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Prioritising agri-environment options for greenhouse gas mitigation

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Abstract

Purpose – This paper aims to assess agri-environment (AE) scheme options on cultivated agricultural land in England for their impact on agricultural greenhouse gas (GHG) emissions. It considers both absolute emissions reduction and reduction incorporating yield decrease and potential production displacement. Similarities with Ecological Focus Areas (EFAs) introduced in 2015 as part of the post-2014 Common Agricultural Policy reform, and their potential impact, are considered.

Design/methodology/approach – A life-cycle analysis approach derives GHG emissions for 18 key representative options. Meta-modelling is used to account for spatial environmental variables (annual precipitation, soil type and erosion risk), supplementing the Intergovernmental Panel on Climate Change methodology.

Findings – Most options achieve an absolute reduction in GHG emissions compared to an existing arable crop baseline but at the expense of removing land from production, risking production displacement. Soil and water protection options designed to reduce soil erosion and nitrate leaching decrease GHG emissions without loss of crop yield. Undersown spring cereals support decreased inputs and emissions per unit of crop yield. The most valuable AE options identified are included in the proposed EFAs, although lower priority is afforded to some.

Practical implications – Recommendations are made where applicable to modify option management prescriptions and to further reduce GHG emissions.

Originality/value – This research is relevant and of value to land managers and policy makers. A dichotomous key summarises AE option prioritisation and supports GHG mitigation on cultivated land in England. The results are also applicable to other European countries.

Keywords Carbon sequestration, Agriculture, Agri-environment scheme, Ecological Focus Area, Greenhouse gas

Paper type Research paper

1. Introduction

In 2013, 9 per cent of UK greenhouse gas (GHG) emissions were attributed to agriculture (Department of Energy and Climate Change (DECC), 2015). The emissions profile of the arable sector is well documented, with supplementary nitrogen (N) fertiliser application, nitrous oxide (N_2O) from soils and fossil fuels consumed by machinery the chief contributors

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(Hülsbergen and Kalk, 2001; Tzilivakis *et al.*, 2005; Williams *et al.*, 2009). Previous analysis of agri-environment (AE) schemes, e.g. Environmental Stewardship (ES) and former set-aside land [Allen *et al.*, 2012; Department for Environment, Food and Rural Affairs, 2015 (Defra)] concluded that they have decreased UK GHG emissions because of smaller agro-chemical inputs (especially nitrogen fertiliser) and lower cultivation frequency. This decline is, however, attributed to the removal of agricultural land from production, which cannot be sustained indefinitely. The analyses do not differentiate emissions reduction from the removal of land from production and true mitigation, which is a decrease in emissions per unit of agricultural output. Within England, an increase in food production is targeted concurrent with ecosystem service provision, within the Biodiversity 2020 strategy (Defra, 2011). For the Strategy to be implemented successfully, and if agriculture is to contribute towards the ambitious 80 per cent reduction in UK GHG emissions targeted by the UK Climate Change Act (2008), food production needs to be maintained while simultaneously reducing its environmental impact, particularly its GHG emissions.

Under ES, which was introduced post reform of the European Common Agricultural Policy (CAP) in the 1990's rural development measure (Defra, 2015; Webb *et al.*, 2013), land managers voluntarily committed (Pillar 2) to implement environmental management beyond the minimum mandatory requirement (Pillar 1) to qualify for subsidy payments under the Single Payment Scheme (Defra, 2013). Post 2014, environmental issues have been factored into all aspects of the CAP, including those funded under Pillar 1 (Allen *et al.*, 2012). Under Regulation (EU) No. 1307/2013, adopted in December 2013, known as CAP "greening", Ecological Focus Areas (EFAs) are to be implemented to "safeguard and improve biodiversity on farms" (European Commission (EC), 2013). Biodiversity is the primary objective of EFAs; however, a number of optional elements selected for England (Defra, 2014) may overlap with former ES options. A key question is how the replacement of existing ES options with EFA elements will impact on agricultural GHG emissions, given that the primary objectives are biodiversity, water quality and flood risk management. Although the proposals were under review, the Royal Society for the Protection of Birds (2011) commented that EFAs offered potential to contribute to environmental objectives, including GHG mitigation, subject to appropriate management and placement. The implementation of EFAs over a large area of agricultural land within England under Pillar 1 has potentially significant implications for GHG emissions. The selection of options with priorities for GHG mitigation and productivity in addition to biodiversity are, therefore, a key consideration. A further aim of this paper is to identify which options, when appropriately located, will mitigate GHG emissions and whether they include and afford the level of prioritisation under Pillar 1 that reflects this potential.

The following paper evaluates existing Entry-Level Stewardship (ELS) AE options, a strand of ES chosen, because of their potential availability to all cultivated land within England. For each option, the following has been undertaken:

- benchmarking of their value to GHG mitigation, accounting for impact on crop yield and potential emissions displacement;
- proposal of a dichotomous decision key to facilitate their selection and prioritisation to maximise net GHG emissions reduction; and
- evaluation of the potential impact of EFA elements on agricultural GHG emissions within England, given potential overlap with existing ELS options and their identified priority.

2. Methods

2.1 Screening of Entry Level Stewardship options for greenhouse gas mitigation potential

A life-cycle assessment approach has been followed in combination with IPCC (2006) guidelines and previous assessments (Hülsbergen and Kalk, 2001; Tzilivakis *et al.*, 2005;

Warner *et al.*, 2010; Williams *et al.*, 2009). The system boundary extends to the farm gate and includes the key agricultural GHGs, namely, carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) (Webb *et al.*, 2013; IPCC, 2006; Williams *et al.*, 2009), standardised as tonnes of carbon dioxide equivalent (t CO_2-eq), with a global warming potential of 100 years (GWP_{100}) (IPCC, 2006). The life-cycle inventory considers three main areas: the combustion of fossil fuels (Scope 1, 2 and 3 emissions), emissions from soils and C sequestration in soils or plant biomass. Baseline scenarios provide a reference point against which to compare new land use or land management practices (Table I) following the implementation of ELS agreements. The baseline and option management scenarios have been constructed from a combination of published literature (Defra, 2010; Natural England, 2013) and interviews with farm managers and Natural England officers. Three soil textures (course, medium and fine) and annual rainfall classes (<600, 600-700, >700 mm) are considered.

2.2 Fossil fuel consumption, product manufacture and machinery depreciation

GHG emissions associated with cultivated land include indirect emissions from agro-chemical manufacture (Audsley *et al.*, 2009; Williams *et al.*, 2009), especially inorganic nitrogen (N) fertiliser manufacture (Brentrup and Pallière, 2008), and from farm machinery (Hülsbergen and Kalk, 2001; Williams *et al.*, 2009). Emissions attributed to each scenario (Table I) are derived for:

- *Direct (on farm) emissions from machinery operation (Scope 1)*: They are from pesticide spraying, fertiliser spreading, tillage depending on soil type, and depth and crop sowing (Table II). Scope 2 emissions are from electricity generation.
- *Indirect emissions from product manufacture (Scope 3)*: They are from pesticides and fertilisers, their packaging, storage and transport (to farm) (Table II).
- *Indirect emissions from machinery manufacture (Scope 3)*: They are depreciation per operation or hours of use (Table II).

Predicted biological N-fixation by leguminous crops (e.g. clover) has been deducted from the recommended supplementary N application rates (Defra, 2010). This is dependent on the extent of clover establishment, for which 30-100 kg N $ha^{-1}yr^{-1}$ (based on Torbert *et al.*, 1996) has been calculated, in combination with the Defra (2010) grass growth classes, as a surrogate indicator of potential clover establishment. The allocation of lower N fixation potential reflects soil and annual rainfall classes conducive with poor growth class (Defra, 2010). Deductions are further restricted to applications made during later spring months, when soil temperatures are sufficient for fixation to proceed (Defra, 2010).

