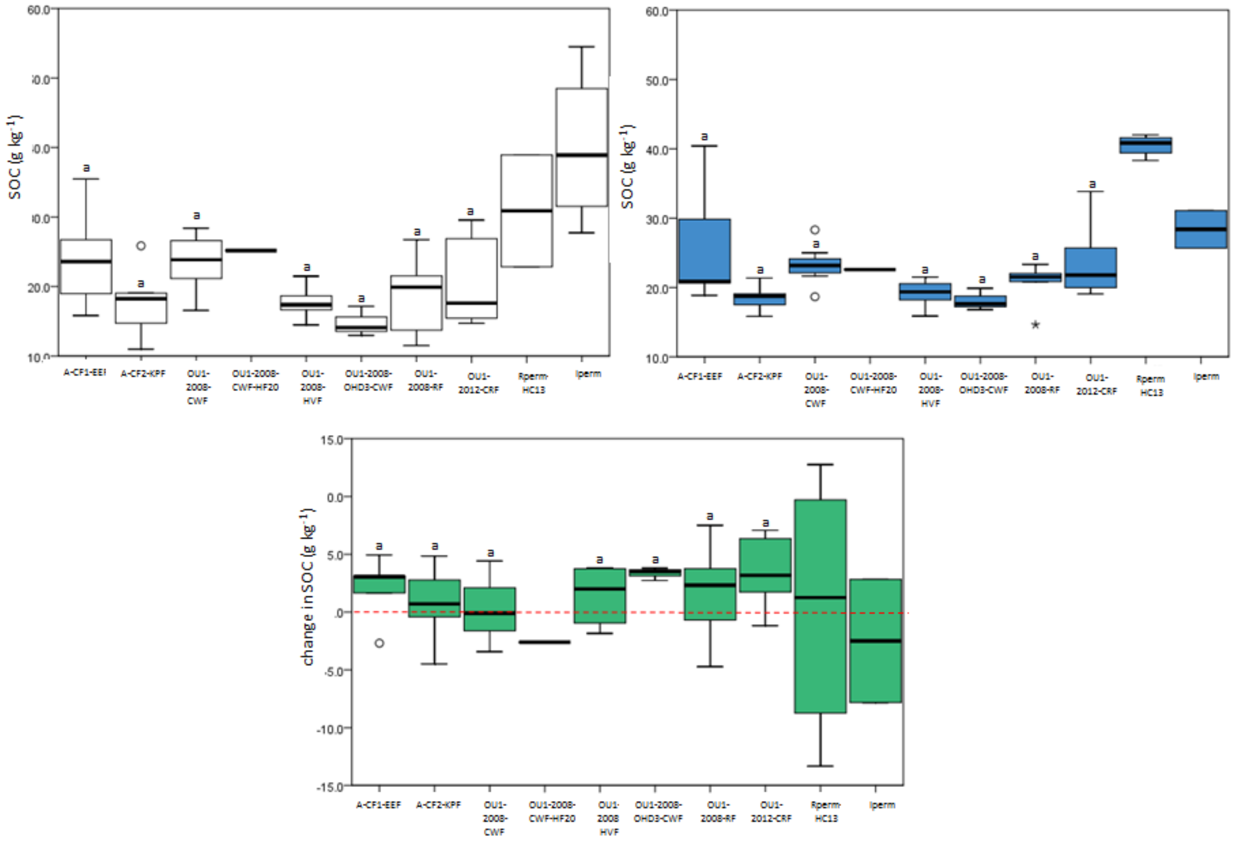

Figure 3.2.2. Boxplot of SOC (g kg^{-1}) in the resampled sites as measured (a) in 2008 by Bell (2011), (b) in 2018 and (c) change 2008-2018 (red dashed line indicates zero change in SOC). Data points with different letters indicate a significant (p<0.05) difference. HF20 was excluded from the post-hoc analysis due to one sample point. Acronyms: A-CF1 / A-CF2 arable counterfactual 1 or 2, EEF – Eight Elms Farm, KPF – Kingston Pastures Farm, CWF – Cobbs Wood Farm, HVF – Home Valley Farm, RF – Rectory Farm, CRF – Cambridge Road Farm; ES options OU1, HF20, OHD3.

A summary of the key management variables for land classed as arable in 2008 are provided in Table 3.2.4.

Table 3.2.4. Key management variables for management scenarios on land classified as arable on the Wimpole Estate in 2008.

Management / option	Tillage + frequency	Ley (% rotation)	Organic fertiliser	Crop residue incorporation	Grazing
A-EEF-CF1	1 (20cm)	0	0	stubble + WW straw	-
A-KPF-CF2	1 (20cm)	0	biosolids	stubble	-
OU1-2008-CWF	1 (^{a}12cm)	1 – 3 year grass / clover ley (20-43%)	25 t FYM	stubble	^{c}sheep (ley)
OU1-2008-CWF-HF20	1 (^{a}12cm)	1 – 3 year grass / clover ley (20-43%)	25 t FYM	stubble	^{c}sheep (ley)

OU1-2008-HVF	1 ([a]12cm)	1 – 3 year grass / clover ley (20-43%)	25 t FYM	stubble	[c]sheep (ley)
OU1-2008-OHD3-CWF	1 ([b]10cm)	1 – 3 year grass / clover ley (20-43%)	25 t FYM	stubble	[c]sheep (ley)
OU1-2008-RF	1 ([a]12cm)	1 – 3 year grass / clover ley (20-43%)	25 t FYM	stubble	[c]sheep (ley)
OU1-2012-CRF	1 ([a]12cm)	1 – 3 year grass / clover ley (20-43%)	25 t FYM	stubble	[c]sheep (ley)

Note: [a]since autumn 2017; [b]since autumn 2008; [c] grazing of leys by sheep during the winter from external farms

No significant difference [F(5,26)=0.956, *p*=0.462] exists for SOC sampled in 2008 between scenarios disaggregated by tenancy and management practice and option relative to the two counterfactual scenarios (Table 3.2.5).

Table 3.2.5. General linear model summary statistics within dominant land use categories for log transformed SOC (g kg^{-1}) to 20 cm depth measured in 2008.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	0.249[a]	15	0.017	1.376	0.230	0.443
Intercept	0.122	1	0.122	10.123	0.004	0.280
Management practice	0.058	5	0.012	0.956	0.462	0.155
Soil series	0.031	5	0.006	0.507	0.769	0.089
Altitude	0.004	1	0.004	0.301	0.588	0.011
pH	0.008	1	0.008	0.668	0.421	0.025
Years management	0.013	1	0.013	1.066	0.311	0.039
Aspect	0.002	1	0.002	0.176	0.678	0.007
Error	0.313	26	0.012			
Total	70.376	42				
Corrected Total	0.562	41				

[a]R Squared = 0.443 (Adjusted R Squared = 0.121); *significant (*p*<0.05)

No significance [F(5,26)=1.656, *p*=0.181] exists between scenarios for SOC sampled in 2018 (Table 3.2.6).

Table 3.2.6. General linear model summary statistics within dominant land use categories for log transformed SOC (g kg^{-1}) to 20 cm depth measured in 2018.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	0.203[a]	15	0.014	4.094	0.001	0.703
Intercept	0.092	1	0.092	27.686	0.000	0.516
Management practice	0.027	5	0.005	1.656	0.181	0.242
Soil series	0.014	5	0.003	0.861	0.520	0.142
Altitude	0.002	1	0.002	0.738	0.398	0.028
pH	0.058	1	0.058	17.633	0.000	0.404
Years mangement	3.339E^{-05}	1	3.339E^{-05}	0.010	0.921	0.000
Aspect	0.002	1	0.002	0.534	0.471	0.020
Error	0.086	26	0.003			
Total	74.275	42				
Corrected Total	0.289	41				

[a]R Squared = 0.703 (Adjusted R Squared = 0.531); *significant (*p*<0.05)

No significant difference [F(5,26)=0.636, *p*=0.674] exists in relation to SOC change attributed to option and management practice (Table 3.2.7).

Table 3.2.7. General linear model summary statistics within arable land disaggregated to tenancy, management and ES option for change in log transformed SOC (g kg^{-1}) to 20 cm depth.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	0.052[a]	15	0.003	0.820	0.648	0.321
Intercept	0.181	1	0.181	42.843	0.000	0.622
Management practice	0.013	5	0.003	0.636	0.674	0.109
Soil series	0.017	5	0.003	0.807	0.555	0.134
Altitude	0.002	1	0.002	0.536	0.471	0.020
pH	0.001	1	0.001	0.179	0.676	0.007
Years management	0.005	1	0.005	1.159	0.292	0.043
Aspect	0.000	1	0.000	0.076	0.785	0.003
Error	0.110	26	0.004			
Total	74.240	42				
Corrected Total	0.161	41				

[a] R Squared = 0.321 (Adjusted R Squared = 0.070); *significant (*p*<0.05)

No significant difference was evident between scenarios disaggregated by tenancy and management practice and option relative to the two counterfactual scenarios according to an independent samples t-test (Table 3.2.8).

Table 3.2.8. Summary statistics from an independent samples t-test comparing arable land management practice categories present in 2018 with arable counterfactual 1 and counterfactual 2 scenarios for change in log transformed SOC (g kg^{-1}) to 20 cm depth.

	A-EEF-CF1			A-KPF-CF2		
	t	df	Sig (2-tailed)	t	df	Sig (2-tailed)
A-EEF-CF1	n/a	n/a	n/a	0.706	9	0.498
A-KPF-CF2	-0.706	9	0.498	n/a	n/a	n/a
OU1-2008-CWF	-1.195	12	0.255	-0.298	13	0.770
OU1-2008-HVF	-0.300	9	0.771	0.517	10	0.617
OU1-2008-RF	-0.194	9	0.851	0.418	10	0.685
OU1-2012-CRF	0.731	9	0.483	1.462	10	0.174
OU1-2008-OHD3-CWF	0.797	6	0.456	1.363	7	0.215
OU1-2008-HF20R-CWF	-1.493	4	0.210	-0.940	5	0.391

*significant difference (*p*<0.05); [a]unequal variances assumed as indicated by Levene's test for equality of means

Descriptive data for each disaggregated land use classification is given as t C ha^{-1} and g kg^{-1} in Table 3.2.9.

Table 3.2.9. Total mean (2018) and change (2008 – 2018) in SOC (t C ha^{-1}) for management on arable land and grassland to 20 cm depth (text in italics and parentheses denotes g kg^{-1}).

Management / option	N	Mean 2018	Mean change 2008 - 2018	Standard error of mean change	Mean change yr^{-1}	relative to CF1	relative to CF2
A-EEF-CF1	5	64.33 *(26.14)*	4.55 *(2.01)*	3.21	0.45	-	0.24
A-KPF-CF2	6	52.07 *(18.55)*	2.12 *(0.69)*	3.56	0.21	-0.24	-
OU1-2008-CWF	9	72.26 *(23.33)*	0.67 *(0.17)*	2.35	0.07	-0.39	-0.15
OU1-2008-HVF	6	61.80 *(19.15)*	4.04 *(1.47)*	2.80	0.40	-0.05	0.19
OU1-2008-RF	6	64.24 *(20.65)*	4.57 *(1.75)*	4.47	0.46	0.002	0.24
OU1-2012-CRF	6	53.94 *(23.71)*	9.65 *(3.40)*	3.65	0.97	0.51	0.75
OU1-2008-OHD3-CWF	3	54.30 *(18.12)*	10.08 *(3.36)*	1.00	1.01	0.55	0.80
OU1-2008-HF20R-CWF	1	55.26 *(22.58)*	-7.41 *(-2.61)*	-	-0.74	-1.20	-0.95
Iperm-WA	2	67.74 *(28.40)*	-5.83 *(-2.50)*	13.36	-0.58	-	-
Rperm-HC13-HR2-WA	4	89.55 *(40.51)*	1.69 *(0.48)*	13.08	0.17	-	-

An increase in SOC is observed for each arable scenario including the two counterfactuals, with the exception of option H20R (Cultivated fallow plots), albeit for only one sample. Counterfactual scenario 1 (A-EEF-CF1) includes a rotation of two winter wheat crops (50% of the rotation), winter barley and field beans. The straw from the winter wheat crops is incorporated post-harvest, non-inversion tillage is undertaken after harvest of the winter bean crop. The incorporation of straw is reported to increase SOC by 0.15 – 0.69 t C ha^{-1} yr^{-1} / UK mean of 0.4 t C ha^{-1} yr^{-1} (Ostle et al., 2009; Smith et al., 2000ab; Vleeshouwers and Verhagen, 2002). On this tenancy, there is an increase of 0.45 t C ha^{-1} yr^{-1}, and 0.24 t C ha^{-1} yr^{-1} relative to counterfactual 2 (A-KPF-CF2). Reduced tillage is implemented after winter beans (25% of the rotation), this has not been included as a possible SOC enhancement measure due to inconsistencies within the published literature and based on the findings of Moxley et al. (2014). Counterfactual 2 (A-KPF-CF2) incorporates crop stubble only.

The organic OU1 tenancies (OU1-2008-CWF, OU1-2008-HVF, OU1-2008-RF, OU1-2012-CRF) typically grow three cereal crops with a break crop such as spring beans followed by a 1 – 3 year grass/clover ley (20-43% of the rotation). Farmyard manure is applied annually at 25 t ha^{-1}. Each organic scenario follows similar management, the rotation is the same, the sequence of cropping may differ. There is a mean change of 0.07 – 0.97 t C ha^{-1} yr^{-1}, or -0.39 – 0.75 t C ha^{-1} yr^{-1} relative to the counterfactual scenarios. There are two potential mechanisms conducive with an increase in SOC on this tenancy that are not present on the counterfactual scenarios. A reduction in tillage frequency through inclusion of the ley, and the incorporation of FYM. A grass/clover ley may increase the SOC of arable land by 0.26 – 0.54 t C ha^{-1} yr^{-1}, the addition of FYM by 0.37 t C ha^{-1} yr^{-1} (Dawson and Smith, 2007; Ostle et al., 2009; Smith et al., 2000ab). The variability between tenancies results in no significant difference in SOC gain overall for the inclusion of these management practices. Although gains in SOC are observed on each of the organic scenarios, there is an increase relative to counterfactual 1 only in OU1-2012-CRF (section 3.2.1). The rotations do however increase relative to counterfactual 2 where straw is not incorporated and reflects a baseline more limited in SOC enhancement practices.

Scenario OU1-2008-OHD3-CWF includes option OHD3 Reduced cultivation on archaeological features. Reduced tillage has not been included as a means to enhance SOC (Moxley et al., 2014) although it may have benefits in preventing soil erosion (section 3.2.4.3). Option HF20R cultivates the crop headland but no crop is drilled, allowing instead the natural regeneration of wild plant species. The return of SOC may potentially be lower in such areas due to the continued cultivation of the ground but without the establishment of vegetation and rooting systems as dense as a sown crop (Warner et al., 2008). Stockmann et al. (2013) predict a decrease of -0.25 t C ha^{-1} yr^{-1} on fallow ground, a decrease of -0.74 t C ha^{-1} yr^{-1} was found for the HF20R sample at Wimpole. There is insufficient sampling of this option to be able to draw conclusions of its overall impact on SOC.

The Rperm increases in SOC by 0.17 t C ha^{-1} yr^{-1} although the variation that exists within the data for this land use scenario is high and not significantly different to other scenarios. The change in SOC within the permanent grassland of Wimpole Avenue was in contrast highly variable between locations, even after removal of one sample location as an outlier. This area is part of the main estate open to the general public and has historically been maintained as permanent grassland. Management interventions are restricted to the mowing of Iperm and grazing of all areas by sheep (as part of option HR2 Grazing supplement for native breeds at risk). Tree lines have been planted along each edge of the strip and now form part of option HC13 Restoration of wood pasture and parkland. The tree lines were present in 2008 so do not represent a change in land use.

3.1.4. Field parcel scale: tenancy, management and ES option

The change in SOC is shown spatially for each tenancy in Figure 3.1.6.

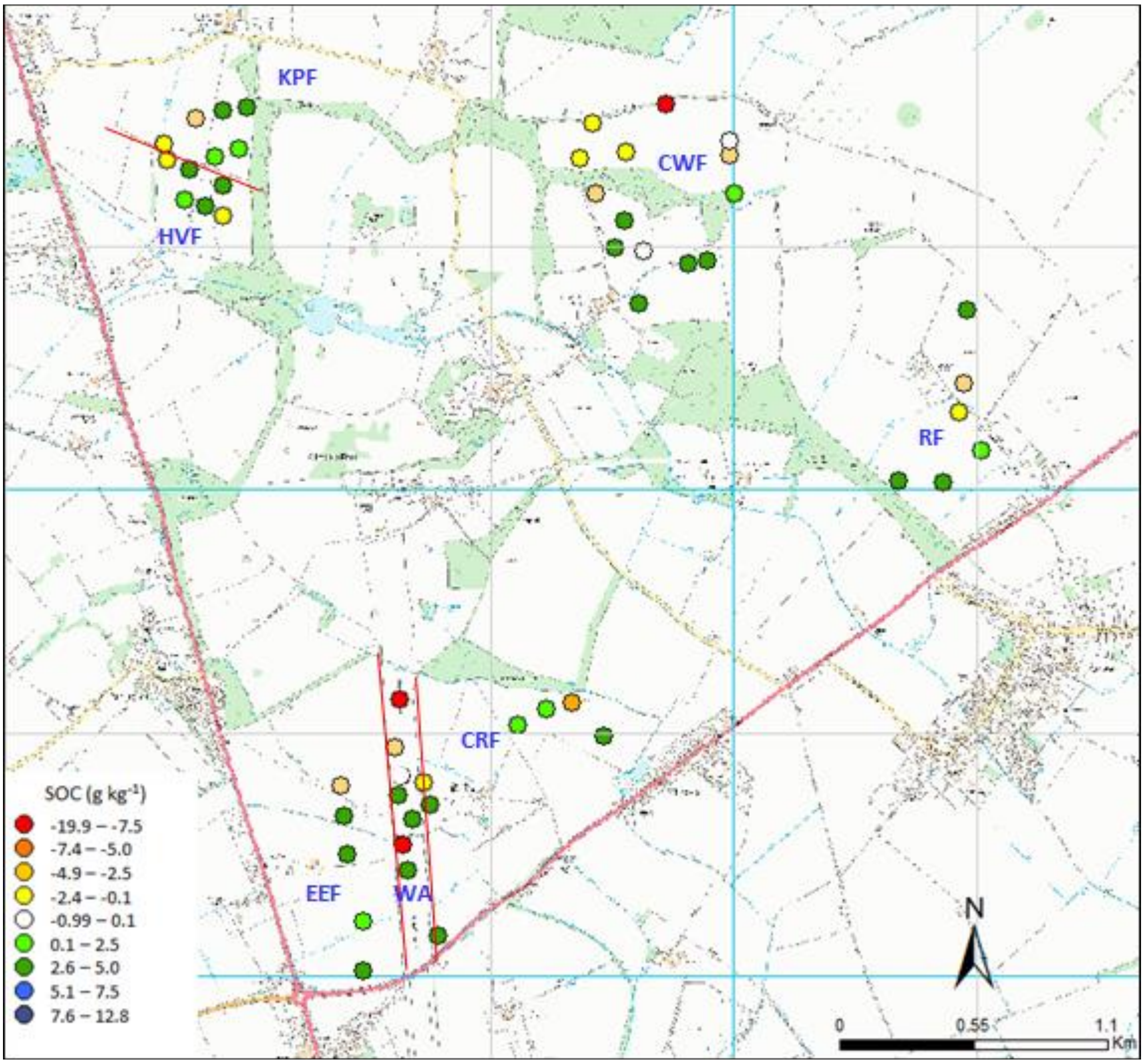

Figure 3.1.6. Spatial representation of change in SOC at each tenancy on the Wimpole Estate: CRF (Cambridge Road Farm), CWF (Cobbs Wood Farm), EEF (Eight Elms Farm), HVF (Home Valley Farm), KPF (Kingston Pastures Farm), RF (Rectory Farm), WA (Wimpole Avenue).

The SOC within arable land on the Wimpole Estate tenancies increased overall. Significant differences do not exist between them. Cobbs Wood Farm to the north of the Estate was the only tenancy where variation exists between land parcels, with the northerly most parcel declining in SOC. There is no difference in management between parcels on this tenancy, except option OHD3 (reduced cultivation) has been implemented on the land parcel to the south since entry into ES. Reduced tillage is not considered a measure to increase SOC overall (Moxley et al., 2014) although it may redistribute SOC within the soil profile. Powlson et al. (2011; 2014) report that there is no significant net gain, rather there may be an increase in SOC in the upper layers but a decrease in the lower soil profile. If the mean increase of 1.01 t C ha^{-1} yr^{-1} is in due to option OHD3 the lower soil layers may carry an associated decrease. Another factor is soil erosion, or risk of. This land parcel is located on a steeply sloping gradient. Carbon loss through soil erosion is estimated between <0.05 t C ha^{-1} yr^{-1} where slopes are negligible to 0.1 – 0.3 t C ha^{-1} yr^{-1} on steeper gradients, where management may reduce SOC loss by up to 0.030 t C ha^{-1} yr^{-1} (Borelli *et al.*, 2016). The latter value is less than the increase observed for the land parcel with OHD3, as is the mean estimated increase of 0.1 t C ha^{-1} yr^{-1} for the UK in the review of Ostle et al. (2009), subject to the caveat that there is no net gain overall. Reduced cultivation was also introduced on the remaining areas in autumn 2017. The Hn soil series and flat site topography are the key differences between the parcel to the north where SOC was noted to decrease and the remaining areas. The presence of the Hn soil series alone does not explain the decrease in SOC as gains were evident where present on the Valley Farm tenancy following the same management.

The samples taken within the Rperm and Iperm and use classifications on Wimpole Avenue are variable and do not alter in SOC consistently, with half of samples demonstrating either a positive or negative flux.

3.3. Aggregation by land use and ES option

3.3.1. Change in SOC by land use, ES option and management practice

This section compares the changes in SOC measured at Wallington and Wimpole with values predicted in the published literature to devise updated values of predicted changes in SOC for the ES options present on the two estates. Management practices of relevance are also included. The figures in Table 3.10 summarise the mean change in SOC as t C ha^{-1} for modification to land use or management practice as reported in Tables 3.3 – 3.6. The mean values below are reported with the caveat that based upon a GLM analysis they are not significantly different to the counterfactual scenarios in most cases. It must also be taken into account that the counterfactual scenarios themselves include management conducive with the accumulation of SOC although declines were observed in both. For example, both counterfactuals 1 and 2 at Wallington include a grass/clover ley of different durations within the rotation. The annual change in measured SOC data on arable land is in general, and subject to the caveat that it is not significant, comparable to figures reported in the literature (Table 3.3.1). The high levels of variation within the grassland scenarios, particularly on Iperm, does not establish any correlation with management practice.

Table 3.3.1. Change in SOC (t C ha^{-1}) for land use change and management on the Wallington and Wimpole Estates 2008-2018 to 20 cm depth and comparison with published literature. The range denotes differences between individual tenancies.