2.3 Nitrous oxide

For CO_2-eq calculations for each baseline and option scenario, N_2O emission is assigned as a function of land use and management, in particular, supplementary N fertiliser application (Table II), following the method described by the IPCC (2006), Webb *et al.* (2013) and Williams *et al.* (2009). The IPCC (2006) Tier 1 and 2 approach stipulates that a default proportion (0.3) of supplementary N is removed via leaching and surface run-off, of which 0.75 per cent forms N_2O (IPCC, 2006). It does not account for spatially variable factors (e.g. soil texture) or management practice (it will not distinguish between a fallow soil during the winter and one that is cropped). To detect the impact of more subtle management changes due to ELS option implementation, the $Frac_{(LEACH)}$ leaching and surface run-off factor have been partitioned between leaching and surface run-off to account for localised variation in rainfall, soil texture, management practice and field gradient (Defra, 2005; IPCC, 2006;

Option	Base	Soil	% yield loss	Cultv^n	Fallow	Sow	N	P_2O_5	K_2O	Crop prot^n	Other	Priority	EFAs	EFA weighting
WW winter wheat	–	–	–	1_{20}	–	CD	160-220	63	96	9	L_4+S	–	–	–
SB spring barley	–	–	–	1_{20}	–	CD	110-140	35	45	6	L_4+S	–	–	–
FMZ fodder maize	–	–	–	1_{20}	–	DD	100-150	25	50	2	L_4+S	–	–	–
$H_{(1.5)}$ Hedgerow 1.5-m	–	–	–	–	–	–	–	–	–	–	–	–	–	–
EB3 Enhanced hedgerow management	$H_{(1.5)}$	Mn	**0**	–	–	–	–	–	–	–	–	1a	Hedges	10 m^2 (1)
EC23 Establish hedgerow trees by tagging	$H_{(1.5)}$	Mn	**0**	–	–	–	–	–	–	–	–	1a	–	–
EJ2 Management maize crops soil erosion	FMZ	**VMn**	**0**	1_{20}	–	DD	40-150	25	50	2	L_4+S	1	CC/GC	0.3m^2 (5)
EJ13 Winter cover crops	SB	**VMn**	**0**	1_{20} + Sh	–	2 CD	110-140	35	45	7	L_4+S	1	CC/GC	0.3m^2 (5)
EJ9 12 m buffer strips watercourses	WW	**VMn**	100	0	–	–	0	0	0	1	M	2	Buffer strips	9 m^2 (2)
EJ5 In-field grass areas prevent erosion	WW	**VMn**	100	0	–	–	0	0	0	1	M	2	CC/GC	0.3m^2 (5)
ED3 Reduced-depth non-inversion cult^n	WW	Mn	**<10**	**Sh**	–	CD	160-220	63	96	9	–	3	–	–
EG1 Under sown spring cereals	WW	Mn	**<30**	1_{20}	–	CD	30-100	35	45	6	L_4+S	4	CC/GC; N fix crops	0.3m^2(5);0.7m^2(4)
EC4 Management of woodland edges	WW	Mn	100	*0*	–	–	0	0	0	1	0.1M	5	Buffer strips	9 m^2 (2)
EE3 6-m buffer strips on cultivated land	WW	Mn	100	*0*	–	–	0	0	0	1	M	6	Buffer strips	9 m^2 (2)
EF4 Pollen and nectar flower mixture	WW	Mn	100	$\mathbf{0.5_{20}}$	–	0.5 CD	0	0	0	2	2M	7	Fallow land	1 m^2 (3)

(*continued*)

Table I. Baseline crop production and ELS option management scenarios, also ranked by priority for GHG mitigation potential (prioritisation criteria in bold text) and availability under proposed EFAs within England

Table I.

Option	Base	Soil	% yield loss	Cultv[n]	Fallow	Sow	N	P_2O_5	K_2O	Crop prot[n]	Other	Priority	EFAs	EFA weighting
EF2 Wild bird seed mixture	WW	Mn	100	**0.5_{20}**	–	0.5 CD	100	25	50	5	–	7	Fallow land	1 m^2 (3)
EF9 Cereal headlands for birds	WW	Mn	>30	**1_{20}**	–	CD	0	0	0	8	–	8	–	–
EF15 Reduced herbicide cereal crop	WW	Mn	<30[a]	**1_{20}**	–	CD	160-220	63	96	8	–	8	–	–
EF10 Unharvest headlands birds & plants	WW	Mn	100	**1_{20}**	–	$CD_{(R)}$	0	0	0	5	–	8	–	–
EF11 Uncropped cultivated margins plants	WW	Mn	100	1_{15}	✓	–	0	0	0	1	–	9	Fallow land	1 m^2 (3)
EF13 Uncropped cultivated areas for birds	WW	Mn	100	1_{15}	✓	–	0	0	0	1	–	9	Fallow land	1 m^2 (3)
EF8 Skylark plots	WW	Mn	100	1_{20}	✓	**CD**	**160-220**	**63**	**96**	**10**	**L_4 + S**	10	Fallow land	1 m^2 (3)

Notes: The EFA weighted states the area of individual option deducted from the target 5% and equivalent priority (in brackets). % yield loss refers to that of the original commodity Cultivation: $1_{20}/1_{15}$ annual cultivation plough (20/15 cm) + power harrow, 0.5 biennial cultivation, Sh shallow cultivation (5 cm with tines), CD conventional drill, $CD_{(R)}$ reduced seed rate, DD direct drill, M mown, L_4 4 t ha^{-1} lime every four years, S 30 kg sulphur $ha^{-1}yr^{-1}$VMn: vulnerable mineral soil, Mn mineral soil $H_{(1.5)}$ 1.5-m hedge [a] yield reduction from reduced pesticides. Option EJ2 has three possible sub-options: cultivate the seedbed post-harvest at the earliest opportunity and follow with a spring crop; harvest before end of September and sow a winter cereal; or undersow the maize crop and allow the cover crop to remain during the winter. EFAs: CC/GC catch crop/green cover

Operation	D	I_m	Product	Composition	I_a
Conventional drill	14.3	5.0	Ammonium nitrate	34.5% N	2.17kg^{-1}[a]
Direct drill	18.7	6.9	Ammonium sulphate	21% N; 60% SO_3	0.34 kg^{-1} product
Disc harrow	38.4	12.1	Triple superphosphate	45.5% P_2O_5 (P_2O_5: 43.6% P)	0.17 kg^{-1} product
Hedgerow cutter	0.01m^{-1}		Rock phosphate	28.5% P_2O_5	0.97 kg^{-1} P
Mower	12.3	1.4	Muriate of potash	60% K_2O (K_2O: 83% K)	0.20 kg^{-1} product
Pesticide application	4.7	1.5	Sylvinite (rock K)	24% K_2O	0.86 kg^{-1} K
Plough (20 cm)	82.0	7.6	Lime (limestone)		0.06 kg^{-1} product[b]
Power harrow	48.5	14.5	Pesticides	20 g/$^{-1}$-80% w/w	0.01-29.6 per application
Fertiliser spreading	5.3	1.5			
Spring tine harrows	15.5	4.0			
Stalk chopper	19.2	2.9			
Subsoil (35 cm)	111.9	7.6			
Subsoil tramlines	17.9	1.2			

Type of change	Description	SOC acc^n rate ($R_{(SOC)}$)	Biomass acc^n rate ($R_{(biomass)}$)
New land use	Fertilised permanent grassland	4.40	0.73[c]
	Sown unfertilised grassland/grass margins	3.67	0.73[c]
	Natural reversion	1.65	0.73[c]
	Hedgerow	3.48	3.67[d]
	Scrub	3.48	1.83[d]
	Broadleaved woodland/tree strips	3.30	10.27
New management practice	Minimum tillage	0.37	0
	Agricultural extensification (grass ley)	0.99	0
	Cover crops	1.10	0
	Undersown clover	1.01	0
	Bare soil with limited natural regeneration	0	−8.07[c]

Notes: Carbon accumulation rate (t CO_2-eq ha^{-1}yr^{-1}) within soil (to 30 cm) and biomass in response to a change in land use or management practice on cultivated land (Dawson and Smith, 2007) [a]includes N_2O released during manufacture; [b]includes application; [c]net gain or loss during year 1 only; [d]post year 1 after initial 8.07 t CO_2-eq ha^{-1} loss of crop biomass

Table II. Direct (D) and indirect (I_m) GHG emissions (kg CO_2-eq ha^{-1}) from field operations (Williams *et al.*, 2009) and chemical composition of fertiliser products, the proportion of active ingredient in pesticides and GHG emissions (kg CO_2-eq) from their manufacture (I_a) (Brentrup and Pallière, 2008)

Kirkby *et al.*, 2004; Smith *et al.*, 1996; USA Department of Agriculture (USDA), 2002). Simulations with the decision support tool SUNDIAL (Smith *et al.*, 1996) have derived factors of NO_3^- leaching between 0.19 on fine textured soils with annual rainfall of <600 mm to 0.39 on coarse soils exposed to >700 mm annual rainfall. Nitrate loss via surface run-off has been based on the surface run-off class (Defra, 2005; USDA, 2002), a measure of the potential (low to high) for water to penetrate the soil profile.

The revised leaching and surface run-off factors have been allocated and combined in response to the spatially variable factors described above, in the baseline scenarios (Table I). The presence of buffer strips of specified width is calculated to reduce surface run-off and indirect N_2O by percentages estimated from Dillaha *et al.* (1986) and are comparable to Zhang and Zhang (2011). Nitrogen fixation by legumes is assumed to occur beneath the soil surface and not removed via surface run-off.

2.4 Carbon dioxide

Carbon dioxide released from soils, determined by sequestration rate relative to CO_2 and CH_4 emission (IPCC, 2006), has been set at zero, i.e. is at equilibrium in the baseline scenarios. Potential soil organic carbon (SOC) gained from management or land use change is described in a later section. When soil is eroded, the SOC contained within the previously undisturbed soil has the potential to oxidise to and emit CO_2. It has been derived [equation (1)] using three Joint Research Centre EU Soil Portal Geographical Information System (GIS) data sets: per cent SOC (Jones *et al.*, 2005), dominant soil texture (Panagos *et al.*, 2012) and the Pan-European Soil Erosion Risk Assessment (PESERA) (Kirkby *et al.*, 2004):

$$\text{SOC removed}\,(\text{t}\,CO_2-\text{eq}\,\text{ha}^{-1}\text{yr}^{-1}) = \text{Soil erosion}\,(\text{t soi lha}^{-1}\text{yr}^{-1}) \times \text{SOC}\,(\text{t}\,CO_2-\text{eq}\,\text{t}^{-1}\text{soil}) \quad (1)$$

Soil bulk density, to allow conversion of per cent SOC (Jones *et al.*, 2005) to t CO_2-eq ha^{-1} per t of soil [equation (1)], has been calculated from the dominant soil texture class (Panagos *et al.*, 2012) as a function of land use and per cent clay, silt and sand composition. Classes of weight of SOC removed [equation (1)], that reflect potential scenarios on cultivated land within England, have been created in combination with the t soil ha^{-1} yr^{-1} at risk to erosion, provided by the PESERA data set (Kirkby *et al.*, 2004). The calculated CO_2 emissions due to erosion range from 0 (mean 0.5 per cent SOC, mean PESERA erosion risk 0.25 t soil $ha^{-1}yr^{-1}$) to 0.85 t CO_2-eq ha^{-1} yr^{-1} (mean 4.7 per cent SOC, mean PESERA erosion risk 3.5 t soil $ha^{-1}yr^{-1}$). Higher PESERA risk categories that are not typically present within England (Kirkby *et al.*, 2004) have been excluded.

2.5 Carbon sequestration

Carbon sequestration following a change in land use or management practice is deducted from the total CO_2-eq calculated. Where the ELS option instigates a change in land use or management practice conducive to a change in SOC, this has been calculated to a depth of 30 cm, summarised in Table II (Dawson and Smith, 2007; Louwagie *et al.*, 2009). Plant biomass includes above- and below-ground-living plant components (roots, stem and leaves), 50 per cent of which is allocated as C (IPCC, 2006) (Table II). Arable crops achieve full biomass potential within one year, whereas woodlands may require several decades (Dawson and Smith, 2007).

2.6 Impact assessment and benchmarking

Generic ELS management data have been extracted from the ELS Handbook (Natural England, 2013) and refined further to account for farm specific factors through interviews with farm managers and Natural England officers. The calculation of GHG emissions from baseline and option management scenarios, and any differential between the two, uses a national inventory Tier 2 approach (IPCC, 2006; Webb *et al.*, 2013) modified to detect the impact of more subtle changes in management and to account for the spatially explicit variables of soil type, and risk of erosion and run-off. It also considers the impact on crop yields for each option individually. Findings are discussed in relation to a standard direct comparison of absolute emissions from the new land management compared to that of the original baseline, as stipulated by the IPCC (2006). They are then also compared with two alternative units of measurement or benchmarks:

(1) baseline yield equivalent ($\text{Base}_{[\text{yield}]}$ eq) that accounts for the impact on crop yield; and
(2) 6 m grass buffer strip on non-vulnerable mineral soil equivalent ($6\text{m}_{\text{GBS(nvms)}}$ eq) used where crop yield is reduced to zero and the $\text{Base}_{[\text{yield}]}$ eq functional unit is not viable.

A yield decrease of, for example, 50 per cent, necessitates production on an equivalent 2 ha, as opposed to 1 ha, to produce a yield equivalent to the baseline. The emissions per $Base_{[yield]}$ eq for the new land use are therefore calculated over 2 ha in total. A further functional unit that benchmarks emissions reduction relative to a 6-m grass buffer strip on non-vulnerable mineral soil ($6m_{GBS(nvms)}$ eq) considers production displacement risk. Where land is removed from production, a direct comparison of GHG emissions from the ELS option management scenario relative to that of the original baseline quantifies the absolute change in emissions. It does not account for the impact of removing land from production, and the risk of displacement and "system leakage" (Smith *et al.*, 2007). The creation of, for example, grass areas on productive agricultural land, may shift the emissions onto land elsewhere. If a theoretical displacement of productivity occurs from a high to a low-risk soil (e.g. from an area of steep to low gradient), a net emissions reduction occurs, equivalent to those embedded within the erosion process (NO_3^- and SOC in surface run-off). Benefit is only realised, however, where an emissions reduction of this nature occurs. Options are allocated mitigation potential and higher priority where the emissions reduction exceeds this benchmark.