Management / option	Mean change yr^{-1}	Mean change yr^{-1} relative to counterfactual	Mean change yr^{-1} published values to 30 cm (mean UK)
Arable land			
+ straw (50% rotation) + reduced tillage (25% rotation)	0.45	0.24	0.69 (0.4) / 0
+ FYM (50% rotation)	0.46	0.73 – 0.74*	0.37
+ broiler manure + straw	0.04	0.31 – 0.32	*0.37*
+ biosolids	0.21	-	0.30

+ grass / clover ley (as part of OU1) 50-60% rotation	0.58	0.85 – 0.86*	0.54 (0.26)
+ grass / clover ley (as part of OU1) 20-40% rotation	0.07 – 0.97	-0.39 – 0.75	0.54 (0.26)
+ grass / clover ley (as part of OU1) 20-40% rotation + OHD3 reduced tillage	1.01	0.55 – 0.80	0.54 (0.26) / 0
to OU1	0.07 – 1.01	-0.39 – 0.86	0.30
to Improved temporary grassland	0.06 – 0.44	0.33 – 0.72	0.03 – 0.35
to HJ3 Reversion unfertilised grassland prevent erosion	1.34	1.61 – 1.63*	0.3 – 1.9 (1.0) / [a]0.03
to OB2 Hedgerow management (margin)	0.87	1.15 – 1.16	0.3 – 1.9 (1.0) / 0.95
to HF20R Cultivated fallow plots or margins for arable plants	-0.74	-1.20 – -0.95	-0.25/ [b]0.45
HE10 Floristically enhanced grass margin	no-OPSA	no-OPSA	0.3 – 1.9 (1.0)
EE3 / OE3 6m grass buffer strip	no-OPSA	no-OPSA	0.3 – 1.9 (1.0)
OHF7 Beetle banks (on organic arable conversion	no-OPSA	no-OPSA	0.3 – 1.9 (1.0)
Improved temporary grassland			
+ UL18 mixed stocking	-0.21	0.33	-
to improved permanent grassland (as EL2) + UL18 mixed stocking	-0.51	0.04	0.2 – 0.5
to improved permanent grassland (as EL3)	0.08	0.63	0.2 – 0.5
Improved permanent grassland			
+ UL18 mixed stocking + increased sward species richness (EL2, EK2)	-1.24	0.04	[c]*1.2*
+ increased sward species richness / N fertilisation max 50 kg N ha^{-1} (EL2, EK2)	-1.24 – 1.67	0.04 – 2.95	[c]*1.2* / 0.08
+ increased sward species richness / N fertilisation max 12.5 t FYM ha^{-1} (EK3)	-1.82	-0.54	[c]*1.2 / 0.08*
Rough permanent grassland			
with summer grazing (3 months)	0.35	-	0.05
+ HL8 Restoration of rough grazing for birds (wetland areas)	-3.37 – -2.46	-	0.05 – 0.23
+ HC13 Restoration of wood pasture and parkland	0.17	-	0.13
+ UOL20 Haymaking	-0.47	-	[c]*1.2*
+ HC9 Creation of woodland in SDA	no-OPSA	no-OPSA	0.1 – 1.3
+ HC17 Creation of successional areas and scrub	no-OPSA	no-OPSA	*0.05*
degraded wetland habitat (previous marshy grassland)	-4.45 – -2.69	-	-2.2 – -5.4 (-4.1)
Conifer plantation			
+ HE10 Floristically enhanced grass margin	0.15	-	0.3 – 0.6

Note: [a]as eroded soil; [b]bare soil / bare soil + natural regeneration; [c]reference to calcareous grassland; [d]10% woodland equivalent; *denotes significant (p<0.05) relative to SOC change in the counterfactual scenario; no-OPSA: no option present in sampling area.

Option EK2 may apply up to 50 kg N ha^{-1} inorganic N or a maximum total N rate of 100 kg N ha^{-1} when in combination with FYM. Nitrogen application ids further restricted in option EK3 to 12.5 t ha^{-1} maximum. Neither option permits an increase in N application above existing baseline quantities. A further factor to be taken into account is that the change in SOC is typically reported in the literature to a depth of 30cm reflecting the zone of disturbance under tillage regimes at the time of reporting (for example Smith et al., 2000ab).

3.3.2. Option and land management capacity for SOC accumulation

The selected options and management at the Wallington and Wimpole Estates are grouped in Table 3.11 based on four categories: the measured change in SOC between 2008 and 2018; the change in SOC relative to the counterfactual (where available – options on Rperm are not included here); the SOC change stated in the published literature; and production displacement risk. The restoration of Rperm on degraded wetland and Rperm with UOL18 have been allocated potential C gain based on the equivalent reversal of the degradation process (i.e. the prevention of further CO$_2$ emission) and the potential for SOC accumulation.

Table 3.11. Change in SOC (t C ha^{-1} yr^{-1}) for each management and ES option scenario as measured, relative to the counterfactual scenario and extracted from the published literature. The range of values where present refer to minimum and maximum values between tenancies for a given scenario. Displacement risk (DRi) refers to production displacement.

Measured SOC change		SOC change relative to counterfactual		SOC change literature		
t C ha^{-1} yr^{-1}	Option / management	t C ha^{-1} yr^{-1}	Option / management	t C ha^{-1} yr^{-1}	Option / management	DRi
[ab]3.76	restoration Rperm degraded wetland	1.62	A to HJ3	4.02	Rperm + UOL8	L
[ab]2.97	Rperm + UOL8	1.21	IpermP + EL2, EK2, EK3	4.02	restoration Rperm degraded wetland	L
1.34	A to HJ3	1.16	A to OB2	1.1	A to HJ3	M
1.01	A + G-C ley (20-40% rotation) + OHD3	0.86	A + G-C ley (50-60% rotation)	1.1	A to OB2	M
0.87	A to OB2	0.74	A + FYM	1.1	A to HE10	M
0.58	A + G-C ley (50-60% rotation)	0.68	A + G-C ley (20-40% rotation) + OHD3	1.1	A to EE3 / OE3	M
0.07 – 1.01	A to OU1	0.63	Itemp to Iperm (as EL3)	1.1	A to OHF7	M
0.52	A + G-C ley (20-40% rotation)	0.53	A to Itemp	0.69	A + straw	L
0.46	A + FYM	0.33	*Itemp + UL18*	0.54	A + G-C ley (50-60% rotation)	L-M
0.45	A + straw	0.32	A + BrM + straw	0.54	A + G-C ley (20-40% rotation)	L-M
[b]*0.35*	*Rperm summer grazing*	0.24	A + straw	0.54	A + G-C ley (20-40% rotation) + OHD3	L-M
0.06 – 0.44	A to Itemp	0.24	A to OU1	0.37	A + FYM	L
0.21	A + biosolids	0.18	A + G-C ley (20-40% rotation)	0.37	A + BrM + straw	L
[b]0.17	Rperm + HC13	0.04	Itemp to Iperm (as EL2) + UL18	0.35	Itemp to Iperm (as EL2) + UL18	M
0.08	Itemp to Iperm (as EL3)	0.04	Iperm + UL18 + EL2, EK2	0.35	Itemp to Iperm (as EL3)	M
0.04	A + BrM + straw	-0.54	Iperm + EL3, EK3	0.26	A + biosolids	L
[b]-0.47	Rperm + UOL20	-1.08	A to HF20R	0.25	A to OU1	L-M

-1.82 – 1.67	Iperm + EL2, EK2, EK3	0.19	A to Itemp	L-M
-0.21	Itemp + UL18	0.1	Rperm + HC9	M
-0.51	Itemp to Iperm (as EL2) + UL18	0.1	Iperm + HC9	H
-0.74	A to HF20R	0.08	Iperm + EL2, EK2, EK3	L
-1.24 – 1.67	Iperm + UL18 + EL2, EK2	0.08	Iperm + EL3, EK3	L
-1.82	Iperm + EL3, EK3	0.08	Iperm + UL18 + EL2, EK2	L
		0.05	Rperm summer grazing	M
		0.05	Rperm + HC17	M
		0.025	Rperm + HC13	L
		-0.25	A to HF20R	H
		nd	Rperm + UOL20	L
		nd	Itemp + UL18	L

[a]accounting for prevention of SOC decline post restoration; [b]no counterfactual on Rperm; nd: no data

Warner et al. (2008) prioritise ES options by GHG mitigation potential including emissions (CO_2, N_2O, CH_4) and C sequestration (SOC and biomass). It does not account for production displacement, subsequently included in Warner et al. (2013, 2017). In reference to the selected options evaluated at the Wallington and Wimpole Estates summarised in Table 3.11, those ES with the highest SOC potential mitigate SOC loss from wetland habitat degradation (section 3.3.2.1). This is followed by options that protect vulnerable soils e.g. from erosion, or sensitive habitat features (section 3.3.2.2).

3.3.2.1. Option HL8 (with OHK15): restoration of wetland / degraded habitats

The apparent decline in SOC on permanent grassland, irrespective of the current form of management, is identified as the greatest cause for concern. Decline has proceeded more rapidly on former wetland areas where marshy grassland has been previously recorded (Wallington Biological Survey, 1999) or still remains present. Options with the capacity to arrest this decline through habitat restoration have the greatest potential benefit in the resampled areas of the Wallington Estate. Rough permanent grassland either on or in proximity to marshy grassland is subject to the greatest declines (mean -4.55 to -2.69 t C ha^{-1} yr^{-1}). Land drainage removes anaerobic soil conditions which occur when soil pore space are saturated with water. It initiates SOC decomposition which is released as CO_2 (Brown et al., 2017; Schils et al., 2008; Smith et al., 2008) and the rate of release increases with increased soil depth (Freibauer, 2003).

The resampled soil series are not deep organic soils such as the Winter Hill series present within forestry land and the periphery of tenancies to the north-west of the estate (Bell, 2011). Instead they include the surface and ground water gley soils Wilcocks and Enborne, and the brown earth series Nercwys (Table 3.1). Based on the observations of Freibauer (2003) the rate of SOC decline would be expected to be lower than for deep peat soils. Indeed Buys et al. (2014) cite SOC loss as low as -0.02 t C $ha^{-1}yr^{-1}$ on drained marshy grassland. The measured SOC decomposition rate is broadly in agreement with the lower end of the range of published values for a degraded peat soil on improved permanent grass (-2.37 t C $ha^{-1}yr^{-1}$), less than cited for cultivated or temporary grassland (-6.11 to -10.00 t C $ha^{-1}yr^{-1}$) (Couwenberg, 2011; Evans et al., 2016; IPCC Wetlands, 2014; Worrall et al., 2011). This value would be expected to be lower for gley soils with a shallow organic layer and certainly for the brown earth series, suggesting that the rate of CO_2 emission and SOC loss is higher than previously documented.

The restoration of degraded wetland habitats through for example 'grip blocking' has the potential to arrest CO_2 release and initiate the accumulation of SOC at a rate of 0.05 to 0.23 t C ha^{-1} yr^{-1} (Dawson and Smith, 2007; IPCC, 2014; Ostle et al., 2009; Worrall et al., 2011). Restoration therefore, when CO_2 emission is removed and SOC gain is included, has a net mitigation potential of 2.74 to 4.78 t C $ha^{-1}yr^{-1}$ (Table 3.11). It should be noted however that the rewetting of land has the potential to increase the emission of N_2O and CH_4. Evans et al. (2017) describe un-deteriorated bogs as being 'climate-neutral', that is, the C sequestered relative to the N_2O and CH_4 emitted balance out. The same authors also point out that if the longer term GWP values are used, the lower GWP_{500} for CH_4 (7.6) results in a net cooling effect attributed to these habitats. Nitrous oxide emission increases in response to higher residual soil N from management such as supplementary nutrient application or grazing deposition, in combination with anaerobic soil conditions (Couwenberg and Fritz, 2012; Lindsay et al., 2010; Worrall *et al.*, 2011). Supplementary N is not applied to areas where this option is present. Livestock are at low to moderate stocking rates and removed during the winter when soils are wetter. Methane emission from bog and fen habitats is a product of the type of management, water level and the vegetation present (Couwenberg and Fritz., 2012; Levy *et al.*, 2012; Lindsay et al., 2010; Turetsky *et al.* 2014; Worrall *et al.*, 2011). It increases in the presence of aerenchymatous vegetation, plants adapted to wetlands in the possession of channels where the direct exchange of gases between the roots and leaves, including CH_4 (known as the 'methane shunt') is possible (Evans et al., 2016; Lindsay et al., 2010; Turetsky *et al.* 2014). The high value indicator target species noted for this tenancy include purple moor grass and cross-leaved heath. They are not within this classification.

On areas of existing or former marshy grassland at Wallington there has been a decline in SOC since 2008, despite the intervention of options HL8 and OHK15, where management targets stipulate partial waterlogging and an increase in vegetation indicative of intermittent flooding and wet soils. In these areas drainage ditches have not been deliberately blocked but have been allowed to degrade passively. Either the drainage ditches continue to function sufficiently to prevent rewetting, or, as Freeman et al. (2003) and Moorby (2007) note (albeit for deep peat soils) the reversal of SOC decline post wetland restoration by rewetting is not immediate. Deliberate blocking of drainage ditches may speed up the process but the impact will not necessarily be realised during the 10 year agreement.