The annual change (△) in CO_2-eq (CO_2-eq option minus CO_2-eq baseline) has been calculated for Years 1-5, compatible with the Kyoto accounting period and the ELS management agreement length. A negative value indicates a decrease in absolute GHG emissions. Equations (2) and (3) convert output to the $Base_{[yield]}$ eq or $6m_{GBS(nvms)}$ eq benchmark, depending on the impact on crop yield:

decrease in yield <30%

$$\Delta CO_2 - eq\ Base_{[yield]}\ eq = \Delta CO_2 - eq/yield\ factor \tag{2}$$

where: *yield factor* = % yield of option relative to baseline/100

decrease in yield >30%

$$\Delta CO_2 - eq\ 6m_{GBS(nvms)}\ eq = CO_2 - eq\ option_{(n)} - CO_2 - eq\ 6m_{GBS(nvms)(n)} \tag{3}$$

where: $CO_2 - eq\ 6m_{GBS(nvms)(n)} = CO_2 - eq$ of a 6m grass buffer strip on non−vulnerable mineral soil during year n

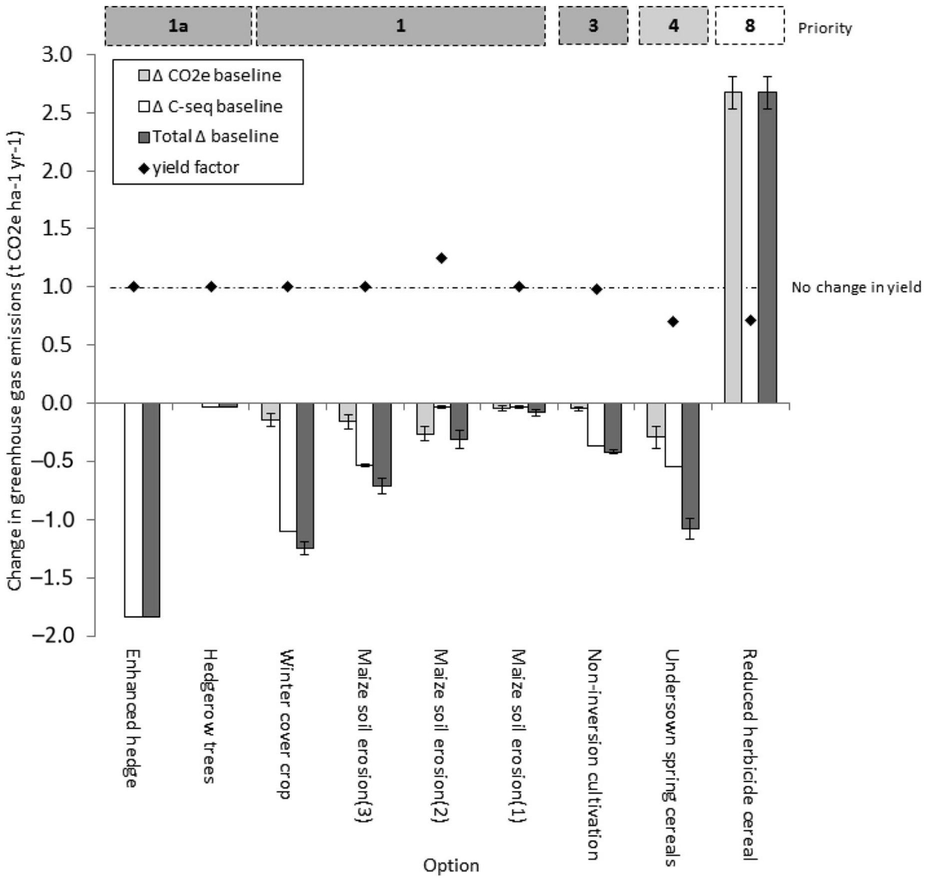
The 30 per cent threshold reflects typical yield difference between a winter and spring cereal crop in England (Nix, 2014).

3. Results

3.1 Potential change in greenhouse gas emission per equivalent hectare of option per year and option prioritisation

The △CO_2-eq is displayed in two categories: per $Base_{[yield]}$ eq where yield reductions are <30 per cent (Figure 1) or where a yield decrease is >30 per cent per ha, relative to both the baseline (existing land use) directly and a $6m_{GBS(nvms)}$ eq (Figure 2).

A yield factor of less than 1 in Figure 1 (below the dashed line) illustrates a decline in yield. Bars below zero represent a decrease in GHG emissions relative to the original land use (i.e. the absolute decrease compared to the baseline). The comparison with a $6m_{GBS(nvms)}$ eq (Figure 2) illustrates the emissions decrease relative to the removal of land from production, i.e. emissions are not purely transferred elsewhere on farm but achieve additional GHG reduction through appropriate spatial targeting on high risk soils. The management



Note: Boxes and number at the top of graph refer to allocated option priority

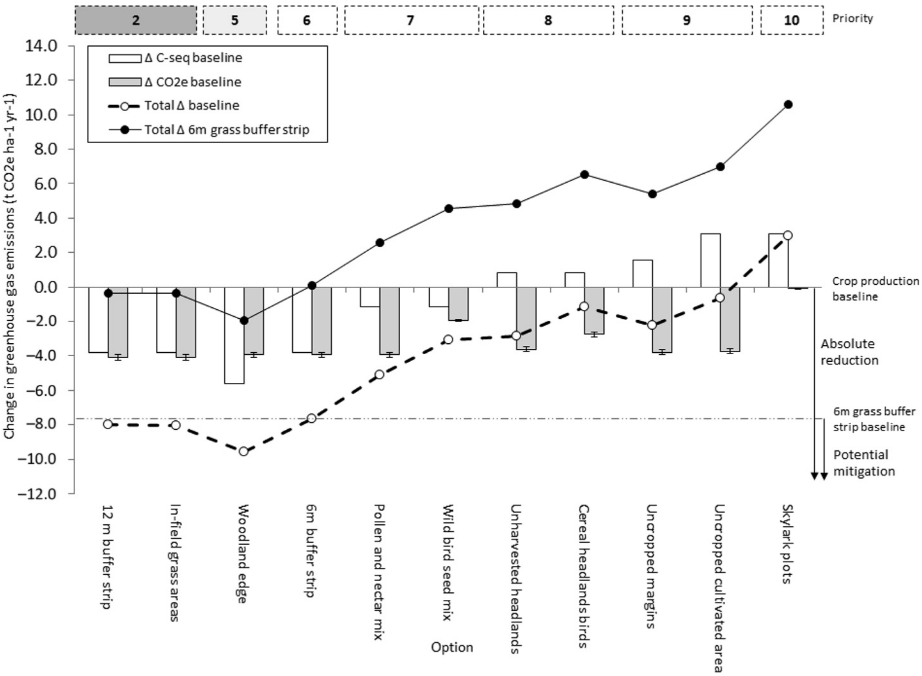
Figure 1.
Net change in GHG emissions (t CO_2-eq $ha^{-1}yr^{-1}$) per $Base_{[yield]}$ eq (below zero indicates a decrease in emissions) and yield factor (1.0 = no change in yield, below 1.0 = a yield decrease) for options with <30 per cent yield reduction

practices attributable to, and used to prioritise each ELS option, are summarised in Table I (bold text). They are used in combination with impact on crop yield and GHG emissions reduction, both absolute compared to the baseline and relative to a $6m_{GBS(nvms)}$ eq (Figures 1 and 2) to allocate priority (Figure 3).

A breakdown of key sources of change in emissions and C sequestration is provided in Table III. The high priority options achieve either a decrease in emissions with a negligible impact on crop yield (options where yield reduction is <30 per cent + crop baseline) or where production is removed, there is a reduction in emissions greater than that of a 6-m grass buffer $strip_{(nvms)}$. The key mitigation categories in the latter are CO_2 from soil erosion and N_2O from soils (Table III).

3.2 Priority 1-3: options for greenhouse gas mitigation

Existing field boundaries in the non-cropped area and where plant biomass is increased do not impact crop yield. Within the cropped area, the soil protection options (management of maize crops to reduce soil erosion) and winter cover crops preceding spring cereals on sandy soils

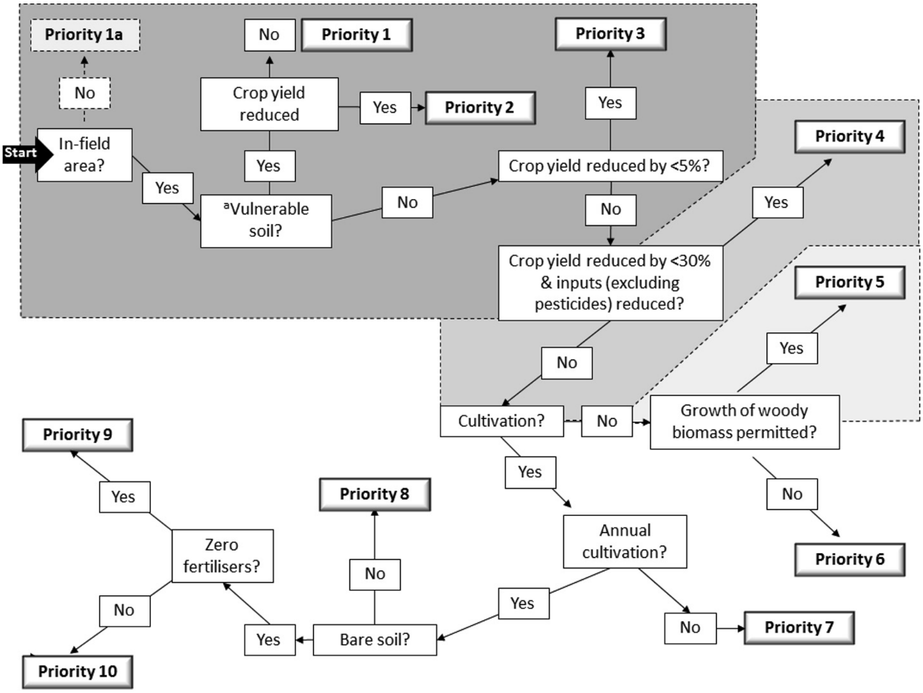


Note: Error bars refer to a standard error of the mean. Boxes and number at the top of graph refer to allocated option priority

Figure 2.
Net change in GHG emissions (t CO_2-eq $ha^{-1}yr^{-1}$) compared directly to a baseline of cropped land (bars) and a 6-m buffer strip on non-vulnerable mineral soil ($6m_{GBS(nvms)}$ eq) (dashed line)

achieve the greatest CO_2-eq reduction, without yield compromise. They have been designated Priority 1. Maize tends to be sown in late spring but harvested as late as the end of October or early November, depending on variety and latitude (Agro Business Consultants, 2013). Crops harvested late do not allow a winter crop to be sown, and a fallow period exists during the winter. Where later harvesting on wetter soils results in compaction, surface run-off may be a problem (Defra, 2005; USDA, 2002). Mitigation of GHG emissions (Table III) is attributed to decreased surface run-off, soil erosion or NO_3^- leaching, and a proportion of supplementary N fertiliser supplied by an undersown legume in EJ2 sub-option [equation (3)]. In this option, SOC and N_2O in run-off decrease by a mean of up to 0.4 and 0.01 t CO_2-eq ha^{-1} respectively, per year, over two years (maize crop and the following crop). The substitution of inorganic N fertiliser equates to 0.6 t CO_2-eq ha^{-1} from manufacture (Brentrup and Pallière, 2008) and application (Williams *et al.*, 2009). The mechanism of emissions reduction beyond that of a $6m_{GBS(nvms)}$ eq in 12 m buffer strips for watercourses on cultivated land and in-field grass areas, to prevent erosion and run-off, is derived via a similar mechanism (Table III). Because of the 100 per cent yield loss incurred, the allocated priority has been decreased to Priority 2 (Figure 2). Inclusion of a winter cover crop on sandy soils before a spring-sown cereal may decrease NO_3^- leaching and the consequent indirect N_2O emissions by 25-50 kg N $ha^{-1}yr^{-1}$ (Silgram and Harrison, 1998), equivalent to 0.06-0.1 t CO_2-eq $ha^{-1}yr^{-1}$. According to Dawson and Smith (2007), removal by light cultivation returns additional biomass to the soil and enhances SOC levels by 1.1 t CO_2-eq $ha^{-1}yr^{-1}$ (Table III).

The benefits of reduced-depth non-inversion cultivation on archaeological features are realised by replacing a 20-cm plough and power harrow combination with a single



Note: [a]vulnerable soil refers to at risk of erosion or leaching

Figure 3.
Dichotomous key to prioritise ELS options for GHG mitigation: ■ supports GHG mitigation; ■ emissions reduction per $Base_{[yield]}$ eq; □ emissions reduction per $6m_{GBS(nvms)}$; □ emissions increase per $Base_{[yield]}$ eq or per $6m_{GBS(nvms)}$

pass of a disc harrow, decreasing diesel consumption by 0.06-0.15 t CO_2-eq $ha^{-1}yr^{-1}$. Estimates of yield penalty for this system vary between 0 and 5 per cent (Knight *et al.*, 2012; National Soil Resources Institute (NSRI), 2001), although it also depends on the time lapsed since inception of the reduced cultivation programme (Knight *et al.*, 2012). Emissions per equivalent ha require utilisation of an additional 5 per cent land area for a worst-case estimate. This option has been classified as Priority 3; emissions are potentially reduced, but a yield decrease, albeit small, may result. Soil organic carbon is enhanced by 0.37 t CO_2-eq $ha^{-1}yr^{-1}$ (Dawson and Smith, 2007).

3.3 Priority 4: options with potential for greenhouse gas mitigation at the expense of yield

Spring cereal crops undersown with clover (EG1) have a clover/grass mixture sown simultaneously. The undersown mix grows in synchrony with the cereal and then remains post-harvest for one year. A winter cereal is substituted within the rotation, for which a 30 per cent yield decrease is typical (Nix, 2014), and this is then followed by a grass/clover ley. It is assumed that the ley is utilised as part of normal farming operations by income foregone calculations (Natural England, 2013). The t CO_2-eq per $Base_{[yield]}$ eq is reduced (Figure 1), despite the yield reduction, provided that the N supplied by the undersown legume is taken into account and deducted from the fertiliser recommendations (Defra, 2010). This option is allocated Priority 4 (Figure 3) because of the t CO_2-eq reduction per unit of yield combined with a 30 per cent yield reduction.

Option	Priority	Farm operations	Crop protection	Fertiliser	N_2O soil	CO_2 soil erosion	SOC	Biomass carbon
Options where yield reduction is <30% + crop baseline								
Enhanced hedge	1a	0	0	0	0	0	0	−3
Hedgerow trees	1a	0	0	0	0	0	0	−1
Winter cover crop	1	1	0	0	−2	−2	−3	0
Maize soil erosion (3)	1	−1	0	−2	−2	−2	−3	0
Maize soil erosion (2)	1	0	0	0	−1	−2	−1	0
Maize soil erosion (1)	1	0	0	0	−1	−2	−1	0
Non-inversion cultivation	3	−1	1	0	−1	−1	−2	0
Undersown spring cereals	4	1	0	−2	−1	0	−2	0
Reduced herbicide cereal	8	−1	−1	0	0	0	0	0
Options where yield reduction is >30% + crop baseline								
12 m buffer strip	2	−2	−1	−3	−3	−2	−3	−2
In-field grass areas	2	−2	−1	−3	−3	−2	−3	−2
Woodland edge	5	−2	−1	−3	−3	−1	−3	−3
6-m buffer strip	6	−2	−1	−3	−3	−1	−3	−2
Pollen and nectar mix	7	−2	−1	−3	−3	−1	−2	−2
Wild bird seed mix	7	−2	−1	−3	−2	−1	−2	−2
Unharvested headlands	8	−1	0	−3	−3	0	0	2
Cereal headlands birds	8	−1	0	−3	−3	0	0	1
Uncropped margins	9	−1	−1	−3	−3	1	0	3
Uncropped cultivated area	9	−1	−1	−3	−3	1	3	3
Skylark plots	10	0	0	0	1	1	3	3
Options where yield reduction is >30% + 6-m grass buffer strip baseline (non-vulnerable mineral soil)								
12 m buffer strip	2	0	0	0	−1	−2	0	0
In-field grass areas	2	0	0	0	−1	−2	0	0
Woodland edge	5	0	0	0	0	0	0	−3
6-m buffer strip	6	0	0	0	0	0	0	0
Pollen and nectar mix	7	1	0	0	0	1	3	0
Wild bird seed mix	7	1	1	3	2	1	3	0
Unharvested headlands	8	2	1	0	1	1	3	2
Cereal headlands birds	8	2	1	0	1	1	3	2
Uncropped margins	9	2	−1	0	1	1	3	3
Uncropped cultivated area	9	2	−1	0	1	1	3	3
Skylark plots	10	2	1	3	3	1	3	3