While the 10 year agreement period for ES options may permit the implementation of management with the potential to arrest the decline in SOC, it will be insufficient to reverse it. Given the magnitude of decline since 2008 (mean -4.55 to -2.69 t C $ha^{-1}yr^{-1}$), even if the accumulation of SOC begins at a rate of 0.05 to 0.23 t C ha^{-1} yr^{-1} (Dawson and Smith, 2007; IPCC, 2014; Ostle et al., 2009; Worrall et al., 2011) it will take an estimated 10 – 100 times as long to restore the SOC lost. A further factor is that this is only for a loss during the 10 years under assessment, it does not account for any previous loss before 2008. The land use is classed broadly as low productivity Rperm. The current 0.75 LU ha^{-1} maximum stocking rate does not decrease the pre-option stocking rate of 0.4 - 0.7 LU ha^{-1}. Under these circumstances option HL8 is assigned a low displacement risk (Table 3.11). Where the complete removal of stock occurs, for example in response to risk posed by liver fluke, the option will be within the low – moderate displacement risk category depending on the baseline stocking rate. Low intensity grazing is permitted at a maximum stocking rate within the range stated by Dawson and Smith (2007) and Thornley and Cannell (1997) and considered as beneficial to SOC accumulation (Table 3.10). In summary, a potentially high return on SOC is provided for a limited impact on productivity. Areas exist on the Wallington Estate where SOC decline was among the highest measured. They included former marshy grassland areas where options specific to wetland habitat restoration were not present.

3.3.2.2. Options HJ3 / OB2 part land use change in sensitive areas on arable land

Options on Rperm tend to be of low production displacement risk. This is not the situation with productive arable land. The conversion of a proportion of arable land to permanent grass for example, may enhance SOC (Dawson and Smith, 2007; Falloon et al., 2004; Smith et al., 2000ab) but carries the risk of production displacement (Warner et al., 2013). The main value of such options to C sequestration lies firstly where soils are protected from for example, wind or water erosion. Secondly where sensitive habitat features that themselves have enhanced C accumulation potential (hedgerows, veteran trees, woodland) are buffered from agricultural farm operations. Soil erosion removes the top layer of soil and the SOC contained within it, exposing SOC in the lower soil layers to the atmosphere, and accelerating the rate of CO_2 emission (Mudgal and Turbé, 2010). Management that maintains season long vegetation cover decreases the risk that topsoil is washed away (Louwagie et al., 2009; Renard *et al*., 1997; Wischmeier and Smith, 1978). Any increase in SOC due to land use change combined with the equivalent SOC erosion mitigation potentially increases the equivalent SOC accumulation rate above that associated with the presence of a grass strip alone (Warner et al., 2017). The level of risk and potential to enhance the SOC accumulation above that of a grass strip is specific to individual land parcels and depends principally on local topography, soil type, soil organic matter content and rainfall. Any loss of productive agricultural land needs to be carefully targeted, taking account of the level of erosion risk, a requirement of this type of option, in order to realise an additional benefit.

Two such options were resampled during 2008. The first, option HJ3 Arable reversion to unfertilised grassland to prevent erosion or run-off, targeted the mitigation of water erosion. The second, option OB2 Hedgerow management (margin), sampled the buffer strip between the hedgerow and the arable area. The SOC where these options were present increased by a mean 0.87 – 1.34 t C $ha^{-1} yr^{-1}$, and by a mean 1.16 – 1.62 t C $ha^{-1} yr^{-1}$ relative to the counterfactual (RCF), comparable to 1.1 t C $ha^{-1}yr^{-1}$ allocated to grass margins by previous assessments (Falloon et al., 2004; Ostle et al., 2009; Smith et al., 2000ab) (Table 3.10). On arable land at Wallington the presence of these options have value in both the enhancement of the SOC, in addition to the habitat mosaic they help create. Option HJ3 is a sown mixture. In theory other SOC accumulation practices such as the selection of deep rooting grass species (3.04 t C $ha^{-1} yr^{-1}$) or species diverse mixtures (1.2 t C $ha^{-1}yr^{-1}$) (Conant et al., 2001; Dawson and Smith, 2007; Fitter et al., 1997; Soussana et al., 2004) could be included. Such strategies are as yet unconfirmed, and limited to a small number of trials.

These types of options are limited spatially with respect to their uptake potential and value in SOC enhancement. The remaining options are more broadly applicable, subject to the presence of the appropriate land management class.

3.3.2.3. Option OU1 inclusion of grass / clover leys on arable land

The inclusion of a 2-3 year grass/clover ley within the rotation improved SOC by 0.18 – 0.86 t C $ha^{-1} yr^{-1}$ RCF at Wallington and Wimpole. The mechanism by which SOC increases is primarily due to a decrease in tillage frequency, the nature of which depends on the rotation and duration of the ley. In New Zealand Rutledge *et al.* (2015) observe declines of 1.0 – 2.0 t C ha^{-1} within the first three months post cultivation of grassland, before CO_2 emission ceases and carbon sequestration begins. Extrapolating this to the cultivation of a grass/clover ley, the longer the period of cultivation between leys and the shorter the duration of the ley, the lower the SOC equilibrium of the land use. The proportion of the rotation occupied by a ley in the case study scenarios varied between 20% and 60%. The published literature cites changes in SOC of 0 – 0.54 t C ha^{-1} yr^{-1} (Dawson and Smith, 2007; Falloon et al., 2004; Freibauer et al., 2004; King et al., 2004) although values as high as 0.71 t C ha^{-1} yr^{-1} are given by Smith et al. (2000ab, 2005b).

At the Wallington and Wimpole Estates the largest increase (0.86 t C ha^{-1} yr^{-1}) was on existing low SOC baseline arable land as a component of option OU1. This arable land also had the highest proportion of ley within the rotation, 50 – 60% and unlike other leys, included lucerne, a deep rooting legume. Deep rooting grasses are cited by Conant et al. (2001) to enhance SOC further, however the presence of lucerne could not be isolated as a variable from the proportion of ley within the rotation. Although option OU1 has instigated the inclusion of grass/clover/lucerne leys on the Donkin Rigg tenancy, this form of fertility building practice is not exclusive to organic management. Leys, albeit variations in the length of, were present on two other tenancies where organic management was not in place.

In terms of production displacement, while land is maintained within the arable land use classification there is a decrease in the number of arable crops grown over the duration of the rotation. This is proportional to the length of rotation and duration of the ley. Of the rotations evaluated, the maximum increase of 0.86 t C ha^{-1} yr^{-1} required 50 – 60% of the rotation to be occupied within a ley and, as a mixed farm, grazing by livestock was possible. This maintains the productivity of the relevant land parcels while returning a proportion of the biomass removed as grazing deposition. For the full potential of this management to be realised, implementation on mixed farms is of benefit, as this sustains a low displacement risk. It is acknowledged that grazing leys may not be viable in all parts of England, particularly in the east where purely arable cropping systems dominate. An alternative strategy under such circumstances would be the use of the grass as for example a feedstock for anaerobic digestion (Curry et al., 2018; FitzGerald et al., 2019). The digestate has the potential to be returned to the soil as a source of organic matter with the potential to enhance SOC further. Although beneficial to levels of SOC the displacement risk increases. An alternative, and one utilised by the Wimpole Estate, is to graze stock from other farms on the leys during the winter.

3.3.2.4. Management practice: organic amendments to arable land

The addition of organic amendments (FYM, straw) are not a component of ES options as there is no income foregone attached to their use. They have been included in the ranking process as a benchmark. Organic amendments have improved SOC where applied to arable land at both the Wallington and Wimpole estates. The importing of organic N within FYM may be necessary to comply with, for example, the requirements of the Nitrate Pollution Prevention Regulations (2015) on land within Nitrate Vulnerable Zones (NVZs). Under such circumstances, the source farm is not penalised for a potential loss of organic matter. Further, if a farm produces excess organic N it is likely to be predominantly grassland based while the enhancement of SOC using FYM is reported to realise its greatest benefit on arable land (Smith et al., 2000ab). The increase in SOC ranged from 0.04 – 0.46 t C ha^{-1} yr^{-1} as measured, or 0 – 0.74 t C ha^{-1} yr^{-1} RCF, compared to 0.26 – 0.69 t C ha^{-1} yr^{-1} according to Dawson and Smith (2007), or straw incorporation specifically by 0.53 – 0.72 t

C ha^{-1} yr^{-1} (Smith et al., 2007). The displacement risk is low and will be negligible when coupled with balanced fertilisation with inorganic sources of supplementary nutrition. Both estates apply FYM as a priority to cultivated land where present, or to Itemp on purely grassland based tenancies, supporting the recommendations of Smith et al (2000ab). The incorporation of wheat straw (50% of the rotation) practiced on the heavy clay soils at Wimpole increased SOC by 0.45 t C ha^{-1} yr^{-1}. In addition to the supply of carbon, it is likely to also improve drainage and prevent soil compaction (Conant *et al.*, 2001; 2005; Freibauer *et al.*, 2004; Louwagie *et al.*, 2009). Soil compaction prevents root penetration while poor drainage risks the creation of anaerobic soil conditions. Both hinder crop growth in arable systems and the potential return of biomass to the soil. The Wimpole Estate is located in the east of England where arable cropping dominates. In reference to the inclusion of grass/clover leys coupled with grazing in the previous section, the incorporation of straw from a proportion of the rotation may be preferable in areas where livestock numbers are lower.

3.3.2.5. Rperm to wood pasture

The introduction of wood pasture on Rperm has parallels with silvo-grassland systems more prevalent in Europe. It is an option that may benefit SOC on mineral soils only. Although the SOC accumulation may be lower than for woodland creation, the risk of displacement is also low because of the existing low productivity system can continue to be grazed at equivalent stocking rates, if the newly planted trees are protected. The 0.17 t C ha^{-1} yr^{-1} accumulated at Wimpole is greater than the 0.1 t C ha^{-1} yr^{-1} estimated for woodland creation in upland areas (Ostle et al., 2009), comparable to the 0.13 t C ha^{-1} yr^{-1} for grassland to forest on 10% of the area (Brown et al., 2017). The tree density for the wood pasture at Wimpole has the potential to be increased, as trees are planted in lines for aesthetic purposes.

3.3.2.6. Itemp to Iperm as EL2 or EL3

The conversion of Itemp to Iperm removed the ploughing and reseed operation typically implemented over a five year cycle. Direct measurement ranged from -0.41 to 0.08 t C ha^{-1} yr^{-1} and by 0.14 – 0.63 t C ha^{-1} yr^{-1} RCF, comparable to the 0.35 t C ha^{-1} yr^{-1} cited by Ostle et al. (2009). The replacement of Itemp with Iperm has the potential to improve the SOC at equilibrium. The magnitude of this increase and the variation within it means that there are a number of caveats to consider. The removal of the reseed operation does not allow the resowing of grassland with productive grass species such as perennial ryegrass for winter animal feed, or red and white clover to supplement nitrogen supply. Legumes such as clover or lucerne are used as high protein forage (Thomas, 2004). The displacement risk category is medium (Warner et al., 2013) due to the potential loss of productivity. Further, importing animal feed into the system risks the impact being a net negative due to the emissions associated with transporting feed from external sources. Due to the risk of production displacement any change in land use of this nature would be best targeted according to the underlying soil series. It is potentially more justified on surface or groundwater gley soils.

The impact of the remaining options on SOC is either uncertain or negligible.

3.3.2.7. Options EK2, EL2, EK3 or EL3 on Iperm low fertiliser inputs and enhanced sward species diversity

This category of options has been ranked lower as it represents changes in SOC that are difficult to quantify and signify an element of uncertainty. It does not mean that such management is not important, as indeed Smith (2014) highlights the importance of appropriate management of grasslands in order to maximise and maintain their value as a C sink. For this group of options there is no change in land use category although the variability in measured SOC change between tenancies is high, -1.82 to 1.67 t C ha^{-1} yr^{-1} and -0.54 to 2.95 t C ha^{-1} yr^{-1} RCF. There are a number of factors that may operate in combination. Methods considered to have the potential to improve SOC on productive grassland include optimal crop nutrition, liming, the presence of a greater sward species diversity, improved productivity grass species, and low to moderate levels of grazing of 0.4 – 0.8 LU ha^{-1} (Conant et al., 2001; Dawson and Smith, 2007; Fornara *et al.*, 2011; 2013; Thornley and Cannell, 1997; Soussana et al., 2004; Stockman *et al.*, 2013).