Notes: Values in cells indicate change in total greenhouse gas balance: −3 (<−1.0); −2 (from −1.0 to −0.1); −1 (from −0.1 to 0); 0 (no change); 1 (0 to 0.1); 2 (0.1 to 1.0); 3 (>1.0)

Table III. Summary matrix of key sources of change in GHG emissions and carbon sequestration for options where yield is reduced by <30% (+ crop baseline); >30% (+ crop baseline, + 6-m grass buffer strip baseline)

3.4 Priority 5 and 6: breaking even with displacement

Priority 6 options have been allocated as the "break even" category. There is no GHG mitigation or net increase in emissions when localised production displacement is considered. The establishment of minimal input grass strips or a similar land use reduces GHG emissions relative to the baseline (from −7.3 to −8.3 t CO_2-eq $ha^{-1}yr^{-1}$). Where they are not specifically targeted on vulnerable soils, this emissions reduction is mainly limited to inputs associated with the production process. No additional mitigation value through the protection of vulnerable soils is gained (Figure 2). The management of woodland edges permits growth of additional biomass as scrub on 50 per cent of the area, which enhances its value (from -9.1 to -10.1 t CO_2-eq $ha^{-1}yr^{-1}$) relative to grass buffer strips, albeit over a finite period of time (15-20 years), until an equilibrium is reached (Priority 5).

3.5 Priority 7 and 8: options with >30 per cent yield loss and/or limited greenhouse gas reductions

Pollen and nectar mixtures and wild bird seed mixtures undergo re-establishment every two years, comparable to a short-term grass/clover ley (Table II). Fuel expenditure decreases compared to annual cultivation by 0.05-0.1 t CO_2-eq ha^{-1} (Table II). Although the CO_2-eq is reduced relative to the original baseline (Figure 2), compared to a $6m_{GBS(nvms)}$ eq, GHG emissions increase by 2.0-4.0 t CO_2-eq $ha^{-1}yr^{-1}$. They are allocated as Priority 7 (Figure 3).

Input reductions limited to crop protection products (e.g. reduced herbicide cereal crops) reduce yield (17 per cent stipulated by income foregone calculations) disproportionally to the associated GHG decrease (<1 per cent), for which an increase in emissions of 2.2-3.6 t CO_2-eq $ha^{-1}yr^{-1}$ per $Base_{[yield]}$ eq (Figure 1) results (Priority 8). GHG intensive inputs, such as supplementary N fertiliser (Table II), continue to be applied.

3.6 Priority 9 and 10: options with fallow

The creation of bare fallow areas, for example, for ground-nesting birds or to allow natural regeneration of arable flora (Priority 9), causes a decline in plant biomass at equilibrium (Figure 2). Operations, although restricted solely to tillage, reduce the CO_2-eq relative to the baseline but cause an increase compared to a $6m_{GBS(nvms)}$ eq (Figure 2). Skylark (*Alauda arvensis*) plots (Priority 10) continue to receive inputs almost identical to the baseline crop because of their small area (minimum size 16 m^2) and location within central crop areas (Natural England, 2013). The CO_2-eq increases relative to both the baseline crop management regime and relative to a $6m_{GBS(nvms)}$ eq (Figure 2).

4. Discussion

4.1 The importance of field boundary options differentiated by structure and in combination

Field boundaries (e.g. hedgerows) and their associated AE options utilise existing non-productive areas of the farm and do not typically impact crop yields further. It is acknowledged that a reduction in yield of the outer crop may result from Local Environment Risk Assessment for Pesticides stipulations, which prohibit the application of certain agrochemicals. Existing boundaries will, however, already be subject to such limitations. Hedgerows are not a component of the productive area in the strictest sense, but warrant inclusion for the sake of completeness and are considered high priority (Figure 3). Hedgerows are included within EFAs in England and receive the highest weighting with respect to area (10 m^2 per 1 m of hedge), although the administration associated with their inclusion has proven problematic (Defra, 2014) and a rather contentious issue. All hedges have required remapping and to be digitally recorded (EC, 2014). The administrative burden associated with remapping of hedgerows has rendered the inclusion of further detail impractical. The presence or absence of a hedge is the only parameter recorded. It is unfortunate, as structural information could be inferred from the type of hedgerow option shown previously under ELS, and this information could be captured from the original farm environment maps for relevant ELS hedgerow options. A number of AE options pertinent to boundary features existed within ELS, including greater hedge height, planting of trees within the hedge and management by hedge-laying (Natural England, 2013). Used in combination, they increased biomass by up to 2.5 times that of a standard 1.5 m vertical hedge. These options, and the promotion of structural difference in hedgerows, is currently absent in EFAs.

4.2 Priority agri-environment options for greenhouse gas mitigation on cultivated land

GHG mitigation may arise from the maintenance of crop production but with a decrease in emissions or a removal of crop production in its entirety and replacement with an alternative low input land use. A number of studies to date comment on mitigation achieved from the latter but fail to acknowledge the risk of production displacement, i.e. the transfer of those emissions to land elsewhere with no net reduction or even an increase. In a country where productive agricultural land is at a premium, its removal from production is counter to Defra's 2020 strategy (Defra, 2011) and the concept of sustainable intensification (Godfray *et al.*, 2010; Royal Society of London, 2009). Option prioritisation has not, therefore, been applied to maximising emissions reduction, rather to maximising reduction coupled with a minimal impact on crop yield. The Priority 1 ELS options in Figure 3, when positioned strategically, mitigate the risk of N_2O emission indirectly from NO_3^-, via leaching or surface run-off, but do not reduce crop yield. Two AE option categories are included within this classification, winter cover crops and options to prevent soil erosion. Winter cover crops preceding spring-sown crops on cultivated sandy soils assimilate a proportion of the residual soil N, which is vulnerable to leaching or surface run-off as NO_3^-, during the otherwise non-cropped period (Machefert *et al.*, 2002; Silgram and Harrison, 1998). The second type of option within this category, those that reduce soil erosion, potentially reduce the loss of SOC (coupled with elevated emission of CO_2) and GHGs associated with NO_3^- transported via surface run-off (IPCC, 2006; Kirkby *et al.*, 2004; Webb *et al.*, 2013). Both winter cover crops and measures to prevent soil erosion are included in the EFA catch crop/green cover component (Defra, 2014). The implementation of these Priority 1 options is now included under Pillar 1 as opposed to Pillar 2, offering the potential for an increase in uptake. The lower weighting of both options (0.3 m^2) within the EFA proposals does not, however, correspond to the GHG mitigation priority identified in this paper. Under the EU optional weighting system (EC, 2014), these options effectively receive a reduced incentive of 0.3 m^2 compared to, for example, the 1 m^2 assigned to fallow land (Defra, 2014), deemed a significantly lower GHG mitigation priority by this paper. From a GHG mitigation perspective, the EFA catch crop/green cover elements would benefit from an increase in area weighting.

The removal of productive agricultural land risks transfer of emissions elsewhere, with zero mitigation overall. Mitigation may be achieved under such circumstances where baseline emissions exceed typical levels because of localised environmental variables such as soil erosion or surface run-off. The transfer of production to land where baseline emissions are lower because of the absence of such variables results in a potential net decrease in emissions. The AE options identified as Priority 2 target the removal of cultivated land from production where soil erosion risk is high, but unlike the Priority 1 options, land is removed from production. Although not consistent with the ethos of maintaining crop production discussed in the previous section, emissions are reduced relative to the $6m_{GBS(nvms)}$ (Priority 6) threshold. Examples include in-field grass areas and 12-m grass buffer strips next to a watercourse (Natural England, 2013). Again, appropriate spatial targeting is critical; otherwise, these options function only in the capacity of a Priority 6 option. The decrease in the CO_2-eq results solely from the removal of productive agricultural land. Grass buffer strips are a component of EFAs, and their stipulated positioning, either adjacent to watercourses or parallel to and on a slope on a trajectory with a watercourse (EC, 2014), includes them within this Priority 2 category. A potential disadvantage of these strips is their minimum specified width of 1 m (EC, 2014). The effectiveness of grass buffer strips at reducing run-off and intercepting NO_3^- reaching watercourses is reported to diminish with width (Dillaha *et al.*, 1986). By this rationale, the GHG mitigation benefit risks being lower than that associated with the 12 m widths are required under the former ELS scheme (Natural England, 2013).