Improved sward species diversity is considered by Dawson and Smith (2007) as a means to enhance SOC on grassland, however, this is for calcareous grassland in the UK. Outside of Europe Cong et al. (2014) and Chen et al. (2018) are also supportive of the principal. The growing of high productivity grass species, such as perennial ryegrass, and the creation of species rich grasslands are not complementary to one another. Grassland species with a lower competitive ability are typically unable to survive in the presence of high productivity species on nutrient rich soils, but are able to exploit low fertility soils more effectively. This refers specifically to soils with a combination of a low P index (Janssens et al., 1998) and where N is not applied (Tallowin et al., 1994). Options EK2/EL2/EK3/EL3 stipulate maximum N application rates but do not eliminate them. Neither do they eliminate application of P. Any enhancement of SOC would most likely be related to Thornley and Cannell's (1997) findings related to low nitrogen inputs although the increase noted by these authors is small (0.08 t C ha^{-1} yr^{-1}). Warner et al. (2008) did not allocate SOC change to the implementation of options EK2/EL2/EK3/EL3 on existing permanent grassland due to the lack of published evidence. Due to the variability in data collected, this conclusion has not changed. Options such as UOL20 haymaking aim to encourage sward species diversity, while mixed grazing (UOL18 / UL18) offer the potential to increase sward structural diversity. Since the sward species or structural diversity has not been measured directly these variables cannot be cited conclusively in the current analysis. No definitive change in SOC has been allocated to these options although option UOL18 / UL18 is discussed further in the next section.

3.3.2.8. Options UL18 / UOL18 grazing management

The impact of grazing on grassland SOC is inconclusive. The timing and intensity of grazing are potential determinants of the rate of SOC accumulation in grassland soils (Conant *et al.*, 2001; 2005; Freibauer *et al.*, 2004). As a caveat Smith *et al.* (2008a) conclude that the inconsistency between studies prevent the recommendation of any one practice with confidence. Options that impact grazing include UL18 / UOL18. A minimum of 30% of livestock units as cattle are required to graze land formerly grazed only by sheep. The change in SOC where this option was implemented was variable, declining by -1.24 to -0.21 t C ha^{-1}yr^{-1} measured, or an increase of 0.04 to 0.33 t C ha^{-1} yr^{-1} RCF at Wallington. Potential changes to the sward include an increase in structure and diversity (section 3.3.2.7) although this was not measured. Cattle are heavier per head and where there is overgrazing, this may cause soil compaction (Conant *et al.*, 2001; 2005; Freibauer *et al.*, 2004; Louwagie *et al.*, 2009). However, this is not exclusive to cattle and may occur with high stocking rates of sheep. Further, the cattle on the Wallington Estate are housed during the winter, typically between November and April, when soils are wet and most vulnerable to compaction. Maximum stocking rates are stipulated within the option agreements. Where option UL18 / UOL18 are present these do not exceed the 0.8 LU ha^{-1} specified by Dawson and Smith (2007) and Smith et al. (2008) as a benchmark maximum to prevent SOC decline. In reference to the previous section and the potential for increased grass species diversity on soils in response to low P indices (Janssens et al., 1998) and zero N application (Tallowin et al., 1994), the land parcel does not receive supplementary nutrients. It was in receipt of basic slag, a source of P_2O_5, until 2010. If enhanced species diversity is to contribute to SOC accumulation in this case the P index will need to be reduced, a possibility given the offtake from haymaking, but a mechanism subject to a lag effect.

3.3.2.9. Management practice Arable to Itemp

Arable land is typically cultivated annually, and Itemp every five years. The SOC at equilibrium is potentially higher in Itemp compared to arable land due to the lower tillage frequency, as noted by Bell (2011). This difference was not so prevalent in the measured SOC in 2018 where although the mean SOC was higher, it was not significantly different. The increase in SOC, 0.25 t C ha^{-1} yr^{-1} or 0.53 t C ha^{-1} yr^{-1} RCF is comparable to including a grass / clover ley. For the conversion of arable land to Itemp to have value as a means of SOC enhancement, the function of the land (animal feed production) must remain in place and the displacement risk to be low. If there is to be a land use change, overall the SOC equilibrium would be better enhanced with conversion to permanent grassland or woodland. It is not considered as a management practice conducive with SOC enhancement.

3.3.2.10. *Option HF20 annually cultivated arable margins*

Cultivated margins are unlikely to enhance SOC on arable land as there is no change in the frequency of tillage. A decline may result because of the decrease in organic matter return from a single year of natural regeneration as opposed to a purposely sown crop. The SOC decreased by -0.75 t C ha^{-1} yr^{-1}, -1.08 t C ha^{-1}yr^{-1} RCF compared to the -0.25 t C ha^{-1}yr^{-1} stated by Dawson and Smith (2007). This option risks decreasing SOC.

4.0 Conclusions

The change in SOC between 2008 and 2018 varies depending on land use. The arable land on both the Wallington and Wimpole estates has increased in SOC overall, albeit not significantly, since 2008. The management of arable land at both locations includes practices conducive with the enhancement of SOC such as grass/clover leys (as part of option OU1), and organic amendments such as straw or farmyard manure. The addition of grass/clover leys on existing low baseline SOC arable land significantly increased the SOC on one tenancy. Increases were noted on others where incorporated into the rotation since 2008. Options that take a proportion of land out of agricultural production, where appropriately targeted to protect sensitive habitat features or vulnerable soils also play an important role in the enhancement of SOC on arable land. These management practices and changes in land use permit continued production, remaining within the low to moderate displacement risk categories.

The story for grassland is not so positive. The SOC of grassland has declined significantly overall, and quite drastically in the case of the rough permanent grassland and marshy grassland land use categories. It is however difficult to account for any potential lag effect in restoring SOC through ES option implementation. Ten years is a relatively short timeframe in monitoring SOC change and a number of options have been implemented since 2008. Where gains are not be immediate, benefit will not be realised within this timeframe. The decline on marshy grassland may indicate wetland habitat where the SOC has continued to deteriorate due to remnant drainage systems. Although these drainage systems have been allowed to deteriorate and no longer function, the benefit of restoration options (for example option HL8-Restoration of rough grazing for birds) was not in this case realised during the 10 year ES agreement itself. The decline in SOC is however likely to be at a potentially slower rate than if a fully functioning drainage system were in place. Successful rewetting of organic soils where gains in SOC have been demonstrated are typically achieved in the medium to long term (Moorby et al., 2007; Worrall et al., 2011). Based on the SOC change measured at Wallington, complete reversal of the SOC lost is estimated to take 10 – 100 times as long, requiring longer term management agreements beyond the current 10 year maximum. Having supplementary options available to permit the removal of stock in rewetted areas to mitigate the risk from, for example, parasites requires consideration.

The creation of wood pasture has a potential benefit for SOC on rough permanent grassland. It also maintains the production levels where implemented on existing low input grassland. The changes in grassland management practice where there is no land use classification change (for example permanent grassland remains as permanent grassland) and their impact on SOC maintain a degree of uncertainty. The current analysis operates at the landscape scale whereby multiple factors exert an influence. For the contribution of factors such as supplementary nutrients, sward diversity and stocking levels toward SOC in grassland be accounted for with more confidence, lower spatial scale field trials with a higher sampling intensity would be more appropriate.

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Appendix 1.0. Sampling strategy for individual Wallington tenancies.

A1.1. Prior Hall Farm (no ES counterfactual 1)

Prior Hall is not in Environmental Stewardship and has been established as a counterfactual for arable land and grassland (improved temporary and improved permanent). It is a mixed farm consisting of arable, improved permanent grassland grazed by sheep and sheep and cattle, and temporary grassland grazed by sheep. To the south-east is an area of poorly draining marshy grassland (Figure A1.1). The river banks were highlighted by Warner et al. (2011a) as being at risk to erosion which was accelerated by unrestricted livestock access. Several field boundary trees are identified as a key feature of interest by the Wallington Biological Survey (1999), in addition to areas characteristic of wood pasture. The area of land to the south-west of the tenancy (blue highlight) formerly in Prior Hall is now a part of the Broomhouse tenancy. The area to the far west (grey highlight) formerly in Broomhouse is now a part of the Prior hall tenancy. This exchange of land occurred in 2014.

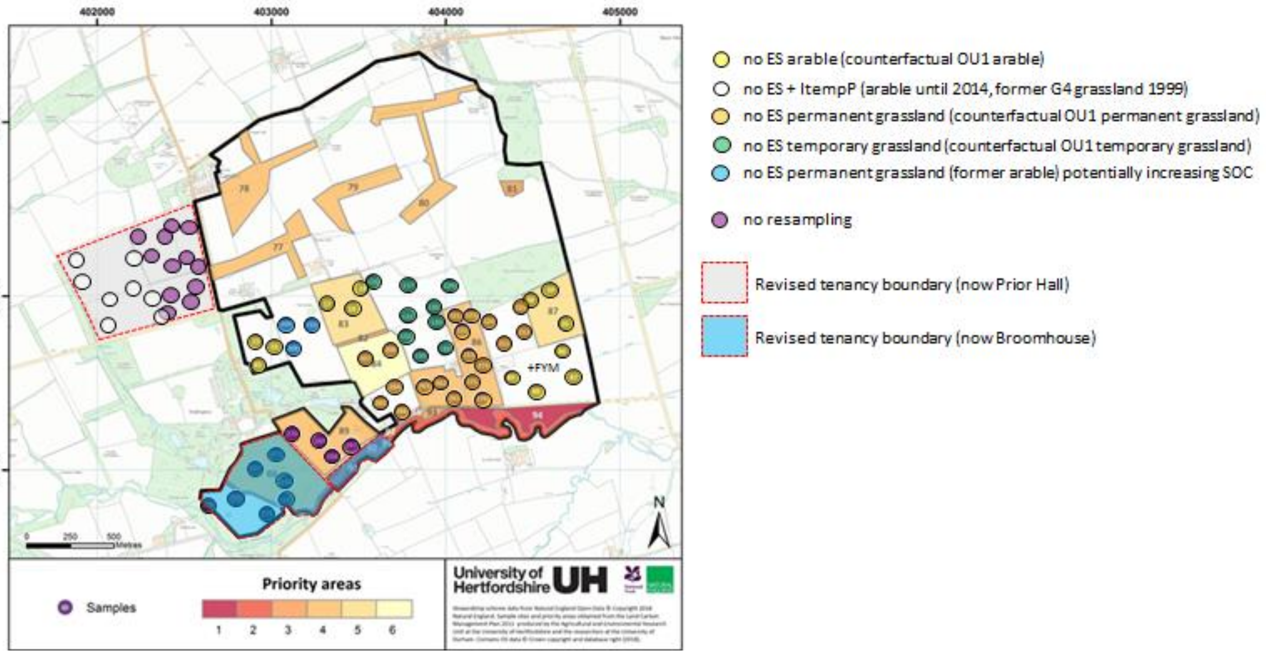


Figure A1.1. Map of Prior Hall tenancy, resampling locations representative of counterfactual samples.

The priority areas refer to the assessment of Warner et al. (2011a). They prioritise areas of the tenancy where appropriate ES options (namely HLS options due to the original objectives for the estate) may be targeted to maximise carbon sequestration in soil and biomass.

A1.2. Newbiggin Farm (including no ES counterfactual 2)

A predominantly arable tenancy with land in both organic (since 2010) and non-organic management (Figure A1.2). An area of rough permanent grassland grazed by sheep is located to the south-west including a small area of marshy grassland in the south-west corner. Mature trees are present throughout the tenancy, 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 (Biological Survey, 1999).