The selection of non-inversion or minimum tillage as a Priority 3 option is undertaken on the proviso that yield reduction does not exceed 5 per cent. Verification of yield loss from the published literature suffers primarily from a lack of long-term data and opinion among authors is divided. The five-year life-span of an ELS agreement is dealt with by Knight *et al.* (2012), who note that yields suffer an initial decline before stabilising at a 2-5 per cent reduction, although NSRI (2001) report negligible yield losses for both light and heavy soil textures. It is not included within EFAs, although the impact of this would appear negligible because of the previous limited availability within the former ELS scheme. Its inclusion would warrant further substantiation of its full impact, something that will only be established under continued long-term minimum tillage trials.

Nitrogen-fixing crops, such as clover, offer the potential to replace a proportion of the supplementary inorganic N applied to crops and to reduce emissions associated with the manufacturing process (Brentrup and Pallière, 2014). The undersowing of spring crops with clover supplements the later inorganic N applications with N fixed by this mechanism (Defra, 2010). To be effective however, uniform clover establishment is needed. Further, any potential N that is fixed must be deducted from the prescribed supplementary N recommendations. The green cover and N-fixing crops EFA elements are the closest comparable options under CAP post 2014 reform, which, as discussed previously, are not attributed a high area equivalent for deduction from the required 5 per cent land total.

4.3 Scope for improvement?

An emissions reduction equivalent to or lower than establishing a zero input 6-m grass buffer strip on a non-vulnerable soil corresponds to ELS Priority 6 or below. Alteration of management under the existing ELS scheme to reduce emissions further is difficult, although options exist for implementation under EFAs. The grass areas may, for example, be purposely sown, offering potential for the selection of grass species with greater biomass accumulation capacity in the absence of supplementary N. Cocksfoot (*Dactylis glomerata* L). or the fescue *Festuca arundinacea* var. *glaucescens* Boiss. are both grass species with deeper rooting ability (Durand *et al.*, 2007) and have the ability to enhance SOC in deeper soil layers when included within sown mixtures (Dawson and Smith, 2007). The importance of Rural Development Programme measures, ELS inclusive, in assisting adaptation to climate change has been highlighted by Tzilivakis *et al.* (2015). Tall fescue grass species, for example, are tolerant of climatic extremes, such as prolonged drought (Finn *et al.*, 2013). Their inclusion in mixtures warrants further consideration where climate projections predict future increases in drought frequency, particularly in the Southeast and East of England (Murphy *et al.*, 2010).

4.4 Potential clashes

The soil and water protection options and to a degree the hedgerow options post 2014 are sympathetic to agricultural GHG mitigation. A potential clash of objectives exists where fallow areas are retained for biodiversity, for birds, pollinating insects or arable flora. Fallow is defined as uncultivated ground with no sown crop (EC, 2014), equivalent to the ELS Priority 9 option. Under the EC (2014) EFA optional weightings system, a higher weighting and apparent priority is granted to fallow areas relative to the cover or catch crops previously identified in this paper as high-priority ELS GHG mitigation options. In England, this weighting has been applied as a means to maximise the area that each option contributes to the target 5 per cent EFA area, thereby maintaining this hierarchy. The sowing of pollen and nectar or wild bird seed mixtures, comparable to ELS Priority 7, within the EFAs selected for fallow has, however, been permitted. Below the Priority 6 "break-even" benchmark, the sown mixtures represent an improvement compared to bare ground (Priority 9).

In summary, it appears that existing ES options beneficial to GHG reduction will be continued. The majority of EFA elements, with the exception of fallow areas, are of Priority 6 ("break-even") or above, suggesting a mostly positive impact on agricultural GHG emissions from EFAs. The main caveat is the apparent lower importance afforded in EFAs to area for the high-GHG-priority cover and catch crops relative to lower GHG priority fallow areas.

5. Conclusions

Under proposed modifications to cross-compliance in England (Defra, 2014), grass buffer strips along watercourses, maintenance of a minimum ground cover, management to minimise soil erosion within high risk areas and maintenance of soil organic matter will be a requirement of good agricultural and environmental conditions in England. The high-priority ELS GHG mitigation options outlined above will potentially become a part of Pillar 1, a mandatory requirement for the basic farm payment, as opposed to Pillar 2, undertaken voluntarily. The mitigating effect of these options would, in principle, extend to all farms, not solely those that chose to enter the scheme voluntarily. The lower weighting within the EFAs (EC, 2014) of these high-priority GHG mitigation options does, however, risk that their selection will not be afforded the same level of importance.

Many AE options within the ELS scheme were already managed, given their primary objectives, in a manner that minimised the CO_2-eq, although potential improvements have been highlighted. Subtle changes may be possible to EFA elements not necessarily of value in reducing agricultural GHG emissions as a whole, but that provide other key ecosystem services such as crop pollination or biodiversity enhancement, to further reduce the CO_2-eq while continuing to fulfil these objectives. Although this paper reports on ELS within England, many of the options discussed, or their variants, are implemented in AE schemes across Europe, and the findings are equally applicable.

References

Agro Business Consultants Ltd. (2013), *The Agricultural Budgeting and Costing Book*, 75th ed., ABC Books, Melton Mowbray, Leicestershire.

Allen, B., Buckwell, A., Baldock, D. and Menadue, H. (2012), *Maximising Environmental Benefits through Ecological Focus Areas*, Institute for European and Environmental Policy, London.

Audsley, E., Stacey, K., Parsons, D.J. and Williams, A.G. (2009), *Estimation of the Greenhouse Gas Emissions From Agricultural Pesticide Manufacture and Use*, Cranfield University, Bedfordshire.

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

Climate Change Act (2008), *Chapter 27*, The Stationary Office, London.

Dawson, J.J.C. and Smith, P. (2007), "Carbon losses from soil and its consequences for land-use management", *Science of the Total Environment*, Vol. 382 Nos 2/3, pp. 165-190.

Department for Environment, Food and Rural Affairs (2005), *Revitalisation of the FSR/FEH Rainfall Runoff Method*, FD1913/TR, The Stationary Office, London.

Department for Environment, Food and Rural Affairs (2010), *Fertiliser Manual (RB209)*, 8th ed., PB13381, The Stationary Office, London.

Department for Environment, Food and Rural Affairs (2011), *Biodiversity 2020: A Strategy for England's Wildlife and Ecosystem Services*, PB13583, The Stationary Office, London.

Department for Environment, Food and Rural Affairs (2013), *The Guide to Cross Compliance in England*, The Stationary Office, London.

Department for Environment, Food and Rural Affairs (2014), *Consultation on the Implementation of CAP Reform in England: Government Decisions on Greening*, Crown Copyright, UK.

Department for Environment, Food and Rural Affairs (2015), *United Kingdom – Rural Development Programme (Regional) – England*, 014UK06RDRP001 Version 1.2, Department for Environment, Food and Rural AffairsLondon.

Department of Energy and Climate Change (2015), *2013 UK Greenhouse Gas Emissions, Final Figures, Statistical Release 3rd February 2015*, URN [15D/031], London.

Dillaha, T.A., Sherrard, J.H. and Lee, D. (1986), *Long-Term Effectiveness and Maintenance of Vegetative Filter Strips*, Bulletin 153, VA Water Resources Research Center, Blacksburg, VA.