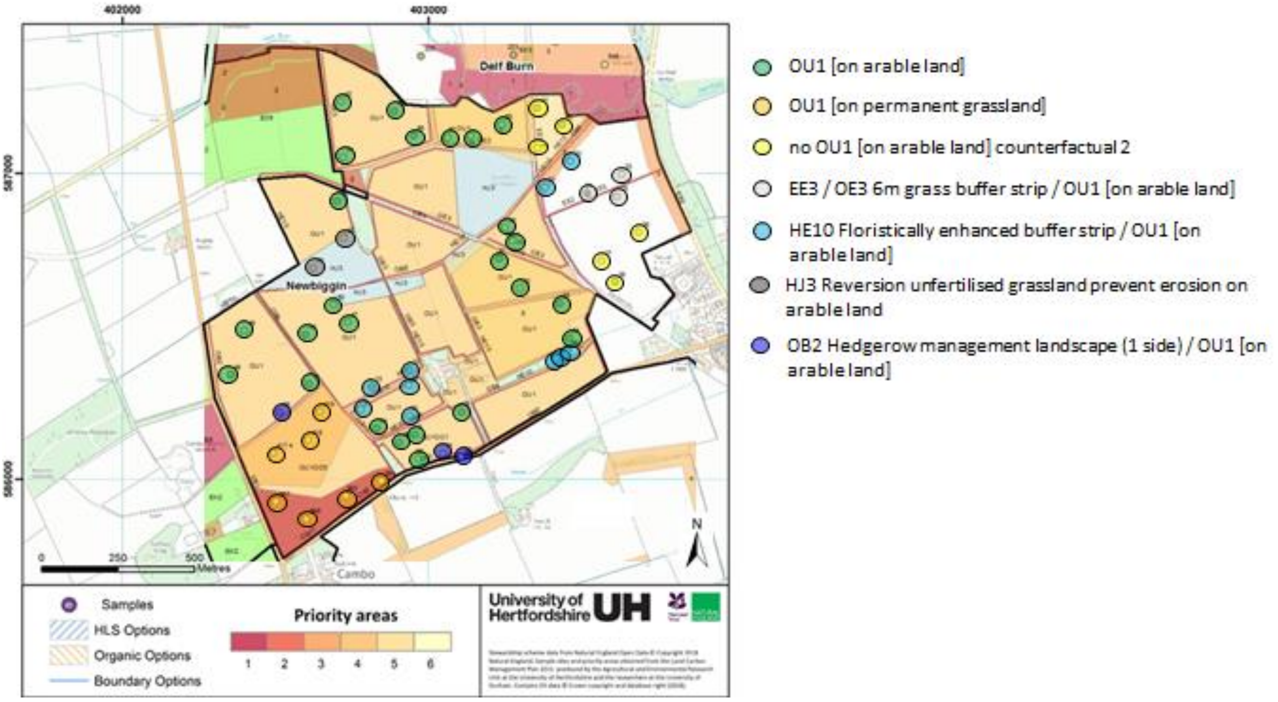


Figure A1.2. Agreement map for Newbiggin Farm tenancy, ES options and resampling locations (©Natural England).

ES options:

- OU1 [on arable land]
- OU1 [on permanent grassland]
- EE3 / OE3 6m grass buffer strip / OU1 [on arable land]
- HE10 Floristically enhanced buffer strip / OU1 [on arable land]
- HJ3 Reversion to unfertilised grassland prevent erosion on arable land
- OB2 Hedgerow management landscape (1 side) / OU1 [on arable land]

Counterfactual no OU1 [on arable land]

The priority areas refer to the assessment of Warner et al. (2011a). They prioritise areas of the tenancy where appropriate ES options (namely HLS options due to the original objectives for the estate) may be targeted to maximise carbon sequestration in soil and biomass.

A1.3. Donkin Rigg Farm

Similarly to Newbiggin Farm this tenancy has also undergone organic conversion in 2010. It is a mixed farm consisting of arable land to the south-west, with predominantly rough permanent grassland grazed by sheep, or sheep and cattle on the remainder of the land (Figure A1.3). An area of improved temporary grassland is located to the east. Marshy grassland and semi-improved calcareous grassland are situated to the north.

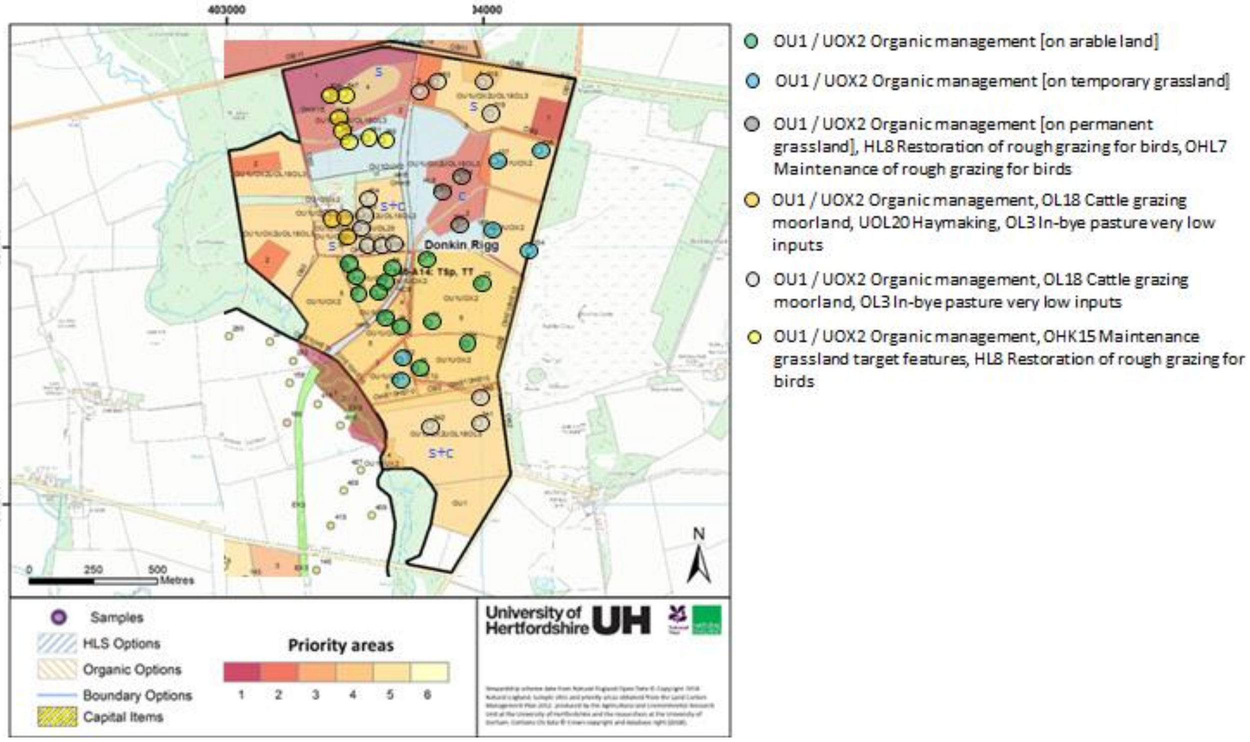


Figure A1.3. Agreement map for Donkin Rigg Farm tenancy, ES options and resampling locations (©Natural England).

ES options:

- OU1 / UOX2 Organic management on arable land
- OU1 / UOX2 Organic management on temporary grassland
- OU1 / UOX2 Organic management on permanent grassland
- UOL18 Cattle grazing moorland
- UOL20 Haymaking
- OL3 In-bye grassland very low inputs
- HL8 Restoration of rough grazing for birds
- OHK15 Maintenance grassland target features

The priority areas refer to the assessment of Warner et al. (2011a). They prioritise areas of the tenancy where appropriate ES options (namely HLS options due to the original objectives for the estate) may be targeted to maximise carbon sequestration in soil and biomass.

A1.4. Broomhouse Farm

In 2010 this tenancy was 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. Between 2009 and 2012 the number of stock were reduced coupled with an increase in the arable area to produce animal feed sold off farm. From 2014 onwards the arable component was phased out completely and replaced with temporary grassland. The boundaries of this tenancy have also been modified since 2014 with two land parcels now a component of the Prior Hall Farm tenancy (Figure A1.4). Areas of coniferous and broadleaved woodland are located in the centre of the tenancy. A river flanked by mature trees and species rich grassland is located to the south, with a pond and areas of marshy ground to the west.

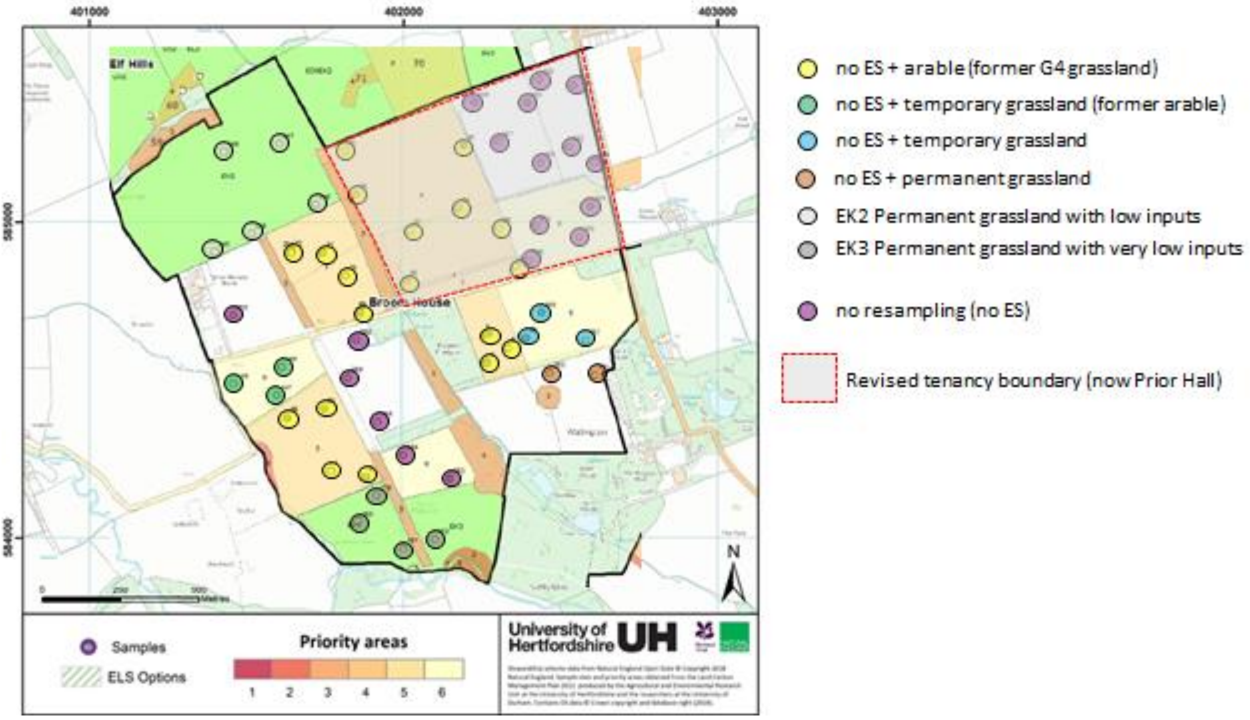


Figure A1.4. Agreement map for Broomhouse Farm tenancy, ES options and resampling locations (©Natural England).

ES options:

- EK2 Permanent grassland with low inputs
- EK3 Permanent grassland with very low inputs

Other factors that require consideration include changes in land use between 2008 and 2018 from temporary grassland to arable back to temporary grassland.

The priority areas refer to the assessment of Warner et al. (2011a). They prioritise areas of the tenancy where appropriate ES options (namely HLS options due to the original objectives for the estate) may be targeted to maximise carbon sequestration in soil and biomass.

A1.5. Gallows Hill Farm

No arable land is present on the Gallows Hill Farm tenancy (Figure A1.5). In 2010 improved temporary, improved permanent and rough permanent grassland types were present. 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. To the east of the tenancy is a burn with mature trees on the eastern side and marshy grassland to the west. Lowland calcareous grassland is present on the southern boundary and along the crags/quarry near the farmhouse.