Durand, J.L., Bariac, T., Ghesquière, M., Biron, P., Richard, P., Humphreys, M.W. and Zwierzykowski, Z. (2007), "Ranking of the depth of water extraction by individual grass plants using natural ^{18}O isotope abundance", *Environmental Experimental Botany*, Vol. 60 No. 1, pp. 137-144.

European Commission (2013), "Regulation (EU) No 1307/2013 of the European Parliament and of the Council of 17 December 2013 establishing rules for direct payments to farmers under support schemes within the framework of the Common Agricultural Policy and repealing Council Regulation (EC) No 637/2008 and Council Regulation (EC) No 73/2009", *Official Journal of the European Union*, Vol. L347, pp. 608-670.

European Commission (2014), "Commission delegated regulation (EU) No 639/2014 of 11 March 2014 supplementing regulation (EU) No 1307/2013 of the European Parliament and of the Council Establishing Rules for Direct Payments to Farmers Under Support Schemes Within the Framework of the Common Agricultural Policy and Amending Annex X to that Regulation", *Official Journal of the European Union*, Vol. L181, pp. 1-47.

Finn, J.A., Kirwan, L. and Connolly, J. (2013), "Ecosystem function enhanced by combining four functional types of plant species in intensively managed grassland mixtures: a 3-year continental-scale field experiment", *Journal of Applied Ecology*, Vol. 50 No. 2, pp. 365-375.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M. and Toulmin, C. (2010), "Food security: the challenge of feeding 9 billion people", *Science*, Vol. 327 No. 5967, pp. 812-818.

Hülsbergen, K.J. and Kalk, W.D. (2001), "Energy balances in different agricultural systems – can they be improved?", *International Fertiliser Society Proceedings*, Vol. 476.

Intergovernmental Panel on Climate Change (2006), *IPCC Guidelines for National Greenhouse Gas Inventories*, IGES Publications.

Jones, R.J.A., Hiederer, R., Rusco, E., Loveland, P.J. and Montanarella, L. (2005), "Estimating organic carbon in the soils of Europe for policy support", *European Journal of Soil Science*, Vol. 56 No. 5, pp. 655-671.

Kirkby, M.J., Jones, R. and Huting, J. (2004), *Pan-European Soil Erosion Risk Assessment: The PESERA Map*, European Commission, Ispra.

Knight, S., Kightley, S., Bingham, I., Hoad, S., Lang, B., Philpott, H., Stobart, R., Thomas, J., Barnes, A. and Ball, B. (2012), "Desk study to evaluate contributory causes of the current 'yield plateau' in wheat and oilseed rape", HGCA Project Report No. 502, Agriculture and Horticulture Development Board, London.

Louwagie, G., Gay, S.H. and Burrell, A. (2009), *Sustainable Agriculture and Soil Conservation (SoCo)*, European Commission, Brussels.

Machefert, S.E., Dise, N.B., Goulding, K.W.T. and Whitehead, P.G. (2002), "Nitrous oxide emission from a range of land uses across Europe", *Hydrological Earth System Science*, Vol. 6 No. 3, pp. 325-337.

Murphy, J., Sexton, D., Jenkins, G., Boorman, P., Booth, B., Brown, K., Clark, R., Collins, M., Harris, G. and Kendon, L. (2010), *UK Climate Projections Science Report: Climate Change Projections, Version 3*, Met Office Hadley Centre, Exeter.

National Soil Resources Institute (NSRI) (2001), *A Guide to Better Soil Structure*, Cranfield University, Bedfordshire.

Natural England (2013), *Entry Level Stewardship (ELS) Handbook*, 4th ed., Natural England, Bristol.

Nix, J. (2014), *Farm Management Pocketbook*, 44th ed., Imperial College, London.

Panagos, P., Van Liedekerke, M., Jones, A. and Montanarella, L. (2012), "European soil data centre: response to European policy support and public data requirements", *Land Use Policy*, Vol. 29 No. 2, pp. 329-338.

Royal Society for the Protection of Birds (2011), "The common agricultural policy after 2013 - Written evidence submitted by The Royal Society for the Protection of Birds (RSPB)", available at: www.publications.parliament.uk/pa/cm201011/cmselect/cmenvfru/671/671we02.htm (accessed 2 December 2014).

Royal Society of London (2009), *Reaping the Benefits: Science and the Sustainable Intensification of Global Agriculture*, Royal Society, London.

Silgram, M. and Harrison, R. (1998), *The Mineralisation of Nitrogen in Cover Crops: A Review*, MAFF, London.

Smith, J.U., Bradbury, N.J. and Addiscott, T.M. (1996), "SUNDIAL: a PC-based system for simulating nitrogen dynamics in arable land", *Agronomy Journal*, Vol. 88 No. 1, pp. 38-43.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U. and Towprayoon, S. (2007), "Policy and technological constraints to the implementation of greenhouse gas mitigation options in agriculture", *Agriculture Ecosystems and Environment*, Vol. 118 No. 1, pp. 6-28.

Torbert, H.A., Reeves, D.W. and Mulvaney, R.L. (1996), "Winter legume cover crop benefits to corn: rotation vs. fixed-nitrogen effects", *Agronomy Journal*, Vol. 88 No. 4, pp. 527-535.

Tzilivakis, J., Warner, D.J., May, M., Lewis, K.A. and Jaggard, K. (2005), "An assessment of the energy input for sugar beet (*Beta vulgaris*) production in the UK", *Agricultural Systems*, Vol. 85 No. 2, pp. 101-119.

Tzilivakis, J., Warner, D.J., Green, A. and Lewis, K.A. (2015), "Adapting to climate change: assessing the vulnerability of ecosystem services in Europe in the context of rural development", *Mitigation and Adaptation Strategies for Global Change*, Vol. 20 No. 4, pp. 547-572.

United States Department of Agriculture (2002), *National Soil Survey Handbook, 430-VI*, available at: http://soils.usda.gov/technical/handbook/ (accessed 25 November 2012).

Warner, D.J., Davies, M., Hipps, N., Osborne, N., Tzilivakis, J. and Lewis, K.A. (2010), "Greenhouse gas emissions and energy use in UK grown short-day strawberry (*Fragaria xananassa*) crops", *Journal of Agricultural Science*, Vol. 148 No. 6, pp. 667-681.

Webb, N., Broomfield, M., Cardenas, L., MacCarthy, J., Murrells, T., Pang, Y., Passant, N., Thistlethwaite, G. and Thomson, A. (2013), *UK Greenhouse Gas Inventory, 1990 to 2011: Annual Report for submission under the Framework Convention on Climate Change*, Ricardo-AEA, Didcot.

Williams, A.G., Audsley, E. and Sandars, D.L. (2009), *Environmental Burdens of Agricultural and Horticultural Commodity Production – LCA (IS0205), Version 3*, Cranfield University, Bedfordshire.

Zhang, X. and Zhang, M. (2011), "Modelling effectiveness of agricultural BMPs to reduce sediment load and organophosphate pesticides in surface runoff", *Science of the Total Environment*, Vol. 409 No. 10, pp. 1949-1958.

Appendix

Table AI.
List of acronyms

Acronym	Description
AE	Agri-environment
$Base_{[yield]}$ eq	Baseline yield equivalent
CAP	Common agricultural policy
EC	European Commission
EFAs	Ecological Focus Areas
ELS	Entry-level stewardship
ES	Environmental stewardship
GAECs	Good agricultural and environmental conditions
GHG	Greenhouse gas
GIS	Geographical Information System
LCA	Life-cycle assessment
LERAPs	local environment risk assessment for pesticides
PESERA	Pan-European Soil Erosion Risk Assessment
SOC	Soil organic carbon
SPS	Single payment scheme
$6m_{GBS(nvms)}$ eq	6-m grass buffer strip on non-vulnerable mineral soil equivalent

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