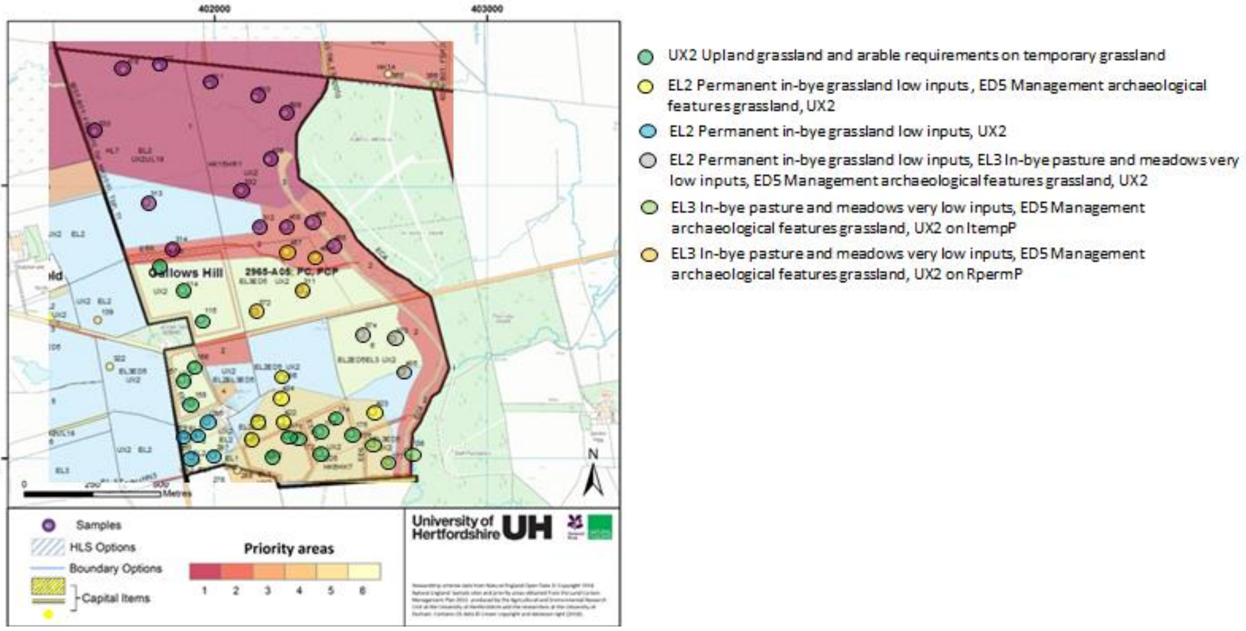


Figure A1.5. Agreement map for Gallows Hill Farm tenancy, ES options and resampling locations (©Natural England).

ES options:

- UX2 Upland grassland and arable requirements on temporary grassland
- EL2 Permanent in-bye grassland low inputs
- ED5 Management archaeological features grassland
- EL2 Permanent in-bye grassland low inputs
- EL3 In-bye grassland and meadows very low inputs

The priority areas refer to the assessment of Warner et al. (2011a). They prioritise areas of the tenancy where appropriate ES options (namely HLS options due to the original objectives for the estate) may be targeted to maximise carbon sequestration in soil and biomass.

A1.6. Catcherside Farm

This tenancy has no arable land but improved temporary, improved permanent and rough permanent grassland are present (Figure A1.6). Rough permanent grassland (MG6, G3-G4) grazed by sheep and cattle, and sheep only are located to the south and north respectively. Improved temporary grassland grazed by sheep is present in the centre, with improved permanent grassland to the west. The Wallington Biological Survey (1999) lists relict moorland habitats to the west.

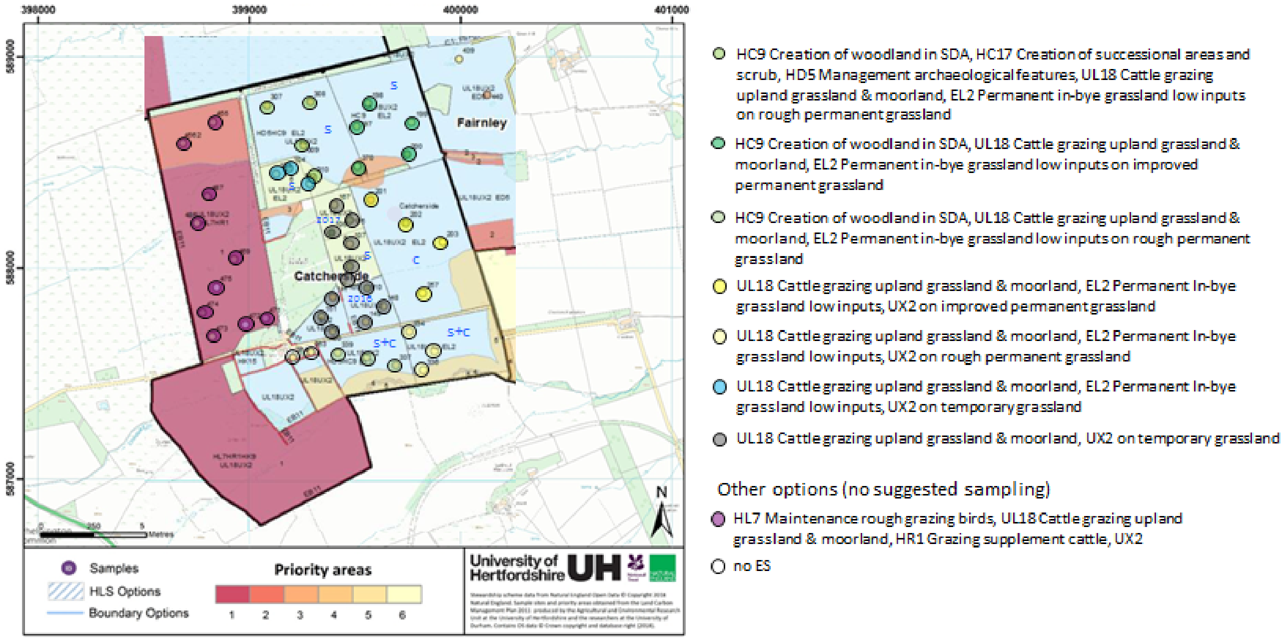


Figure A1.6. Agreement map for Catcherside Farm tenancy, ES options and resampling locations (©Natural England).

ES options:

- HC9 Creation of woodland in SDA (part parcel)
- HC17 Creation of successional areas and scrub (part parcel)
- HD5 Management archaeological features
- UL18 Cattle grazing upland grassland & moorland
- EL2 Permanent in-bye grassland low inputs
- UX2 on permanent grassland
- UX2 on temporary grassland

The priority areas refer to the assessment of Warner et al. (2011a). They prioritise areas of the tenancy where appropriate ES options (namely HLS options due to the original objectives for the estate) may be targeted to maximise carbon sequestration in soil and biomass.

Appendix 2.0. Sampling strategy for individual Wimpole tenancies.

A2.1. Eight Elms Farm (no ES counterfactual 1)

Eight Elms Farm is an arable farm located to the south-west of the estate (Figure 2.2.1). It has not been entered into ES and has been sampled as a counterfactual measure, particularly for comparison with the Cambridge Road tenancy situated directly eastwards the other side of the Wimpole Avenue (light green band in Figure A2.1). The assessment of Warner et al. (2011a) did not include the Wimpole Estate. There are no priority zones marked on the maps of the Wimpole tenancies.

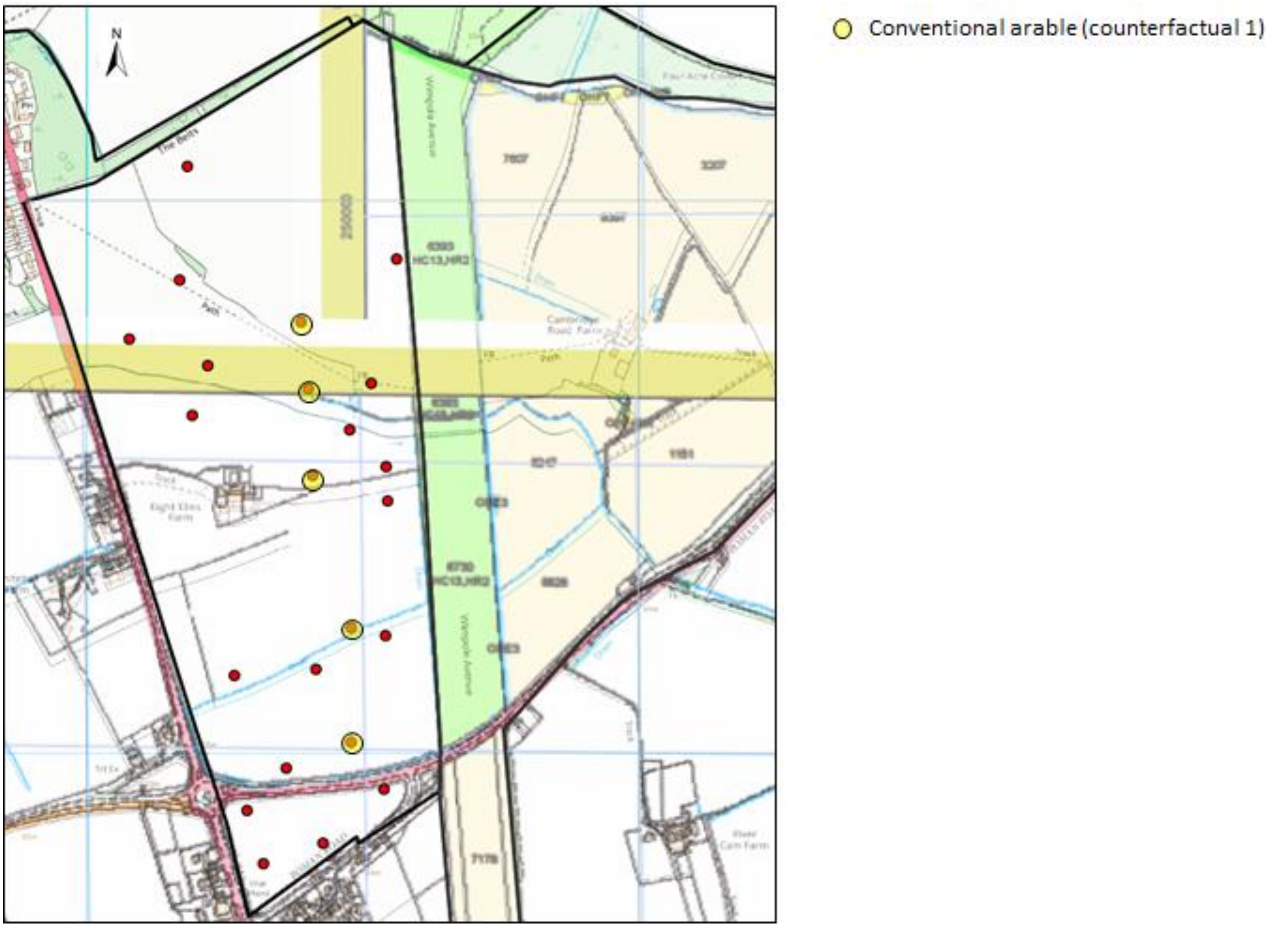


Figure A2.1. Agreement map for Eight Elms Farm tenancy and resampling locations (©Natural England).

- Counterfactual arable 1 no ES options

The field boundaries consist of a network of hedgerows, grass margins and deep drainage ditches. The site topography is purely flat land with no gradients situated on slumped boulder clay (National Trust, 2018).

A2.2. Kingston Pastures Farm (no ES counterfactual 2) and Valley Farm

Kingston Pastures is the second tenancy resampled on the Wallington Estate not entered into ES agreements and established as counterfactual 2 (Figure A2.2). It is an arable farm located to the north-west of the estate. The field boundaries consist mainly of grass margins and deep drainage ditches, with woodland to the east of the sampling area and gently sloping land with a southward facing slope.

- Counterfactual arable 2 no ES options

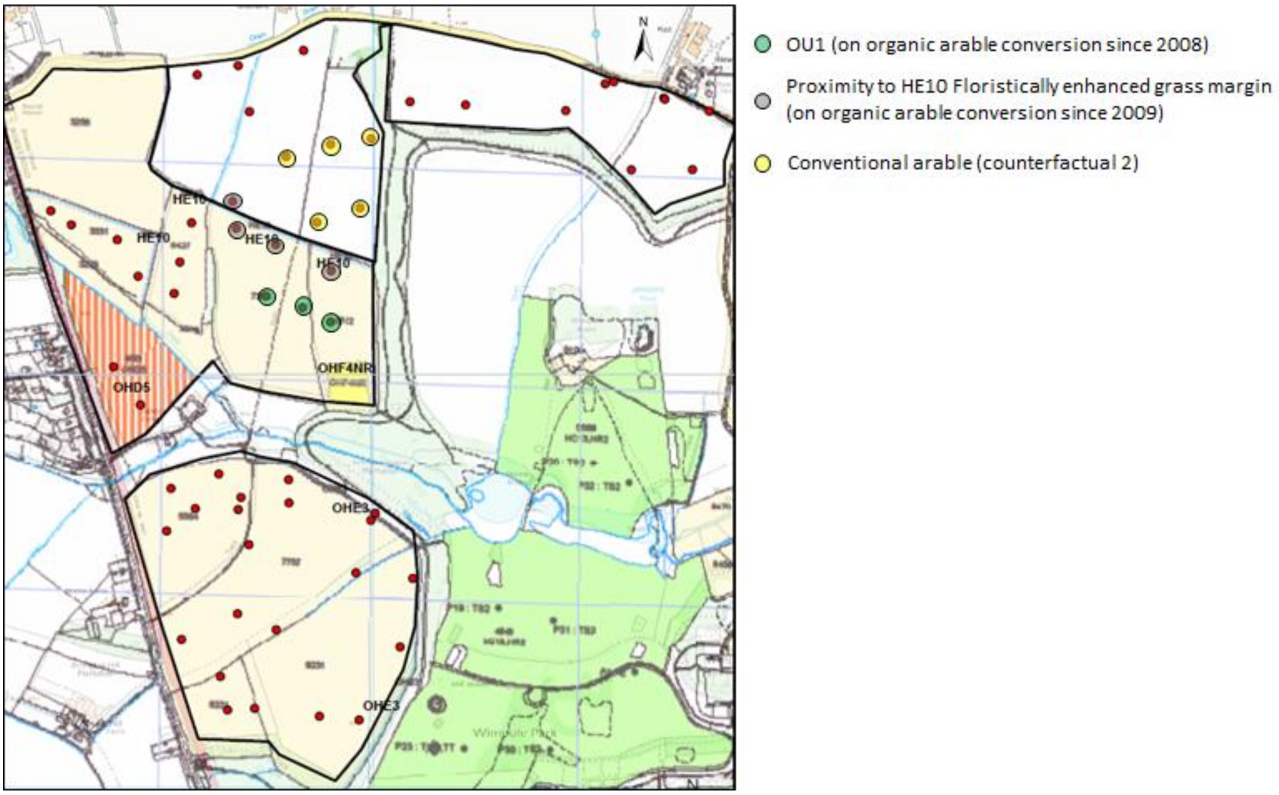


Figure A2.2. Agreement map for Kingston grasslands Farm and Valley Farm tenancies, ES options and resampling locations (©Natural England).

Valley Farm is located immediately to the south of Kingston Pastures. It is also an arable farm but was converted under ES to organic management in 2008. It consists of flat land with no gradients. Deep drainage ditches and hedgerows are located along the field boundaries.
ES options:

- OU1 (on organic arable conversion since 2008)
- Proximity to HE10 Floristically enhanced grass margin

A2.3. Cambridge Road Farm and Wimpole Avenue

Cambridge Road Farm is an arable tenancy adjacent to Eight Elms Farm (Figure A2.3). It was converted to organic management under ES in 2012. The field boundaries consist of hedgerows in combination with deep drainage ditches, with woodland to the north of the sampling area. The tenancy consists of flat land with no gradients.

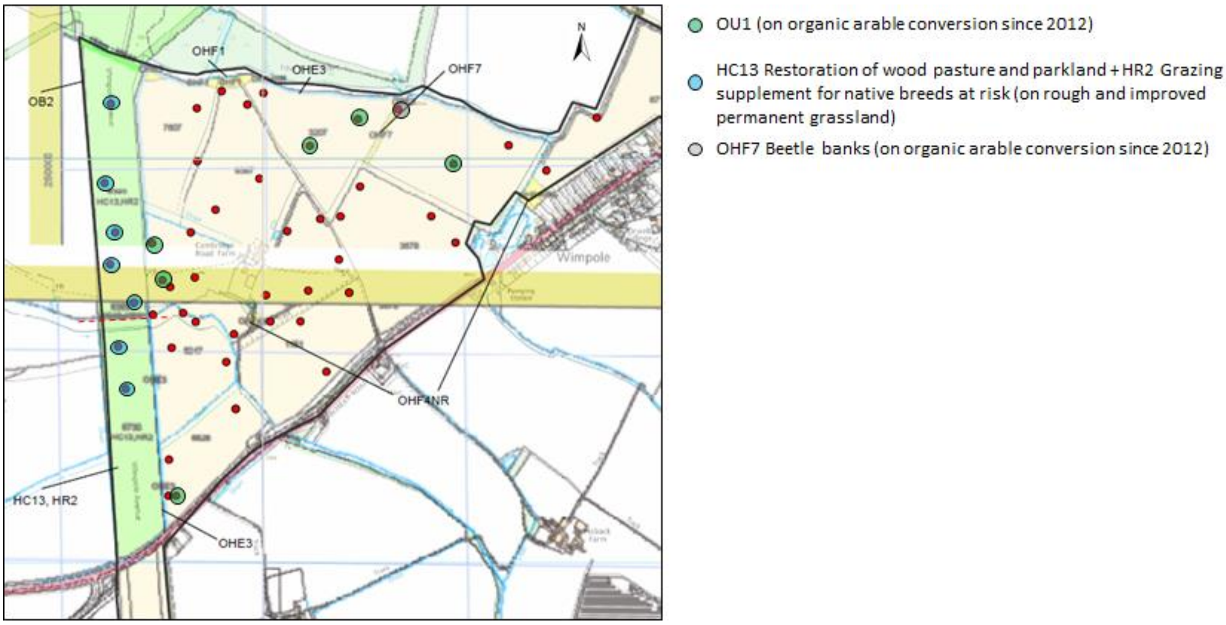


Figure A2.3. Agreement map for Cambridge Road Farm tenancy and Wimpole Avenue, ES options and resampling locations (©Natural England).

ES options:

- OU1 (on organic arable conversion since 2012)
- OHF7 Beetle banks

Wimpole Avenue consists of a permanent grass area with treelines adjacent to a hedgerow and deep drainage ditches either side. The sward is short to the south and classed as Iperm (Bell, 2011) with Rperm located proceeding northwards (above the red dashed line in Figure A2.3). The area is grazed by sheep.

ES options:

- HC13 Restoration of wood pasture and parkland + HR2 Grazing supplement for native breeds at risk (on improved grassland)

A2.4. Cobbs Wood Farm

An arable farm converted to organic management in 2008. The field boundaries include hedgerows and grass margins, with a woodland strip running through the centre (Figure A2.4). Areas of steeply sloping land are located in the centre of the tenancy and to the east.

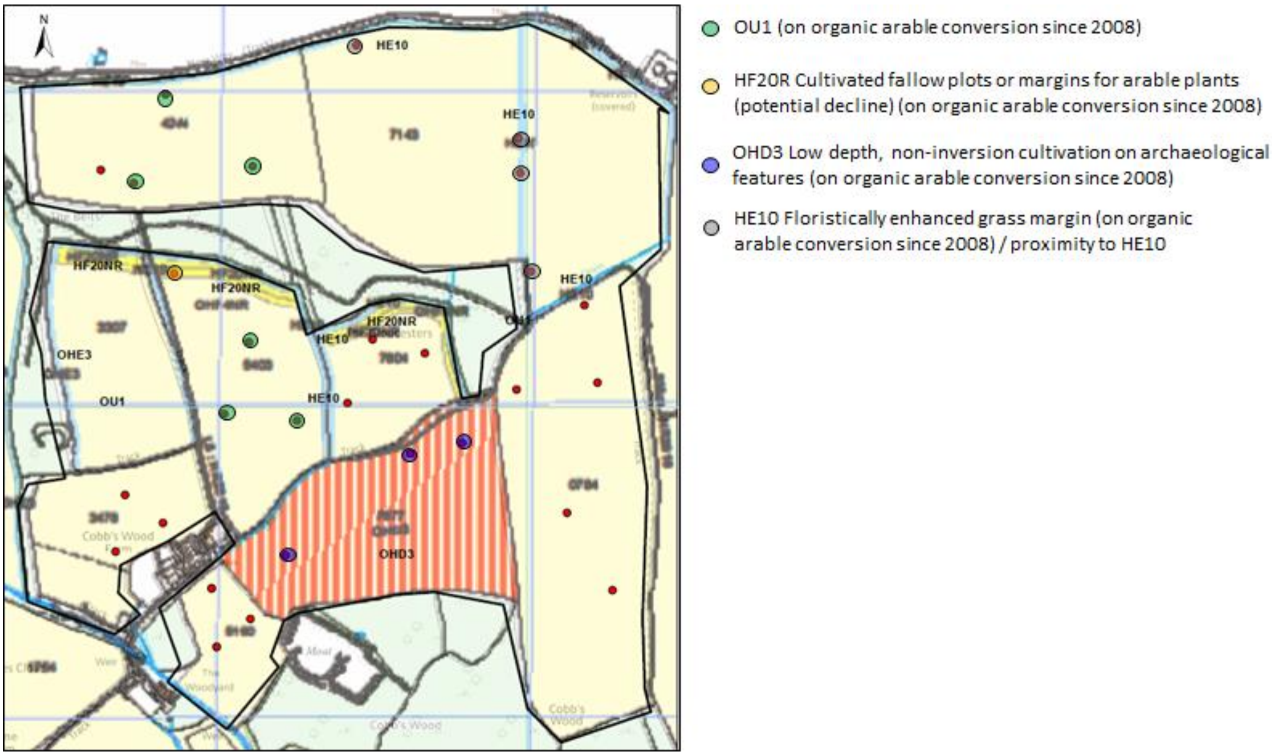


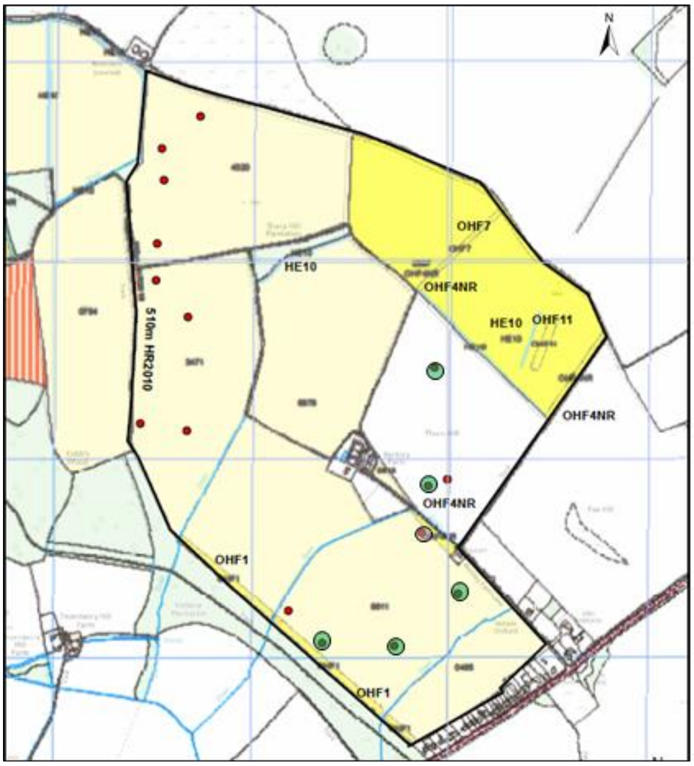
Figure A2.4. Agreement map for Cobbs Wood Farm tenancy, ES options and resampling locations (©Natural England).

ES options:

- OU1 (on organic arable conversion since 2008)
- HF20R Cultivated fallow plots or margins for arable plants
- OHD3 Low depth, non-inversion cultivation on archaeological features
- HE10 Floristically enhanced grass margin

A2.5. Rectory Farm

Rectory Farm was converted under ES to organic management in 2008 and is a purely arable farm. The sampling area to the south is flat, with steeply sloping land to the north. Woodland is present to the south-west of the sampling area, combined with hedgerows and deep drainage ditches running along the field boundaries (Figure A2.5).



● OU1 (on organic arable conversion since 2008)

○ OHF4NR Nectar flower mixture (on organic arable conversion since 2008)

Figure A2.5. Agreement map for Rectory Farm tenancy, ES options and resampling locations (©Natural England).

ES options:

- OU1 (on organic arable conversion since 2008)
- OHF4NR Nectar flower mixture